Hygrothermal behavior of flat cool and standard roofs on residential and commercial buildings in North America

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Abstract

Installing roofs with high solar reflectance and high thermal emittance, known as "Cool roofs", are becoming popular because of their cooling energy saving potentials, cost effectiveness and sustainability. Cool roofs may affect the hygrothermal performance of roofing systems and hence their performance should be characterized in different climates.

We simulated the performance of several roofing systems including: Typical, smart, and self-drying roofs for residential and commercial buildings. In addition, we proposed vented roofs with smart vapor retarders in different climate regions across North America. We also developed an algorithm to investigate the effect of snow on hygrothermal behaviour of black and white roofs.

Results showed that office buildings never experience moisture accumulation problem in the simulation period (5 years). In residential buildings, white typical roofing compositions with conventional vapor retarders experienced moisture accumulation problems in cities such as Anchorage, Edmonton and St. John's. Using smart vapor retarder (smart roofs) or self-drying roofs helped to decrease risk of moisture accumulation. We showed that in these climates, adding a ventilated air space along

with using smart vapor retarder eliminated risk of moisture accumulation and prevented excessive OSB (oriented strand board) moisture content. Furthermore, our simulation results showed that risk of mold growth was significantly lower in vented smart roofs than other systems. Simulating the effect of snow on the roof for Anchorage, Montreal and Chicago showed that the hygrothermal performances of white roofs improved with snow accumulation on the roof.

Acknowledgment

I would like to express my sincere gratitude to my supervisor, Dr. Hashem Akbari, for his guidance and valuable advices and constant support during this research. I also thank my colleagues Ali Gholizadeh and Hatef Aria for their help along the way.

Dedication

This thesis is dedicated to my beloved wife, **Mehrsa** for her love, understanding, patience and encouragement she has given me.

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Symbol	Unit	Definition	Symbol	Unit	Definition
A	m^2	Area of material	P_{atm}	Pa	Atmospheric pressure
b	%	Thermal conductivity supplement	P_i	Pa	indoor vapor pressure
c_e	J/kg.K	Specific heat capacity of ice	P_L	Pa	Ambient air pressure
c_s	J/kg.K	Specific heat capacity	P_O	Pa	Outdoor vapor pressure
c_w	J/kg.K	Specific heat capacity of liquid water	P_{OC}	Pa	Cooling outdoor vapor pressure
D_m	1/ m^2s	Mass-related diffusion coefficient	P_{sat}	Pa	Saturated vapor pressure
D_T	kg/ m^2sK	Thermal diffusion coefficient	**Q**	W	Heat flow through material
D_w	m^2/s	Capillary transport coefficient	Q_{1-2}	W/ m^2	Radiant heat transfer between surfaces 1 to 2
d_w/d_ϕ	kg/ m^2	Derivative of moisture storage function	q_s	W/ m^2	Absorbed solar energy by surface
D_φ	kg/ m^2s	Liquid conduction coefficient	**sd**	m	thickness of air layer with equivalent Vapor diffusion resistance of a material
F_A	-	View factor	**t**	s	Time
F_E	-	Emissivity factor	**T**	K	Temperature
g_v	kg/ m^2s	Vapour diffusion flux density	T_a	K	Ambient temperature
g_W	kg/ m^2s	Liquid flux density	$T_{o,24h}$	°C	24 hour running average of outdoor temperature
h_c	W/ m^2K	Convective heat transfer coefficient	T_s	K	Surface temperature
h_e	J/kg.Km^2	Specific melting enthalpy	**U**	W/ m^2 K	Material conductance
h_r	-	Radiative heat transfer coefficient	**V**	m^2m^2	Building volume
H_s	J/ m^2	Enthalpy of the dry	**w**	kg/ m^2	Total water content
H_w	J/ m^2	Enthalpy of moisture in building material	W_e	kg/ m^2	Frozen water content
I	W/m^2	Solar radiation intensity	α	m^3	Surface solar absorptance
I_e	1/h	Air exchange rate	δ	kg/ m^2sPa	Water vapour diffusion coefficient in air
k	W/mK	Moist thermal conductivity	ε	-	Surface thermal emittance
K_o	W/mK	Dry thermal conductivity	μ	-	Water vapour diffusion resistance factor
l	mmK	Material thickness	ρ_s	kg/ m^2	Bulk density
m	kg	Mass fraction of water vapour	σ	W/ m^2K	The Stefan-Boltzmann constant = $5.67x10^{-8}$
MC	kg/m^2	Moisture content	ϕ	%	Relative humidity10^{-8}
m_s	kg/s	Moisture source rate			
P	Pa	Water vapour partial pressure			

List of Acronyms

Abb.	Full name
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CDD	Cold degree day
CMHC	Canada Mortgage and Housing Corporation
CSPE	Chlorosulfonated Polyethylene
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EMC	Equilibrium moisture content
EPDM	Ethylene Propylene Diene Monomer
HAM	Heat, air and moisture
HDD	Heating degree days
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IRC	Institute for Research in Construction
MC	Moisture content
NIR	Near infrared
NRC	National Research Council Canada
ORNL	Oak Ridge National Laboratory
OSB	Oriented strand board
PA	Polyamide
PVC	Polyvinyl chloride
RH	Relative humidity
SR	Solar reflectance
SRI	Solar reflectance index
TPO	Thermoplastic olefins
WUFI	Wärme Und Feuchte Instationär, (Transient heat and moisture)

Chapter 1 Introduction

1.1 Moisture Behaviour of Cool Roofs

Roofs as a large part of the building envelope play an important role in energy consumption of buildings. Roofs that stay cool in the sun, having a low solar absorption and high thermal emission are called ‘cool roofs’. (Akbari & Levinson, 2008). Cool roofs can offer savings in air conditioning energy use. Advantage of using cool roofs is not only limited to reduction of cooling loads in buildings, but they also can help to reduce air pollution and greenhouse gas emissions. (Akbari, et al., 2009).

In cold climates with short summers, lower surface temperature of cool roofs may reduce the drying potential of moisture which may lead to the risk of moisture accumulation in the roofing assembly. Furthermore, higher thermal emission of cool roofs (non-metallic surfaces) may result in overcooling of the surface below ambient temperature. Such low temperature during the night can cause the temperature to drop below the dew point, followed by condensation of moisture in roof. Consequently, it is essential to investigate hygrothermal behavior of cool roofs and design roofing assemblies with lower risk of moisture.

The possible moisture-related roof problems are: reduced thermal resistance of insulation, mold growth leading to deterioration of indoor air quality (IAQ), metal corrosion, decay of wood-based material and ice built up.

1.2 Objectives of Project

The objective of the research is to improve the understanding of the hygrothermal performance of cool roofs for residential and commercial buildings in North America.

1.3 Approach

The research initiated with review of existing literatures associated with cool roofs fundamentals and transport of moisture in building envelope. We reviewed characteristics of several simulation models for analysis of the effect of the roof surface temperature on moisture transport. We selected an existing model and simulated the roof's moisture content for a variety of roofing systems in several representative climates in North America.

1.4 Thesis organization

This thesis is organized in five other chapters in addition to this introductory chapter. (Chapter 1)

Chapter 2 presents a review of the literature relevant to the study of both cool roofs and mechanism of condensation. The chapter begins with a brief description of cool roofs, various roofing systems, and an overview of self-drying and smart roofs. This is followed by a discussion of condensation phenomenon in various roofing systems. Finally, we review existing studies on the hygrothermal performance of cool roofs in different climates.

Chapter 3 presents a concise overview of heat and moisture transfer principles in porous building materials. Moisture and thermal storages in building materials is also discussed in this chapter.

Chapter 4 discusses our research methodology. We review and compare the capabilities of various simulation programs and select an appropriate program for our analysis. A new algorithm in this chapter is developed to simulate the effect of snow on hygrothermal behaviour of roofs. This chapter concludes with a discussion of several standards, guidelines and criteria for evaluation of hygrothermal behaviour of roofs.

Chapter 5 consists of two major parts. In the first part, boundary condition and characteristics of each simulation scenarios are described such as; outdoor conditions, indoor conditions and roofing systems. Second part of this chapter presents results of our simulations and evaluates hygrothermal behaviour of roofs.

Chapter 6, Summary and Conclusion, provides a brief overview of simulation results and compares potential moisture problems in cool and standard roofs.

Chapter 2 Literature review

2.1 Introduction

Roofs as a part of building envelope protect building and its inhabitants from the outdoor elements such as rain, sun, and snow. Proper designs of roofs play an important role in energy consumption of buildings. In addition to structural functions, the building envelopes also control transfer of heat, air and vapor ; prevent rain penetration; and control solar radiation, noise, airborne pollutants, and smoke and fire propagation . Furthermore, the envelope must be structurally sound, durable, aesthetically pleasing and economical and have a correct functionality. For these purposes, the building envelope is composed of various components in order to fulfill required functions (Hutcheon, 1963).

Thermal insulation is used in building envelopes to control heat transfer across the assembly. Insulation in building envelopes can be installed between structural components or on the exterior side of the structure. Many insulation systems are used including: blown or sprayed in place, installed in batt, semi-rigid or rigid panels. Current insulation materials are glass fiber, cellulose, extruded and expanded polystyrene and polyurethane, polyisocyanurate, glass foam, vermiculite and perlite.

In order to prevent excessive moisture content in building envelopes, vapor transfer across the roofing assembly must be controlled. This is typically accomplished by installing vapor retarders on the interior side of thermal insulation.

The control of air is achieved with using of airtight materials, tightly joined one to the other. The air barrier is a strategy applied to the whole envelope assembly, and more importantly, to all junctions encountered in the envelope. Acceptable air barrier materials must have an air leakage lower than 0.02 $l/(s \cdot m^2)$, measured under a differential pressure of 75 Pa (National Building Code of Canada, 2010). Gypsum board, steel sheet, elastomeric bituminous membranes, concrete can act as air barrier in building envelopes (Bomberg & Brown, 1993).

2.2 Cool roofs

Roofs that have high solar reflectance and high thermal emittance, under the sun, stay cooler than dark ones. Cool roofs are not necessarily light colored materials. A class of cool-colored roofing materials have become available recently. Cool-colored materials reflect the Near-Infrared (NIR) part of the solar radiation and, hence, will be cooler under the sun compared to standard material of the same color that absorbs the NIR radiation. In air conditioned buildings, lower surface temperature of cool roofs helps to reduce energy demand in summer time for cooling. In buildings without air conditioning, cool roofs improve interior comfort during summer (Levinson, et al., 2006).

Solar reflectance and thermal emittance (ranging between 0 and 1) are the two key material surface properties that determine a roof's temperature under the sun. Surface temperature of roof is reduced by increasing amount of solar reflectance and thermal emittance when sun is shining (Urban & Roth, 2010). It should be mentioned that a roof with lower thermal emittance but exceptionally high solar reflectance can also have lower surface temperature rather than dark roofs.

Several countries and states have adopted cool roof standards for residential and commercial buildings (Akbari & Levinson, 2008). The standards for cool roof definition vary. For example, California Title 24 defines minimum solar reflectance and minimum thermal emittance requirements for a cool roof as shown . California Title 24 also uses Solar Reflectance Index (SRI) for minimum cool roof requirements. SRI is a parameter used to compare coolness of roof surface which can be computed based on the solar reflectance and thermal emittance of the roof. SIR is equal to 100 for a roof with solar reflectance of 0.80 and thermal emittance of 0.9. Based on title 24, a standard dark roof with solar reflectance of 0.05 and thermal emittance of 0.9 has solar reflectance index equal to zero (Title 24, 2010) (ASTM E1980, 1998).

Roof type	**Solar reflectance (3 year aged)**	**AND**	**Thermal emittance (3 year aged)**		**Solar reflectance index, SRI (3 Year Aged)**
Low sloped[1]	0.55		0.75	OR	64
Steep sloped[2]	0.2		0.75		16

Table 2-1.Cool roof requirements (Title 24, 2010)

[1] Low sloped roofs have a pitch of 9.5˚or less (2:12)
[2] Steep sloped roofs have a pitch of 9.5˚or greater (2:12)

2.2.1 Types of cool roofs

Roofing assemblies compose of one or more materials layers. There are generally two categories of roofs: low-sloped and steep-sloped. A low-sloped roof is essentially flat; with only enough slopes (less than 2:12) to provide drainage. Steep-sloped roofs have slopes greater than a 2:12. Many roofing materials are used in both low and steep sloped roofs such as Fiber glass asphalt shingles and single ply membranes.

2.2.1.1 Low-sloped cool roofs

Single-ply Membranes are prefabricated sheets that are applied in a single layer to a low-sloped roof and installed by either mechanical fasteners, or adhered with chemical adhesives, or held in place with ballast. Most common cool Single-Ply Materials are:

- **EPDM** (Ethylene Propylene Diene Monomer) a synthetic rubber material,
- **CSPE** (Chlorosulfonated Polyethylene), a polymer material,
- **PVC** (polyvinyl chloride) and **TPO** (thermoplastic olefins), thermoplastic materials.

Typically PVC and TPO membranes are white color and reflect sunlight well but EPDM membranes are normally in black, and must be formulated differently or coated with a white (or light colored) layer to make them reflective surfaces.

Built up roofs are composed of a base sheet, reinforcing fabrics layers, and a surface layer that is traditionally dark. The cool surface options include:

- Mineral aggregates (gravel), creating cool roofs by substituting reflective marble chips or gray slag with dark gravel.
- Mineral surfaced sheet, using reflective mineral granules or with a factory-applied coating can be made cool.
- Asphalts which can be made cool by coating in white or light colors.

Modified Bitumen Sheet Membranes are asphalt based system designed for low-slope or flat roofs. Mineral granule and smooth finish are two different alternatives as a surface layer for these types of roofing systems. These surfaces can be made cool roof by coating at the factory.

Spray Polyurethane Foam roofs are constructed by mixing and spraying of two liquid components that forms the base of an adhered roof system. One of these components is protective surfacing to avoid mechanical damage and UV exposure. These coating are reflective and provide cool roofs criteria. Another component of SPF roofs is rigid closed cell, spray polyurethane foam insulation.

2.2.1.2 Steep-sloped cool roofs

Shingled Roofs consist of individual overlapping elements with different materials such as Fiberglass asphalt, wood, polymers, or metals that can be coated at the factory or in the field to create cool roofs.

Tile Roofs are made from either clay or slat or cement. Clay and slat can provide cool roofs requirements depending on material composition used to make the tile. In addition to this natural option, tiles can be glazed or coated to make them reflective and meet cool roofs requirements.

Metal Roofs can be used as a low and steep-sloped system. In the majority of cases, because of high solar reflectance and low thermal emittance of unpainted metals, they can get very hot in sun, although some of metal roofs may still have a high enough SRI to identify as a cool roof. Increasing of solar reflectance and thermal emittance of metal roofs is possible by coating the surface in the factory to reach the cool roofs requirements. Alternatively, cool reflective coatings can be applied in the field to both low and steep-sloped metal roofs to make them cool roofs (Cool Roof Design Brief, 2006).

2.2.1.3 Self-Drying Roofs

Excessive moisture in the roofing assembly might lead to various undesired problems. A self-drying roof is a roofing system that is designed to reduce accumulation of moisture in the roofing assembly. Water accumulation in the roofs can be reduced by slowing the rate of water inflow through the roofing membrane and facilitating its controlled outflow to the building interior (downward drying).

Roofing membrane at the outside of a self-drying roofs, usually acts as a vapor barrier. The roofing assembly consists of an insulation core made from materials that do not mechanically degrade in the presence of moisture. There is no need to use vapor retarder in this system to have downward drying potential.

The interior finish can be formed, for instance, by a gypsum board in residential buildings or steel decking in industrial buildings.

Self-drying roofs are used in climate regions where the yearly average vapor pressure drive is downward into the building (outside vapor pressure is higher than inside vapor pressure). It should be noticed that roofs with vapor retarders are not classified as self-drying roofs because downward drying is not possible. As another requirement, self-drying roofs should be able to remove water that has leaked into the roof as quickly as possible since long-term exposure of some roofing system components, such as fasteners, metal decks, can lead to structural degradation (Desjarlais, 1995).

2.2.1.4 Smart roofs

Vapor retarders are used in building envelopes in order to prevent interstitial condensation in cold and temperate climates in winter. But on the other hand, low permeability of traditional vapor retarders can reduce drying potential in the summer time and ultimately can increase the risk of moisture accumulation in the roofing assembly. Smart vapor retarders with flexible water permeability are impermeable enough to avoid condensation in winter while being sufficiently preamble in summer to guarantee a fast drying process in order to prevent accumulating of moisture in the roofing assemblies.

The smart vapor retarder is a film made from polyamide – a generic name for what is referred to in the textile industry as nylon. The vapor permeability of smart vapor retarder increases in proportion to ambient relative humidity as shown in Figure 2-1. This variation is because of smart vapor retarder capacity to absorb water, which creates its own selective pores in the material.

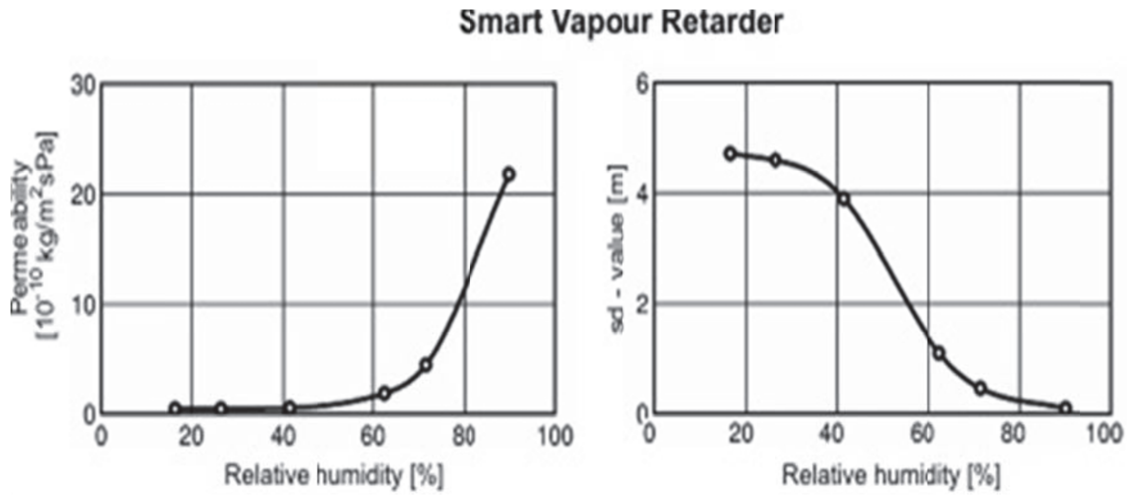


Figure 2-1.Permeability and resistance variation of smart vapor retarders (Bludau & Kunzel, 2009)

Vapor diffusion resistance of vapor retarders and membranes is defined by thickness of air layer with equivalent resistance; the so called "sd-value" given in dimension of meters (Bludau & Kunzel, 2009).

2.2.2 Cool roofs and solar radiation

The steady-state temperature of a surface under the sun (with an incoming solar radiation intensity I) is affected through energy balance of the surface, as shown in Figure 2-2. On an opaque dry surface, the incident solar radiation is either reflected back toward the sky or absorbed by the surface. A portion of the absorbed solar energy (heat) is emitted back to the sky as infrared radiation (IR). A part of heat is also removed from the roof surface through convection. The rest of heat transfers through the roof and interacts with the roofing components and the space under the roof. The amount of this heat depends on different elements such as: temperature difference of roof surface and room and the thermal conductivity and the thickness of the roofing materials (Bludau, et al., 2008).

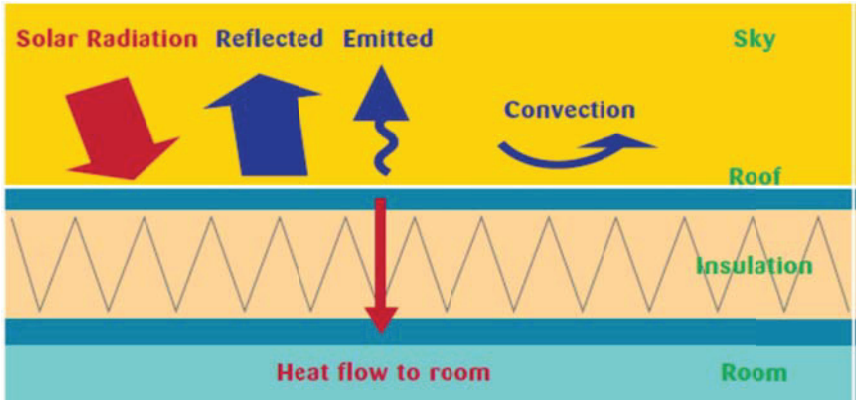


Figure 2-2.Heat transfer through a roof (Cool Roof Design Brief, 2006)

Cool roofs experience lower daytime surface temperatures compare to the dark roofs because of the higher solar reflectance. In 1998, Konopacki et al measured 10-13℃ (50-55℉) reduction of surface temperature after installing cool roofs on several buildings in California (Konopacki, et al., 1998).

Low surface temperature of a cool roof reduces flow of heat toward to the interior of the building and leads to decreasing the cooling load in an air-conditioning building. Cool roofs can also reduce peak energy demand, which occurs between mid to late afternoon, by lowering the heat gain through the roof. Experiments in warm climates have shown a reduction of 10%-30% in peak demand and cooling energy use. On the other hand, using cool roofs can induce a heating penalty during winter time in some cold climates (Konopacki, et al., 1998) (Akbari & Levinson, 2008).

Long wave radiation is emitted by all objects. This thermal radiation can reach several hundred W/m^2 depending on the temperature of the emitting surface and amount of cloud cover in the sky. The amount of thermal emittance ranges between about 180 W/m^2 (cold, dry air) and about 400 W/m^2 (warm, humid air) for a temperate latitude without cloud. Long-wave radiation emitted from other objects can be absorbed by building envelope and emit this radiation as well. Hence, Building envelopes are in continuous radiation exchange with their surroundings. During the day, amount of heat gain by solar radiation is much more than amount of heat loss. During the night, however, the loss is not compensated and usually causes reducing temperature of the surface below ambient air temperature about 5°C to 10°C (overcooling). Such low temperatures during the night can cause the temperature to drop beneath the dew point, followed by condensation of moisture in the construction (Bludau, et al., 2008).

2.3 Condensation in roofs

Condensation can cause moisture accumulation and leads to excessive moisture content in the building envelope. Uncontrolled moisture in the roofing assembly can results in damage to the roof and building. Therefore, it is essential to design a roof that can withstand and control condensation. Generally, there are two types of condensation across the building envelope:

- Interior surface condensation
- Interstitial condensation.

2.3.1 Surface condensation

It occurs on interior surfaces (visible) of the building envelope with temperature below the dew point temperature of the inside air. Uncontrolled surface condensation causes some problems such as:

- Deterioration of moisture-sensitive interior finishes such as wallpaper, paint, wood and gypsum
- Condensation provides moisture for mold growth which causes health problems.

2.3.2 Interstitial condensation

Interstitial condensation occurs within or between the layers of the roofing assemblies or walls. When warm and humid air from interior penetrates into building enclosures and contacts a surface with temperature below the dew point temperature of the air. This causes the air to cool and resulting in condensation on the cold surface. Water vapor in air transfer to an interstitial surface by two mechanisms: diffusion and convection. One way to control interstitial condensation is to use appropriate vapor barriers (control of moisture transfer). However, other complementary approach (e.g. ventilation) is used to control driving forces of moisture transport.

In a roofing assembly, uncontrolled condensation will cause a problem if:

- Insufficient drying by diffusion or convection in the roofing assembly.
- Moisture surpasses safe storage capacity of material.

- The material is vulnerable to moisture damage (Straube & Burnett, 2005).

2.4 Experimental and numerical investigations on moisture behaviour of cool roofs

2.4.1 Moisture behaviour of cool roofs in Arizona

In the winter of 2004-2005, inhabitants of buildings with white roofs in Tucson, AZ reported several cracking problems. These were low-sloped roofs framed with wood trusses, OSB sheathing and R-38 fiberglass batts. The common cause of cracks was identified because of truss uplift or the natural longitudinal dimension change at the top chords and bottom truss chords in insulated assemblies. Various field studies confirmed that the roofing assemblies of these energy efficient houses experienced moisture accumulation and mold growth problem (ln Arizona, White Roofing Causes Wet lnsulation, 2006).

After installation of some sensors in one of the defective roof assembly's, the surface temperature of the roof was measured 5-7℃ colder than outdoor air. The study showed that such a low temperature on the underside of white roofs with clear skies led to excessively high moisture content in the roofing assembly (Rose, 2007).

The study also indicated that higher interior moisture level than typical houses can be another factor, along with using white roofs, which resulted in high moisture content in the roofs of houses with less than one year old. The study recommended installing one inch of foam insulation above the roof sheathing in order to prevent moisture accumulation problem (ln Arizona, White Roofing Causes Wet lnsulation, 2006).

2.4.2 Moisture behaviour of cool roofs in different climates

Bludau, Zirkelbach and Kunzel (2008) summarize a study examining the effect of cool roofs on hygrothermal behaviour of roofing assembly components. Self-drying and typical European flat roofs were studied for five years with the purpose of analyzing risk of moisture accumulation. WUFI [Kunzel, 1994] was used for the simulations and European standard (DIN4108-3, DIN 68800) were applied to evaluate moisture performance of roof. These standards set two criteria: First, total moisture content must be less than 0.5 kg/m^2 in order to prevent risk of water dripping out of the construction. Second, water content higher than 20% by mass in the wood is considered to be critical because it may lead to degradation of the material.

The compositions of both self-drying and typical roofs are illustrated in the following figures:

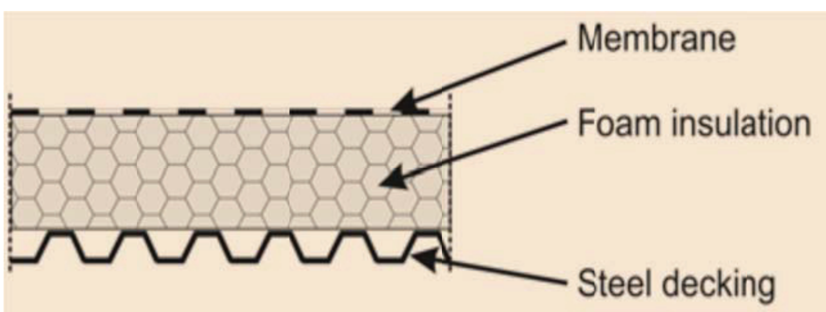


Figure 2-3.Self-drying roof composition (Bludau, et al., 2008)

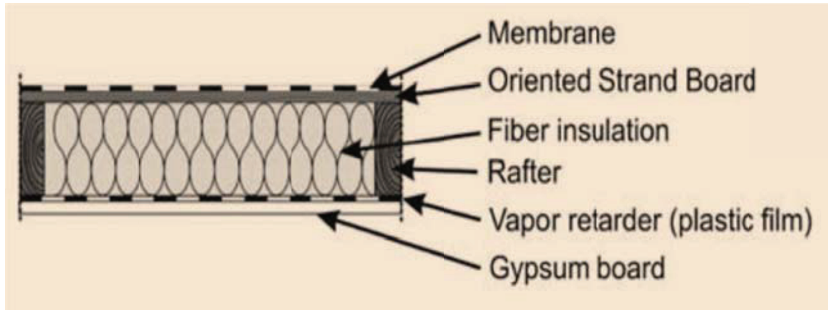


Figure 2-4.Typical European flat roof composition (Bludau, et al., 2008)

The simulations for self-drying roof were carried out for 3 various climates in North America. Phoenix, AZ, was selected as the warm climate; Chicago, IL, as the temperate location and Anchorage, AK, as the cold location. Vapor permeability of roofing membrane was set to sd=1000 m and 3.3 m for steel decking. Solar absorptance assumed to be 0.88 for dark roof and 0.2 for a white surface while a thermal emittance of 0.9 was assumed for both roofs. The moisture accumulations of roofs were analyzed with a five years simulation for each roof.

Result of simulations for self-drying roofs showed that in Phoenix, maximum total water content of white roof was around 0.05 kg/m^2 and black roof experience a dry condition (~0.01 kg/m^2). White roof in Chicago reaches a total water content of about 0.3 kg/m^2 while the dark roof experienced 0.1 kg/m^2. In cold-weather Anchorage, the maximum total water content the roof with the dark surface was 0.35 kg/m^2, while in the roof with the white surface accumulation of water over the simulation period was noticed because of insufficient drying potential. They concluded that self-drying roofs with foam insulation are applicable for most part of North America except very cold climates either in black or white surfaces.

The influence of surface color on typical European flat roof composition was studied in Holzkirchen, Germany and three other cities in North America by Bludau *et al* (2008). The roof composition is shown in Figure 2-4. Solar absorptance for black and white surfaces was assumed 0.88 and 0.2, respectively, while long thermal emittance for both colors was set to 0.9. Interior side of construction was closed by using a vapor retarder (sd=2 m) and gypsum board. Interior climate condition (temperature and relative humidity) was chosen based on European standard (EN15026).

Result showed that in Holzkirchen as a cold climate, maximum surface temperature of black roof reached 60˚C while maximum temperature of white roof only reached 30˚C. After a five year simulation, water content higher than 26% by mass occurred at OSB in roof with white surface which exceed that acceptable German Standards of 20%. Water content of OSB layer in black roof was varying between 11-16% by mass, indicating a much better performance.

In Phoenix, water content of OSB layer always remained less than 20% by mass for both black and white color roofs. In this climate, roofs with either black or white surfaces showed an acceptable moisture behaviour performance. In Chicago as a moderate climate, OSB water content of white roofs exceeded acceptable limit (20% by mass) hence the authors recommended using dark flat roof rather than white one. In Anchorage as a very cold climate, bright color roofs were not recommended due to the rapid increasing of moisture content in OSB layer. On the other hand black roof experienced acceptable moisture behaviour which ranged between14% to 20%.

Bludau *et al* concluded that if a cool roof designed for a cold or temperate climate, its moisture behaviour should be investigated by hygrothermal simulation to prevent excessive moisture accumulation in roof assembly (Bludau, et al., 2008).

Effect of reflectivity on hygrothermal behaviour of typical composition roofs were also studied by Bludau, Zirkelbach and Kunzel (2008). They chose four cities to study moisture behaviour of black roofs (solar absorptivity 0.9) and white roofs (solar absorptivity 0.2). Helsinki (Finland) was used as a cold location, Holzkirchen (Germany) and Copenhagen (Denmark) were representatives of moderate locations and Dubai (United Arab Emirates) was simulated as a warm location. WUFI was used to simulate coupled heat and moisture transport through the roofing assembly (Bludau, et al., 2008).

Results showed that in Helsinki, OSB moisture content of roof increased with time for both black and white roofs. This construction could fail after some years and is not useable at this climate. In Holzkirchen and Copenhagen, the calculations showed that accumulation of water occurs while using a bright surface. In these locations with moderate climates, amount of condensation was more than drying and total water content was increased during the simulation period. Black roofs were recommended for these two cities with no accumulation of moisture and acceptable OSB moisture content. In Dubai the construction was unproblematic. The water contents stayed very low at this location. The roofing assemblies with both colors were almost dry over the simulation period. Thus the assumed composition can be constructed with any color of the surface (Bludau, et al., 2008).

2.4.3 Smart vapor retarder

Blaudau and Kunzel (2009) presented two limit curves (Figure 2-5) in North America and Scandinavia for the application of dark flat roofs with two different vapor retarders with different permeability. One with a moderate vapour retarder (sd = 3 m) and the other contains a smart vapour retarder (PA retarder), where the sd-value ranges between 0.1 m and 4.4 m. To evaluate hygrothermal behaviour of roofs in different climates, total moisture content of the construction and moisture content in the wooden sheathing were considered. Total moisture content shows potential moisture accumulation in the roofing assembly and also based on German Standard DIN 68800 (1996), moisture content in OSB layer should not exceed 20% by mass to avoid damage by rot or mould growth. It should be mentioned that in this study WUFI was used as a simulation model to predict hygrothermal performance of the roofing assemblies.

This study also illustrated the impact of interior relative humidity on position of limit curves. The authors concluded both curves (PA retarder, 3 m retarder) with decreasing of interior relative humidity will move further up to the north (Bludau & Kunzel, 2009).

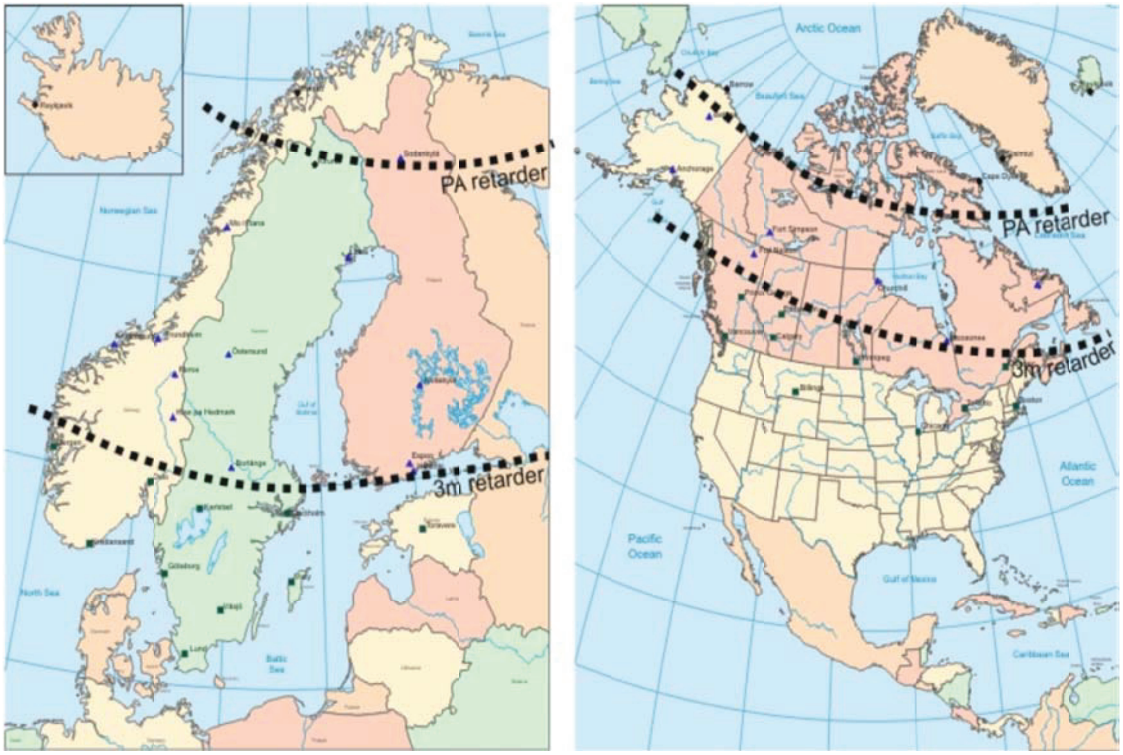


Figure 2-5.Limit curves for the two different vapour retarders in Scandinavia and North America (Bludau & Kunzel, 2009)

2.4.4 Moisture behaviour of black and white modified-bitumen roof in different climates

Saber *et al.* (2011) conducted series of numerical simulations to study the effect of roof color on moisture behaviour of roofs, using "hygIRC-C" developed by the Institute for Research in Construction of National Research Council of Canada. The objective of Saber et al (2011) study was to compare hygrothermal behaviour of black (solar absorptivity 0.88) and white (solar absorptivity 0.2) flat Modified-Bitumen roofing system (Figure 2-6). Toronto, St. John's, Saskatoon, Seattle and Wilmington were selected as outdoor climates to investigate the effect of reflectivity on moisture performance of mentioned roofing assembly.

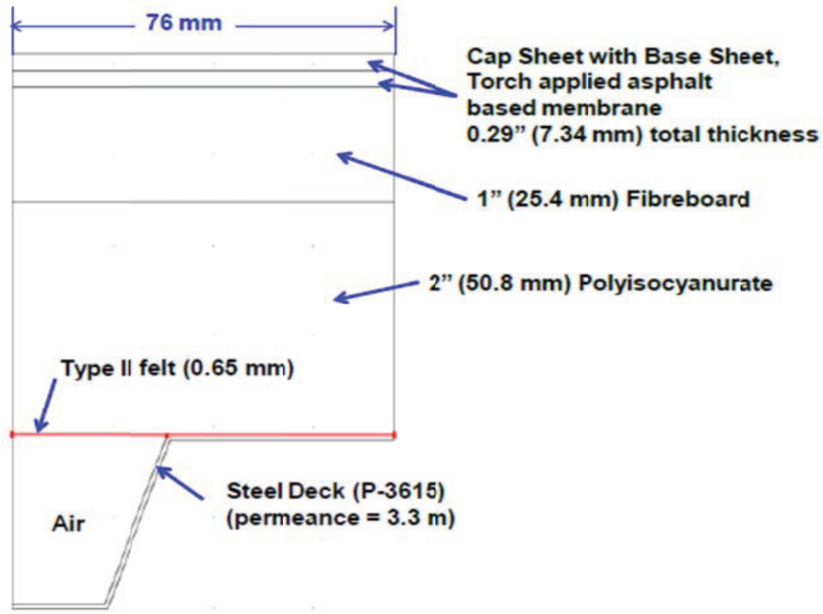


Figure 2-6.A schematic of Modified-Bitumen roofing system (Saber, et al., 2011)

Outdoor climates were chosen from the NRC-IRC weather database and the indoor conditions were obtained based on European standard (EN 15026) and ASHRAE recommendations for conditioned space. By simulating for Toronto, they concluded that the indoor conditions of EN 15026 led to higher moisture content in the both black and white roofing system hence standard EN 15026 was selected for interior climate conditions.

In the beginning, the simulations were established for 5 years and in the case of accumulating moisture over the time after five years, the simulation period was extended. In all material layers, the initial moisture content and temperature were set to correspond to 50%, 10℃.

The authors concluded that black roofs experienced lower moisture content than white roofs in all climates. In St John's and Saskatoon, moisture content for white roof in fiber board were 35.4% and 29.8% by mass which it is higher than allowable limit (19%) based on National Building Code of Canada (2010). Thus for these two locations, the study recommended black roofs to decrease risk of moisture accumulation.

Finally Saber *et al.* (2011) proposed that white roofs have low risk of moisture damage for Toronto, Seattle, and Wilmington meanwhile they pointed out that in these locations building with white roofs result in a net yearly energy savings compared to buildings with black roofs.

2.5 Conclusion

Roofs with high solar reflectance and high thermal emittance, known as cool roofs, experiences lower surface temperature under the sun compared to dark colored roofs. Cool roofs not only help to reduce total and peak cooling energy demand in summer for air conditioned buildings but also in larger scales cool roofs cool urban heat island and improve smog air pollution. On the other hand, lower surface temperature of cool roofs can induce a penalty in heating period which vary by outdoor climate. Consequently, in a cost-benefit analysis should consider both the summertime cooling energy savings and other environmental benefits and the potential wintertime heating penalties.

In addition to energy efficiency issues, lower surface temperature of cool roofs can increases risk of condensation and moisture accumulation in roofing assemblies. Excessive moisture content in roofs can create some problems such as increase thermal conductivity, decay of wooden material, mold growth, ice build-up and metal corrosion. Various studies showed that using smart vapor retarders and self-drying roofs can help decreasing total moisture content of roofs in specific climates by increasing downward drying potential. Therefore, moisture performance of cool roofs should be analyzed in order to prevent destructive problems in the roofing assembly.

Chapter 3 Heat and moisture transport in roofing assembly

Understanding of the heat and moisture transfers as well as thermal and moisture storages are essential to study hygrothermal behaviour of the building envelope. This chapter provides an overview of fundamental principles for moisture and heat transport through roofing assemblies.

3.1. Heat storage capacity in building materials

The enthalpy of a roofing material layer in dry condition can be calculated by:

$$\mathbf{H_s = \rho_s . c_s . T} \qquad \textbf{Equation 3-1}$$

In calculating enthalpy of a moist building material, enthalpy of water in the material also must be added to the enthalpy of material in dry condition. It should be noted that enthalpy of water in building material depends on its physical state (liquid or ice) and can be calculated as follows:

$$\mathbf{H_w = \left[(w - w_e)c_w + w_e c_e - h_e \frac{dw_e}{dT}\right] . T} \qquad \textbf{Equation 3-2}$$

3.2. Heat transfer

Temperature gradient between indoor and outdoor in a building is the driving force for the heat transfer from higher to lower temperature. Heat transfer can affect hygrothermal behaviour of the envelope by moisture accumulation. Heat transfer through the roof involves all conduction, convection and radiation.

3.2.1. Conduction

Heat transfer through a solid roofing section occurs by conduction and originates from the difference in temperature between the warm and the cold side of the section. A one-dimensional steady-state model adequately describes conduction heat transfer through the roofing sections. The dominate equation is:

$$\mathbf{Q = U.A.\Delta T = (k/l).A.(T_1 - T_2)} \qquad \textbf{Equation 3-3}$$

Table 3-1 provides thermal properties of commonly used materials in wooden roof assemblies:

Material	Density (kg/m^3)	Conductivity (W/m.K)	Specific heat capacity (kJ/kg.K)	Thermal conductivity supplement (%)
Roofing surface				
Asphalt shingles			1.3	
Wood shingles			1.3	
PVC	1000	0.16	1.5	
Structural Materials				
Plywood	400-600	0.08-0.11	1.5	1.5
OSB	575-725	0.09-0.12	1.7	1.5
Gypsum board	800-900	0.16	1.1	8
Softwood lumber	510	0.1-0.14	1.4	
Hardwood lumber	720	0.15-0.18	2.4	
Carbon steel	7680	40-80	0.5	
Aluminum	2800	160-200	0.9	
Insulations				
EPS Type 1	16	0.039	1.2	0.05
EPS Type 2	24-32	0.034	1.2	0.05
EXPS Type 3 and 4		0.029	1.2	0.1
Batt insulation		0.036-0.048	0.85	

Continued

Polyurethane		0.024	1.6	
Polyisocyanurate	24-30	0.02-0.024	1.6	
Cellulose fiber	37-51	0.039-0.046	1.4	1
Other				
Fresh snow	190	0.19		
Compacted snow	400	0.43		
Ice at -1° and -20 °C	920	2.24-2.45	2.04-1.95	
Water at 20 °C	1000	0.6		

Table 3-1.Thermal properties of some common building materials

Based on Kunzel (1995), the influence of moisture on thermal conductivity of a moist building material can be calculated as follows:

$$\mathbf{k = k_o \left(1 + \frac{b.w}{\rho_s}\right)}$$

Equation 3-4

Thermal conductivity supplement (b) shows increasing amount in percentage of thermal conductivity per mass percent of moisture in building material. Table 3-1 shows amount of thermal conductivity supplement for various common building materials.

3.2.2. Convection

The convection through the roofing assembly (air layers and surface air film) is calculated by:

$$\mathbf{Q = h_c.A.\triangle T = h_c.A.(T_S - T_\infty)}$$ **Equation 3-5**

In general, convection is divided in two types, natural convection and forced convection. Natural convection occurs when a fluid is in contact with a surface with different temperature. As the fluid's temperature increases or decreases, the fluid density is changed causing movement in the fluid. During sunny days the roof surface temperature is high and it will heat the air next to it, causing the density of the air to decrease and to rise. The rising air is replaced by cool air and the process continues. On the contrary, when roof surface temperature is low at night time, it cools the air next to it, causing the density of the air to increases and the air to fall. The falling air is replaced with warmer air and the process continues.

The term forced convection is used when the fluid is forced to flow over the surface by external means such as fans and pumps.

3.2.3. Radiation

Radiation is a significant component of heat transfer in buildings envelope. Reflectivity and emissivity are the two properties of a surface that affect radiation heat transfer in building envelopes. The following mechanisms can be considered in transferring heat by radiation in the roofing assemblies.

3.2.3.1. Solar radiation

Sun as a source of energy provides a large portion of heat for drying of moist materials in a roof assembly. The amount of solar radiation that is absorbed by a surface is calculated from:

$$\mathbf{q_s = \alpha . I} \qquad \textbf{Equation 3-6}$$

The solar radiation intensity on the surface is calculated as a function of day of year, hour, latitude, azimuth (i.e. orientation) and slope of the surface (ASHRAE Handbook, 2009).

3.2.3.2. Radiation exchange between roof and sky

The net radiant energy exchange between a building roof and sky is calculated by:

$$\boldsymbol{q = \frac{Q}{A} = \varepsilon . \sigma . (T_s^4 - T_a^4)} \qquad \textbf{Equation 3-7}$$

3.2.3.3. Radiation exchange between roof and other surfaces

The net long wave radiation between two surfaces can be estimated from:

$$\mathbf{q_{1-2} = \sigma . F_E . F_A . (T_1^4 - T_2^4)} \qquad \textbf{Equation 3-8}$$

Where

q_{1-2}: The net radiant heat transfer between surfaces 1 to 2 (W/m^2)

σ : The Stefan-Boltzmann constant ($5.67x10^{-8}$ W/m^2K^4)

T_1, T_2: Surface 1, 2 temperature (K)

F_E: Emissivity factor between surface 1 and 2

F_A: View factor between surface 1 and 2

Emissivity factor is computed from surface thermal emittance of surfaces $(\varepsilon_1, \varepsilon_2)$ by following formula:

$$\mathbf{F_E} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\boldsymbol{\varepsilon_1}}+\frac{\mathbf{1}}{\boldsymbol{\varepsilon_2}}-\mathbf{1}}$$ **Equation 3-9**

It should be noted that view factor (F_A) of small objects (roof) exposed to a large object (sky) are assumed to be constant at one. Figure 3-1 shows view factors (F_A) for some common geometries in building enclosures.

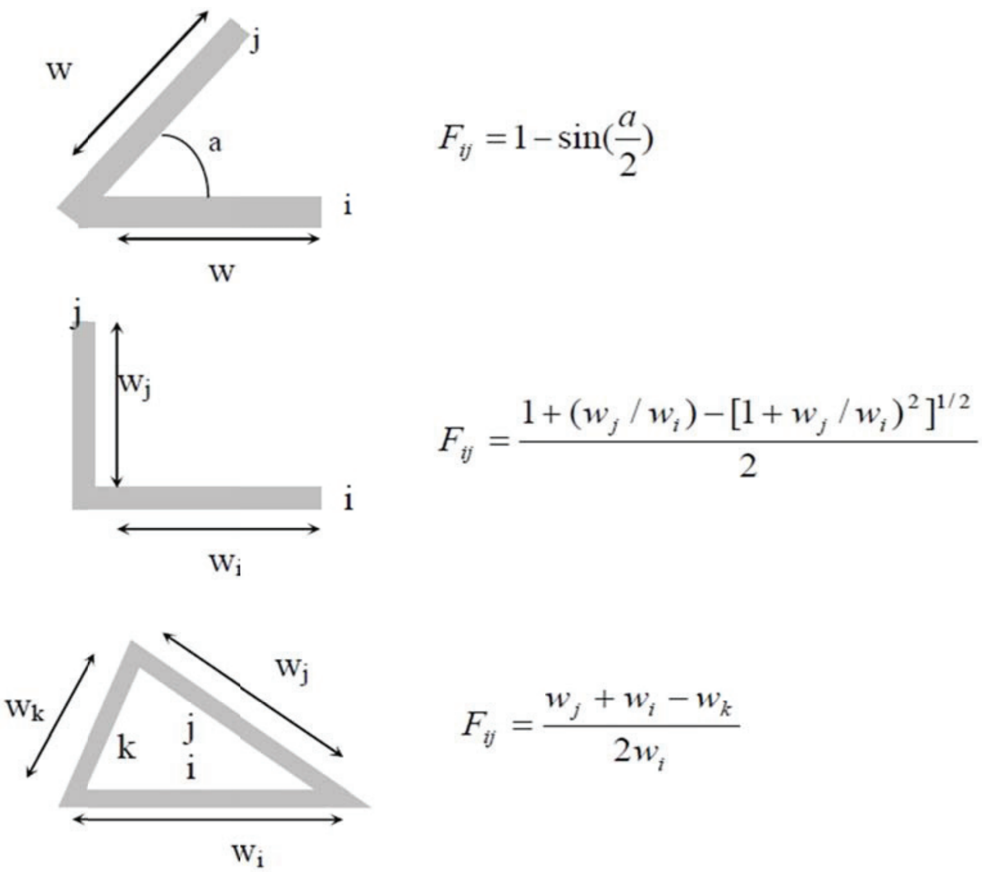


Figure 3-1.View factors for common situations in building enclosures (Hangentoft, 2001)

For simplicity, Equation **3-8** can be rewritten for assemblies with F_A=1 in the following form:

$$\mathbf{q = h_r.(T_s - T_a) = F_E.\sigma.(T_s^4 - T_a^4)}$$

Equation 3-10

Where h_r defines as radiative heat transfer coefficient

$$h_r = \frac{F_E.\ \sigma.\ (T_s^4 - T_a^4)}{(T_s - T_a)}$$ **Equation 3-11**

3.3. Moisture storage in building materials

Most building materials are porous and have the ability to absorb water from surroundings. The shape, size and distribution of the micro pores define the moisture storage performance of a material.

Porous materials, while appearing solid to the naked eye, contain a solid particle matrix surrounding a network of voids or “pores”. In some materials pores are connected to each other (i.e. materials open-cell pores) while some others materials comprise of dead end pores with trapped air (i.e. materials with closed-cell pores). Air and water vapor molecules are able to move in and out of any of the pores that are connected to the exterior, so that some water vapor in the pores is stored in the air. This “free water vapor” represents a very small amount of the water vapor that can be stored in a porous material. Significantly more water can be stored on the surfaces of the pores and in their volume. Figure 3-4 shows moisture storage capacity as a function of relative humidity for several materials that are commonly used in the construction of buildings.

Based on Kunzel (1995), effects of temperature can be ignored in moisture absorption process and moisture content of a building material is a function of ambient relative humidity. The relation between moisture content and ambient relative humidity is non-linear (sorption curve) as shown in Figure 3-2. Moisture absorption process can be divided in the following three regions:

- Region A is a hygroscopic region ranging from dry state (0% RH) to equilibrium moisture of about 95% relative humidity. In this part, the relationship between material's water content and equilibrium relative humidity is defined as sorption isotherm.

- Region B or the capillary water region follows the hygroscopic region reaching capillary saturation (free water saturation) and similar to previous region is characterized by states of equilibrium which is determined by ambient relative humidity. In this region, larger pores of building material are filled by water up to the capillary saturation. Capillary saturation is a critical level of moisture content that higher moisture up to maximum saturation can be reached only by applying pressure or by water vapor diffusion by temperature gradients (see Figure 3-2).

- Region C is called supersaturated region and it is achieved by applying pressure in laboratory under temperature gradients. It should be noted that in this region, all of pores in building material are filled by water. In addition, there is no more state of equilibrium (relative humidity in this region is always 100% regardless of the water content).

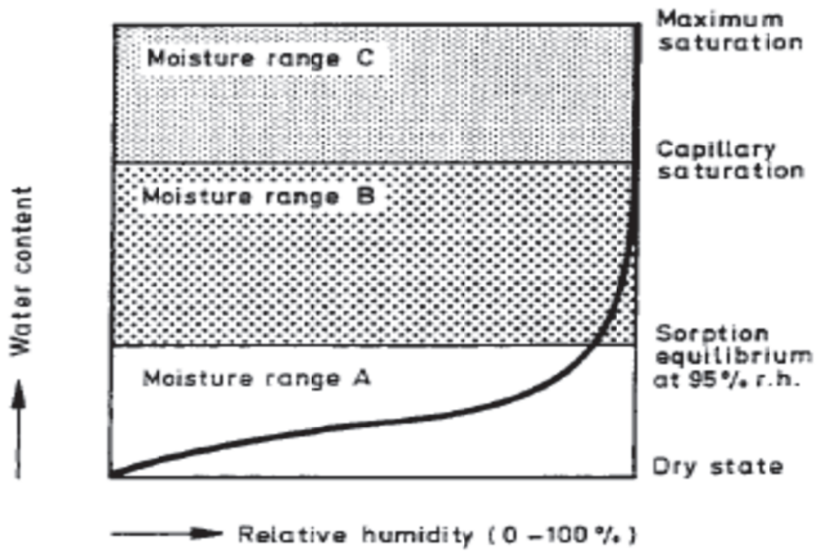


Figure 3-2.Schematic diagram of the moisture storage functions of a porous building material (Künzel, 1995)

In literatures difference between absorption and desorption curve is called hygroscopic hysteresis which it is negligible in most of building materials (Figure 3-3).

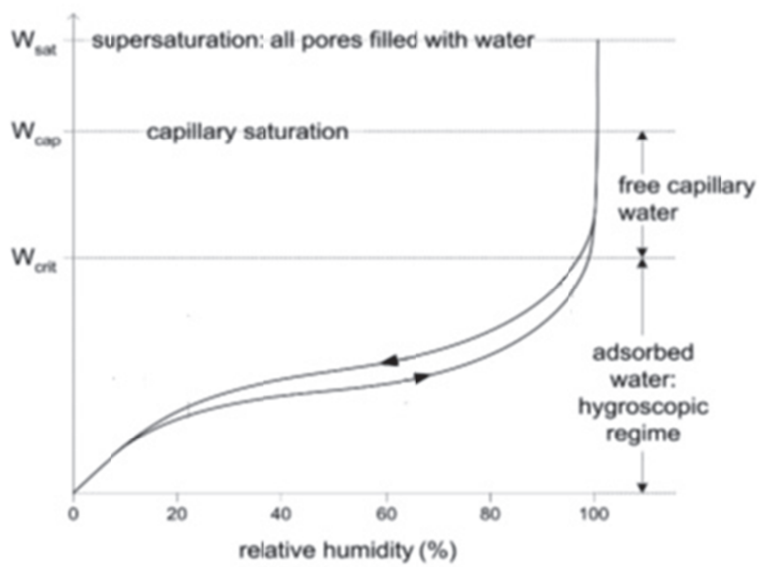


Figure 3-3.Adsorption and desorption (Straube & Burnett, 2005)

Not all materials have all of the above three mentioned moisture regions in their moisture storage curve. Some materials are hygroscopic but not capillary and vice versa and some are non-hygroscopic and non-capillary. For example some fibrous insulation materials, such as mineral wool, do not absorb moisture from ambient air when temperature is below dew point. (Künzel, 1995).

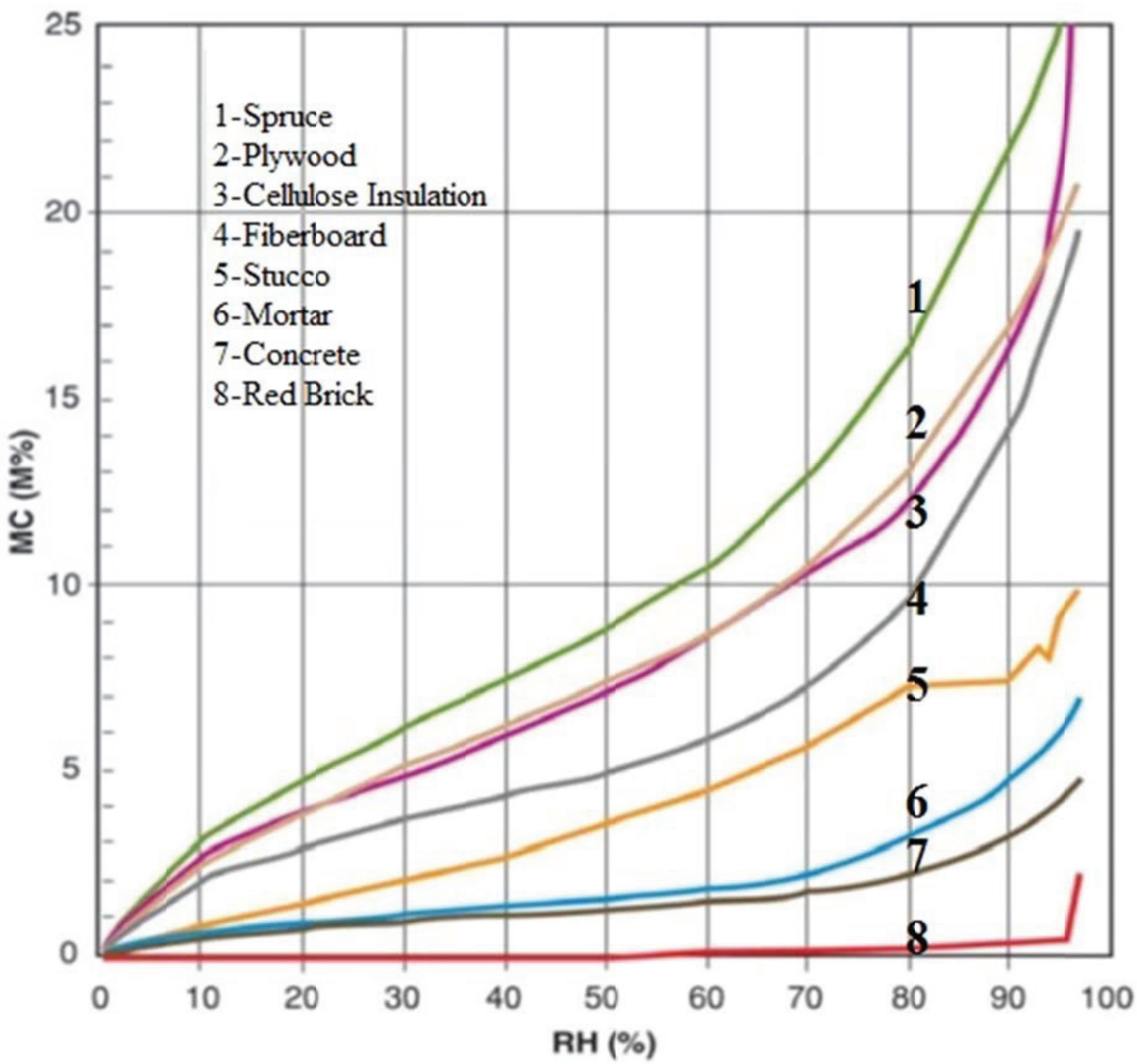


Figure 3-4.Moisture isotherms for different building material (Straube, 2006)

3.4. Moisture transport through roofing sections

For many hours during the year, there is a significant difference between the moisture content of the inside and outside air. This difference between the moisture contents in the air acts as a driving force and result in moisture transport in the roofing assembly. Studying hygrothermal behaviour of building envelope is essential to prevent excessive moisture content in the roofing assembly. For this purpose, understanding of different moisture transport mechanisms and accurate determination of driving potential in the roofing sections are required.

Strube (1998) listed the following four necessary conditions in order to have a moisture-related problem and point out that in order to avoid problems, one of these factors must be eliminated.

- a moisture source
- a path for moisture transfer
- driving force(s) to cause moisture transport
- the material must be vulnerable to moisture damage.

In evaluating hygrothermal behaviour of building envelopes, it is much easier to show aggregate moisture content (liquid, ice and vapor) rather than moisture contents for each phase because of continuous changing of individual states (Künzel, 1995).

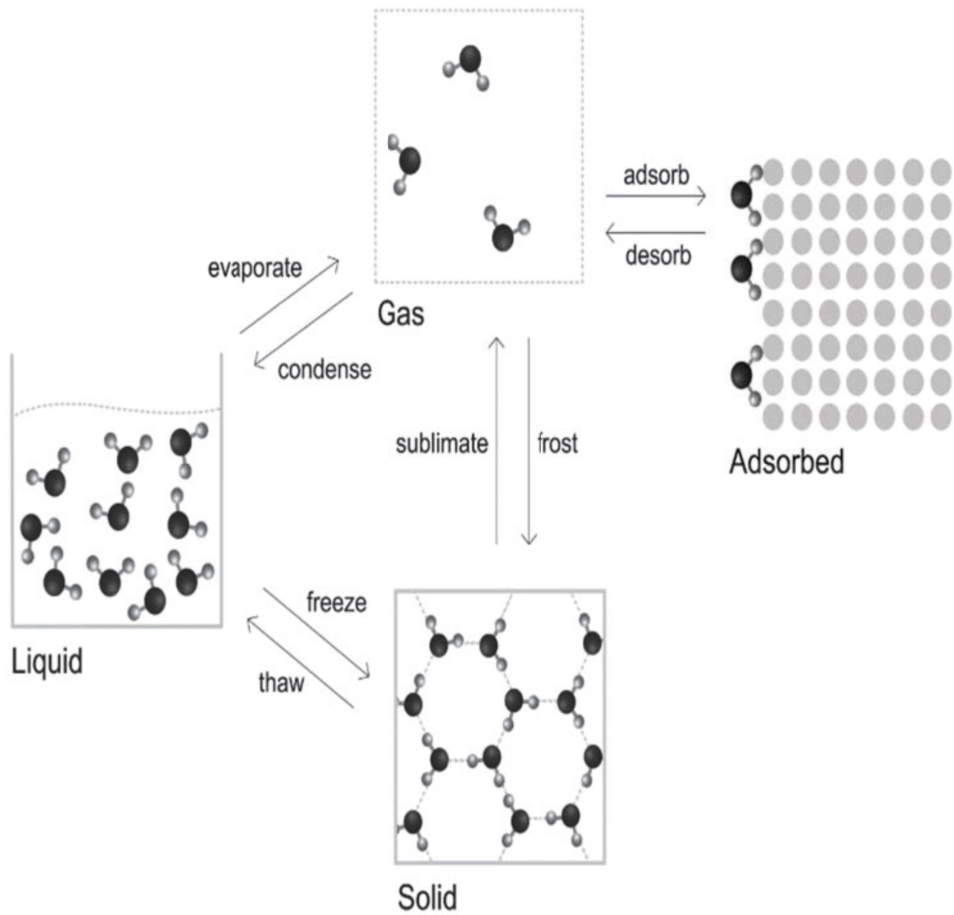


Figure 3-5.Moisture states and state changes (Straube & Burnett, 2005)

Different types of moisture transport and their driving forces which are listed in Table 3-2. Among those moisture transport mechanisms water vapor diffusion, surface diffusion and capillary conduction are main mechanisms governing moisture transport in the porous building materials in roofing assemblies.

Phase	Transport mechanisms	Cause & potential of transport
Vapor transport	Water vapor diffusion	Vapor pressure (temperature, total pressure)
	Molecular transport (effusion)	Vapor pressure
	Solution diffusion	Vapor pressure
	Convection	Total pressure gradient
Liquid transport	Capillary conduction	Capillary suction stress
	Surface diffusion	Relative humidity
	Seepage flow	Gravitation
	Hydraulic flow	Total pressure differentials
	Electrokinesis	Electrical fields
	Osmosis	Ion concentration

Table 3-2.List of moisture transport mechanisms and their driving potentials (Künzel, 1995)

The combined effect of water vapor diffusion and liquid transport mechanisms (surface diffusion and capillary conduction) in building envelope is shown by Figure 3-6.

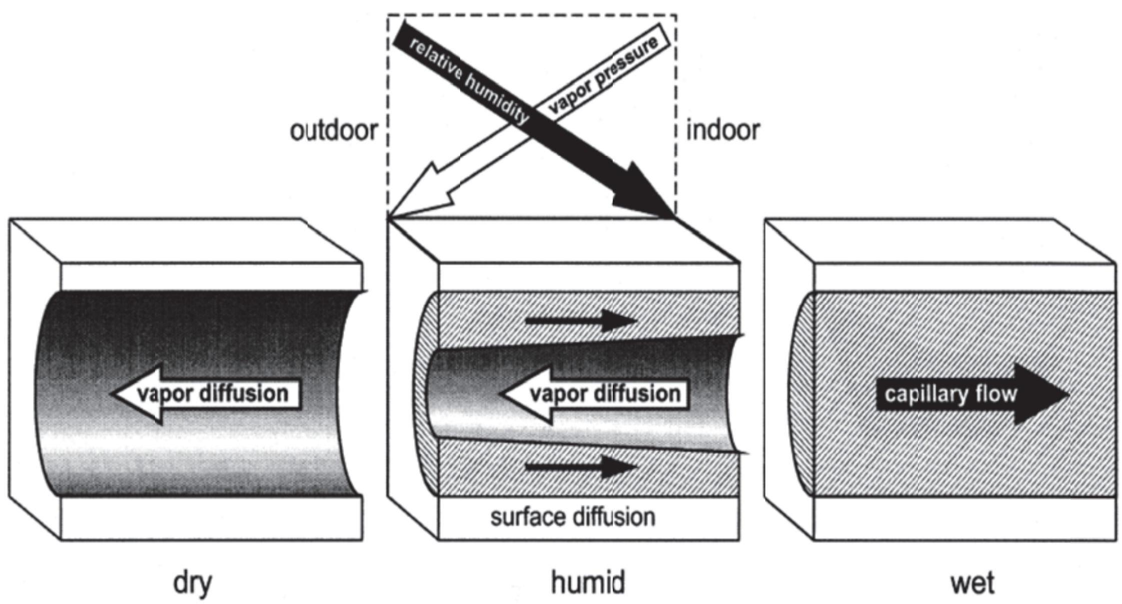


Figure 3-6.Moisture transport mechanisms (Karagiozis, et al., 2001)

It should be noted that water vapor diffusion occurs in materials with equilibrium moisture content less than 60% RH or non-hygroscopic materials. By increasing the amount of moisture content in a material in presence of relative humidity differential, the pores are covered with adsorbed film water that has higher density (thicker) on the outside than inside. By increasing the thickness of the film, the absorbed water moving from thicker section (outside) to the thinner section (inside). This type of moisture transfer is called surface diffusion and its driving potential is relative humidity. In the case of a wet condition, by increasing total moisture content of component and reducing outward vapor diffusion, capillary conduction sets in.

Governing equations and detail of these three major moisture transport mechanisms in building envelopes are explained in the following sections.

3.4.1. Water vapor diffusion

The amount of moisture transported by water vapor diffusion in air depends on mass fraction, temperature and the total pressure (Bear, 1972). The water vapor diffusion through the air can be calculated by:

$$g_v = (D_m \nabla m + D_T \nabla T) \qquad \textbf{Equation 3-12}$$

The thermal diffusion component ($D_T \nabla T$) in the above equation is negligible in comparison to the mass fraction term ($D_m \nabla m$) known as Fick's diffusion. Considering the relationship between the mass fraction and the total pressure, can then simplified as:

$$g_v = -\delta \nabla p$$ **Equation 3-13**

Water vapor diffusion coefficient in air is a function of temperature and air pressure and can be calculated from the following equation.

$$\delta = 2{,}0\,.\,10^{-7}\,\mathrm{T}^{0.81}/\mathrm{P_L}$$ **Equation 3-14**

Water vapor diffusion equations in air only can be applied for porous building material with large pores (radius bigger than 10^{-6} m). Therefore, water vapour diffusion resistance factor (μ) for each material is introduced in order to reflect the size of pores in computing water vapor diffusion in building envelope materials. Water vapour diffusion resistance factor or vapor permeability is a ratio of diffusion coefficients of water vapor in air and in the building material. Kunzel (1995) shows that water vapor diffusion resistance factor is independent from temperature but is a function of water content.

$$\mathrm{g_v} = \frac{\delta}{\mu} \nabla \mathrm{p}$$ **Equation 3-15**

Where

$\mathrm{g_v}$:Water vapour diffusion flux density (kg/m^2s)

p: Water vapour partial pressure (Pa)

δ: Water vapour diffusion coefficient (permeability) in air (kg/m^2sPa) μ: Water vapour diffusion resistance factor (dimensionless parameter)

3.4.2. Surface diffusion

Surface diffusion only occurs at hygroscopic region in building materials and is categorized as a liquid transport mechanism. Its driving force is relative humidity. In addition, it should be noted that due to the temperature dependence of the surface diffusion coefficient, the amount of surface diffusion rises by increasing of temperature.

3.4.3. Capillary conduction

Capillary conduction in contrast to surface diffusion only occurs at water content above the critical moisture and it is classified as a form of liquid transport similar to surface diffusion. Because of simultaneous occurrence of capillary conduction and surface diffusion in building materials, it is much easier to calculate total liquid transport instead of computing separately. Liquid transfer in porous building material can then be described by:

$$g_w = D_\varphi \nabla \varphi \qquad \textbf{Equation 3-16}$$

And liquid conduction coefficient can be obtained from:

$$D_\varphi = D_W . \frac{dw}{d\varphi} \qquad \textbf{Equation 3-17}$$

Where

D_W: Capillary transport coefficient (m^2/s)

$\frac{dw}{d\phi}$: Derivative of moisture storage function (kg/ m^3)

In capillary region (RH>95%), measuring relative humidity is very difficult. So based on

amount of liquid conduction coefficient can be estimated as a function of moisture storage and capillary transport coefficient.

Chapter 4 Methodology

In this chapter, we will first briefly discuss and compare capabilities of a few simulation models. Then, we will discuss the fundamentals of the selected model used in this study. The selected model is then used to perform parametric simulations for moisture transport in several roofing assembly in different climates. It should be noted that a part of our simulations account for the effect of snow accumulation on the roof. Finally, we discuss several criteria used to evaluate hygrothermal performance of roofs.

4.1. Introduction

Over the last five decades, several simulation models have been developed to analyzing moisture transport through building envelops. A list of these models can be found in the U.S Department of Energy publications (U.S. Department of Energy website, 2011).

Dew point (Glaser) method is one of the first techniques used to investigate moisture balance of a building component. (Glaser, 1958) (Glaser, 1959). This method computes amounts of interstitial condensation in winter and evaporable water in summer. According to Glaser method, a building assembly needs to provide two requirements to be in the safe zone: first, amount of evaporation water must be more than condensation water and second, amount of condensation water must be less than specified limits. Glaser method is mostly applicable for light weight structures since it is entirely based on vapor diffusion mechanisms and ignores liquid transport and assumes steady state condition in one direction. Thus, a general hygrothermal assessment can be predicted by Glaser method but there is a need for more advanced simulation models to simulate transient heat and moisture phenomena shown in Figure 4-1 (Künzel, 2000).

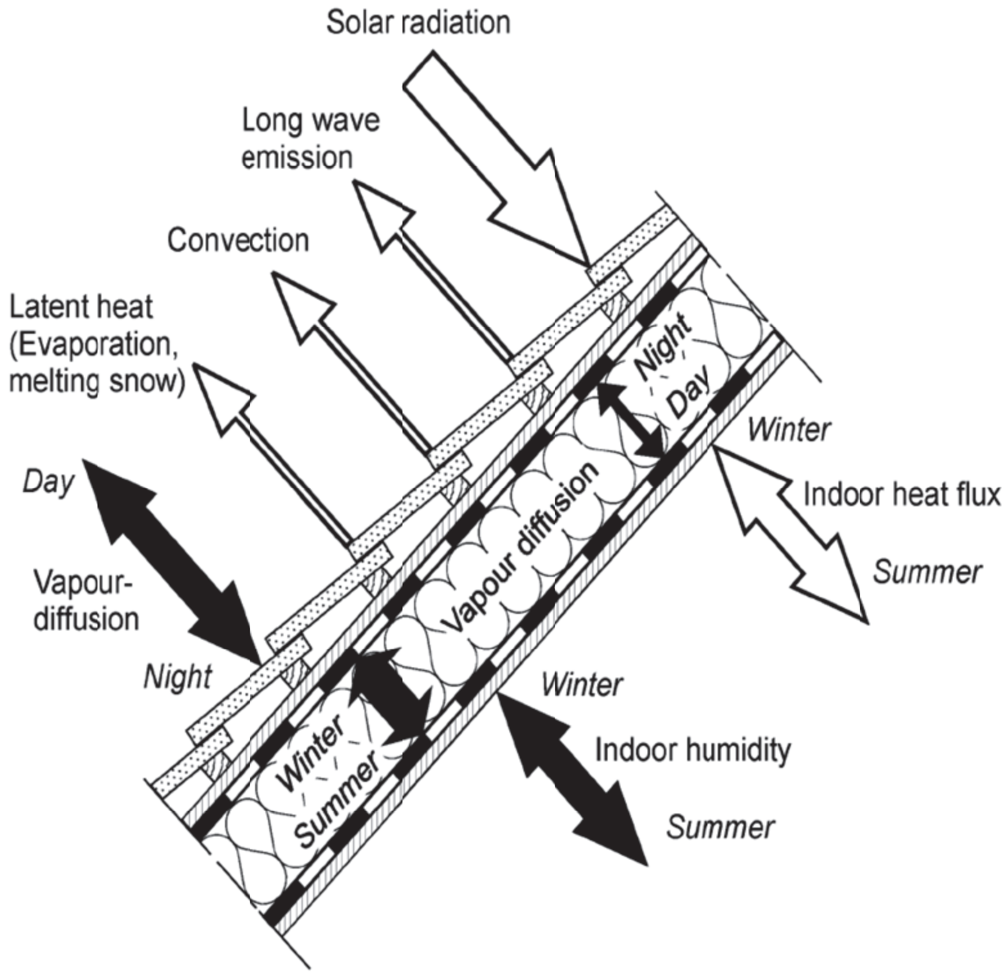


Figure 4-1.Indoor and outdoor hygrothermal loads and fluxes in a sloped roof (Künzel, 2000)

4.2. An overview of hygrothermal simulation models

There are several computer-based tools to couple heat, air and moisture (HAM) models. These tools can be used to simulate the performance of a single component of a building envelope or simulate the whole building. Mathematical sophistication of these tools is determined by different elements such as: moisture transfer dimension and type of flow (steady state, quasi-static, or dynamic) (Delgado , et al., 2010).

Hens et al. (1996) reviewed 37 available heat, air and moisture transport models (developed in 12 countries) and concluded that 26 of these programs were non-steady state models (Hens, 1996).

In 2003, Canada Mortgage and Housing Corporation identified 45 hygrothermal modeling tools and pointed out that 37 of them are not available to public outside of the organisation where they were developed. Based on this report, the following eight models are available to public: DELPHIN4, EMPTIED, GLASTA, MATCH, MOIST, 1D-HAM, UMIDUS and WUFI. (CMHC, 2003) While in 2010 according to Delgado *et al* (2010) 12 new hygrothermal models were developed since 2007. Table 4-1 shows the complete list of different HAM models with their detail.

Program	Model type	Numerical scheme	Developer
WAND	1D Heat/Moisture	Steady state-Glaser scheme	Catholic University of Leuven, Belgium
KONVEK	3D Heat/Air/Moisture	Steady state	
NATKON	2D Heat/Air	Steady and non-steady state	
HYGRAN24	1D Heat/Air/Moisture	non-steady state	
HAM	1D Heat/Air/Moisture	non-steady state	
HMSOLVER	2D Heat/Moisture	non-steady state	
GLASTA	1D Heat/Moisture	Steady state-Glaser scheme	Physibel,Maldegem, Belgium
UMIDUS	1D Heat/Moisture	non-steady state	Pontifical Catholic University of Parana, Brazil
Power Domus	1D Heat/Moisture	non-steady state	
HAMPI	1D Heat/Moisture	non-steady state	University of Saskatchewan, Canada
WALLDRY	1D Heat/Air/Moisture	steady state	Canada Mortgage and Housing Corporation, Canada
WALLFEM	1D Heat/Air/Moisture	non-steady state	
EMPTIED	1D Heat/Air/Moisture	steady state	
LATENITE	2D Heat/Moisture	non-steady state	National Research Council Canada
HygIRC-1D	1D Heat-Air-Moisture	non-steady state	
HygIRC-2D	2D Heat-Air-Moisture	non-steady state	Concordia University, Canada
HAMFitPlus	1/2D Heat-air-moisture	non-steady state	
MATCH	1D Heat/Moisture	non-steady state	TUD-Thermal Insulation Laboratory , Denmark
BSim2000	1D Heat/Moisture	non-steady state	Danish building research institute, Denmark
TRATMO2	2D Heat/Air/Moisture	non-steady state	VTT (Technical Research Centre) of Finland
TCCC2D	2D Heat/Air/Moisture	non-steady state	
LTMB	1D Heat/Moisture	non-steady state	INSA, National Institute of Applied Science ,France
CHEoH	2D Heat/Moisture	non-steady state	IMF (Institute of Fluid Mechanics), France
TONY	2D Heat/Moisture	non-steady state	
V30	1D Heat/Moisture	non-steady state	CSTB (Centre for Building Science and Technology), France
V320	2D Heat/Moisture	non-steady state	
SPARK2.01	1D Heat/Moisture	non-steady state	LEPTAB-University of La Rochelle,France
WFTK	1D Heat/Moisture	non-steady state	Fraunhofer Institute for Building Physics (IBP), Holzkirchen, Germany
WUFI-2D	2D Heat/Moisture	non-steady state	
WUFI-PLUS	1D Heat/Moisture	non-steady state	IBP, Germany
JOKE	1D Heat/Moisture	non-steady state	FH (University of Applied Science) , Germany
COND	1D Heat/Moisture	steady state Glaser scheme	TU-Dresden/FH - Lausitz
DIM 2.5	2D Heat/Air/Moisture	non-steady state	TU (Technical University) of Dresden, Germany
DELPHIN5	2DHeat/Air/ Moisture/Salt	non-steady state	
TRNSYS ITT	1D Heat/Moisture	non-steady state	

Continued

HYGTHERAN	1D Heat/Moisture	non-steady state	NBRI Israel
XAM	1D Heat/Moisture	non-steady state	Kinki University,Japan
HYGRO	1D Heat/Moisture	steady state Glaser scheme	TNO Building and Construction Research, Netherlands
WISH-3D	3D Heat/Air	Steady and non-steady state	
HORSTEN	2D Heat/Air/Moisture	non-steady state	
HAMLAB	1/2/3D Heat/Air/ Moisture	non-steady state	Eindhoven university of Technology,Netherlands
BRECON2	1D Heat/Moisture	steady state Glaser scheme	Building Research Establishment, Scotland
NEV3	1D Heat/Moisture	non-steady state	Slovak Academy Of Science, Slovakia
NPI	1D Heat/Moisture	non-steady state	
P1200A	1D Heat/Moisture	non-steady state	SP (Swedish National Testing and Research Institute), Sweden
VADAU	2D Heat/Moisture	non-steady state	Chalmers Technical University, Gothenburg, Sweden and University of Lund, Sweden and Blocon operating as buildingphysics.com in Lund, Sweden & Reading, MA USA
1D-HAM	1D Heat/Air/Moisture	non-steady state	
AHCONP, ANHCONP	2D Heat/Air	Steady and non-steady state	
JAM1	1D Moisture	non-steady state	
JAM2	2D Moisture	non-steady state	
HAM-Tools	1D Heat/Air/Moisture	non-steady state	Technical University Of Denmark,/Chalmers Technical University,Sweden
FUNKT 74:6	1D Heat /Moisture	non-steady state	Gullfiber AB (now Saint-Gobain Isover), Billesholm, Sweden
IDA-ICE	1D Heat/Air/Moisture	non-steady state	EQUA Simulation, AB, Sweden
MOIST	1D Heat/Moisture	non-steady state	National Institute for Standards and Testing, Gaithersburg, MD USA
FSEC	3D Heat/Air/Moisture/ Contaminants	non-steady state	Florida Solar Energy Centre, Cocoa, FL USA
WUFI/ORNL	1D Heat/Moisture	non-steady state	Fraunhofer IBP/Oak Ridge National
MOISTURE-EXPERT	2D Heat/Moisture	non-steady state	Oak Ridge National Laboratory, Oak Ridge TN, USA

Table 4-1.List of building hygrothermal models (Delgado , et al., 2010)

Simulation results from each model significantly depend on the accuracy of governing equations of the model. Selecting an accurate model is important in predicting realistic hygrothermal behaviour of a building envelope. After initial screening the capabilities of each model, we investigated of four models: WUFI, WUFI+, hygIRC and Moisture-Expert.

4.2.1. WUFI

WUFI, *Wärme Und Feuchte Instationär*, (Transient heat and moisture) is a one dimensional hygrothermal model that couples heat and moisture transfer in multilayer building envelopes subjected to outdoor climate. The program developed jointly by the Fraunhofer Institute in Building Physics (IBP) in Germany and Oak Ridge National Laboratory (ORNL), Tennessee, USA. The initial version of this program was released in Europe in 1994 and has since been widely used by building envelope designers, architects, building physicists, consulting specialists, and universities in Europe. WUFI has large material property and outdoor climate databases that are available in the software for selection and simulation. Climate database of this software includes a complete weather data set (including temperature, relative humidity, rain and solar radiation *etc*.) for more than 50 cities in North America. The model can also simulate the effects of wind-driven rain (as a function of building height) and night sky radiation (to accounts for surface wetting during the night) (Karagiozis, et al., 2001).

Heat transfer occurs by conduction, enthalpy flow (including phase change), shortwave solar radiation and long wave thermal radiation emission.

Moisture transfer is modeled by vapor diffusion, surface diffusion and capillary conduction (Delgado , et al., 2010). As a limitation, it is noted that convection by air is neglected in this model due to the complex process (Künzel & Karagiozis, 2004).

In addition to simulating hygrothermal performance of building envelope, WUFI can be used for the development and optimization of innovative building materials and components. One such example is the development of the smart vapor retarders, a humidity controlled vapor retarding PA-film (Künzel, 1998).

4.2.2. WUFI+

WUFI+ is a simulation model that solves heat and moisture balance equations for whole building. Governing equations are the same as WUFI but indoor conditions are different. The indoor room temperature is linked to the heat fluxes into the room. This means that not only the heat flux over the envelope (transmission and solar input) is considered, but also the internal thermal loads and the air exchange because of natural convection or HVAC systems are taken into account. The moisture condition in the room are a consequence of the moisture fluxes over the interior surfaces, the user dependent moisture production rate and the gains or losses by air infiltration, natural or mechanical ventilation as well as sources or sinks from HVAC systems (Holm, et al., 2003).

4.2.3. hygIRC-1D

It is a one dimensional program to simulate heat, air and moisture in building envelope. This is the updated version of LATENITE model by National Research Council of Canada (NRCC). The hygIRC is used to model common wall systems and retrofits to improve airtightness and insulation levels in the walls (Delgado , et al., 2010).

The model simulates the heat, air and moisture transport through the assembly on hourly basis. There is a weather database and a material database included in the software. Climate database includes 30-40 years of hourly weather data for 25 cities in North America. Material database of this program is one of the most updated databases in North America including hygrothermal properties of 80 common construction materials (NRCC web page, 2012).

4.2.4. Moisture-Expert

This model was developed to simulate 1-dimesional and 2-dimesional heat, air and moisture transport in building envelopes. The model simulates vapor and liquid transport separately. Energy transport driving force is the temperature and for moisture transfer potentials are vapor pressure and relative humidity. The two advantages of this model are capability of determining sorption isotherm based on temperature and liquid transport properties as a function of drying or wetting mechanisms (Auer, et al., 2007).

The MOISTURE-EXPERT as a complex model requires more than 1000 inputs for the 1D simulation. These input data contain boundary conditions, material properties, and envelope system and subsystem information (Delgado , et al., 2010).

4.3. Selected simulation model

After studying different simulation models, WUFI Pro 5.1, a menu-driven PC software, was selected for the purpose of assessing hygrothermal performance of roofs in this study because of some reasons. Firstly, it is one of the most advanced in use simulation models that is available to public. Basic version of this software is available for free to download on the internet. Secondly, Accuracy of WUFI for different components of building envelope has been validated versus various full-scale field and experimental studies. (Künzel, 1995) (Hens, 1996). The reliability of this model also has been confirmed by different authors by comparing experimental measured data with WUFI results (Straube & Schumacher, 2003) (Kalameesa & Vinha, 2003).

4.3.1. Governing equations

The governing equations used in WUFI are as follows:

Energy Transfer:

$$\frac{\partial \mathbf{H}}{\partial \mathbf{T}} \cdot \frac{\partial \mathbf{T}}{\partial \mathbf{t}} = \nabla . (\mathbf{k} \nabla \mathbf{T}) + \mathbf{h_v} \nabla \cdot \left(\delta_p \nabla (\phi \mathbf{p_{sat}}) \right) \qquad \textbf{Equation 4-1}$$

Moisture transfer:

$$\frac{\partial \mathbf{w}}{\partial \phi} \cdot \frac{\partial \phi}{\partial \mathbf{t}} = \nabla \cdot (\mathbf{D_\phi} \nabla \phi + \delta_p \nabla (\phi \mathbf{p_{sat}}) \qquad \textbf{Equation 4-2}$$

Where

D_{ϕ} : Liquid conduction coefficient (kg/ms)

H: Total enthalpy (J/m^3)

h_v : Latent heat of phase change (J/kg)

k : Thermal conductivity (W/mK)

p_{sat} : Saturation vapor pressure (Pa)

t : Time(s)

T: Temperature (K)

w: Moisture content (kg/m^3)

δ_p : Vapor permeability (kg/msPa)

ϕ : Relative humidity

The left sides of Equations 4-1 and 4-2 are storage terms. Fluxes are on the right sides of these equations and are coupled by heat and moisture. In the energy equation, heat flux and the enthalpy flux by vapor diffusion with phase changes strongly depend on the moisture fields and fluxes. In moisture equation, vapor flux is influenced by temperature and moisture because of the dependency of saturation vapor pressure to the temperature (Karagiozis, et al., 2001). Equations 4-1 and 4-2 are solved simultaneously during the simulation period to determine temperature and relative humidity at each simulation node.

4.3.2. Calculation Procedure and Features

The flow chart of WUFI including input data and outputs are illustrated in Figure 4-2.

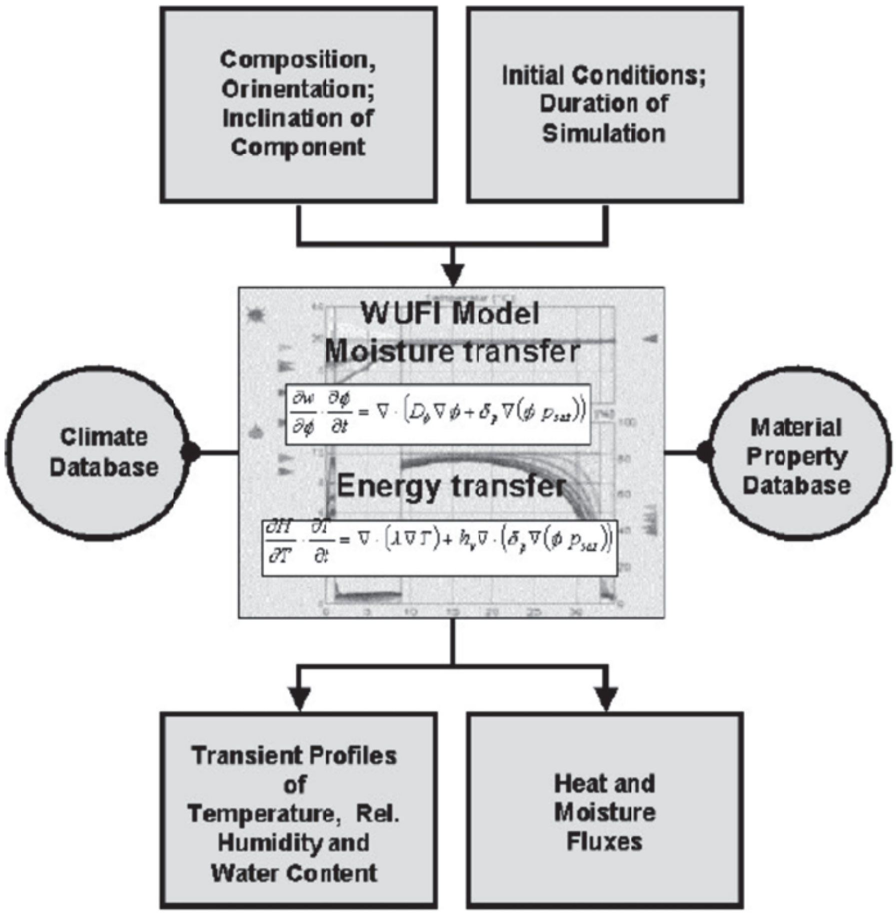


Figure 4-2.Flow chart of WUFI ORNL/IBP (Karagiozis, et al., 2001)

The required input data to simulate a building envelope includes:

- The geometry and composition of the building assembly
- The hygrothermal properties of building materials
- The indoor and outdoor boundary conditions
- The time steps and calculation period.

The outdoor climate can be chosen from an internal database which it includes more than 50 cities weather data. On the other hand for indoor climate, WUFI 5.1 Pro offers following four models based on different standards:

- Sine Curve (WTA Guideline 6-2-01/E)
- EN13788
- EN15026
- ASHRAE-160

The first three models are based on European standards have some suggestions to determine indoor temperature and relative humidity based on outdoor climate conditions. WUFI also can derive interior climate based on Standard ASHRAE Standard-160: Criteria for Moisture Control Design Analysis in Buildings.

Roofing material parameters can be selected from the program database. After compilation of input data, the calculations start from initial temperature and moisture content. At each time step, the energy and moisture equations are solved with a continuous update of the transport and storage coefficients until the convergence criteria are achieved. The resulting output includes the calculated moisture and temperature distributions and the related fluxes for each time step. The results may be presented as animated moisture and temperature profiles over the cross section of the building component or as plots of the temporal evolution of the variables.

Some of WUFI key features are:

- The model includes a visual animation that can help to a better understanding of heat and moisture transfer in the building assembly.
- The model can employ either SI or IP units.
- The model is equipped with both data and material database.
- The model computes night sky radiation. This feature allows the model to predict surface wetting (condensation) during the night time.
- The model calculates the effect of wind as a function of building height.
- The model determines interior climate conditions based on exterior climate conditions (Karagiozis, et al., 2001).

4.4. Effect of snow

WUFI ORNL/IBP considers all precipitation as rain so it neglects potential effects of snow on hygrothermal performance of building envelopes. Bludau *et al* (2008) point out that neglecting the snow in simulations can lead to a lower accumulation of condensation water by underestimating the prevailing temperature (Bludau, et al., 2008).

In this study, we developed an algorithm to predict the effect of snow on the hygrothermal behaviour of roofs. The algorithm uses the existing WUFI code in two simulations to account for the effect of the snow on the roof. In this algorithm, surface temperature and relative humidity of roofs were assumed to be 0˚ C and 100%, respectively, during snow covering. Otherwise, surface temperature and relative humidity are calculated by surface energy and moisture balance equations. The assumptions of this algorithm are based on different field measurements in literatures to determine surface temperature of roofs with snow. (Bludau, et al., 2008) (TenWolde, 1997).

The algorithm for simulating the effect of snow or roof includes the following steps:

- Running WUFI for a normal simulation case for a given roof;
- Exporting surface temperature and relative humidity of roof;
- Creating a new climate file which includes exported surface T, RH for the periods without snow and assuming 0 ° C and 100% for surface temperature and relative humidity for the days with snow covering;
- Assigning exterior surface heat resistance to zero in order to keep surface temperature of roof equal to new climate file temperature and relative humidity;
- Repeating simulation again to characterize the effect of snow on hygrothermal performance of roof.

4.5. Criteria to evaluate hygrothermal performance

In a wooden material assembly, analysis of hygrothermal behaviour is essential to ensure the moisture content does not exceed the critical limit throughout the year. The most important factor to monitor is accumulation of water over the time. Other criteria for avoiding mold growth and degradation of wooden material are also developed in standards such as ASHRAE Standard-

160 (Criteria for Moisture Control Design Analysis in Buildings) and National Building Code of Canada (Standard-160, 2009) (National Building Code of Canada, 2010).

Since moisture plays an important role in degradation of building envelope materials, systems and subsystems, there is a need to have criteria for moisture design. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers published ASHRAE Standard 160 with title of "Criteria for Moisture-Control Design Analysis in Buildings" that identify minimum requirements for moisture performance of roofing assemblies. The purpose of this standard is to identify performance-based design methods for predicting, preventing, mitigating or reducing moisture damage depending on climate, construction type and system operation. These methods consist of:

- Criteria for selecting analytic procedures
- Design input values
- Criteria for evaluation and use of outputs.

In the standard, after applying specified design values the results are evaluated with the performance criteria described in the standard. This standard is applicable for new buildings, additions, or retrofit and renovation of existing buildings.

ASHRAE standard 160 accounts for construction moisture by defining initial moisture content for different components. Construction moisture is described by amount of water which is absorbed by different components at the construction time. The standard proposes equilibrium moisture content (EMC) of each material at 80% relative humidity as an initial condition. Based on this standard, EMC 80 is the highest possible moisture level that does not lead to mold growth.

Indoor temperature can be chosen from Table 4-2 based on outdoor weather and the HVAC equipment.

24-h Running average of outdoor temperature	**Indoor design temperature ˚C (˚F)**	
	Heating only	**Heating and air conditioning**
$\boldsymbol{T_{o,24h} \leq 18.3^{\circ}C (T_{o,24h} \leq 65^{\circ}F)}$	21.1°C (70°F)	21.1°C (70°F)
18.3˚C≤$\boldsymbol{T_{o,24h}}$≤ 21.1˚C	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$
$\boldsymbol{T_{o,24h}}$ **≥21.1˚C ($\boldsymbol{T_{o,24h}}$≥70˚F)**	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$	23.9°C (75°F)

Table 4-2.Default design indoor temperatures

As a performance criteria, standard focus on surface mold growth because in most cases, it is likely to be the most stringent of all performance criteria. In 2011, after publishing an Addendum by ASHRAE, three necessary conditions to avoid mold growth decreased to just one following condition.

> *"In order to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, the following condition shall be met: a 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)"*

(Standard-160, 2009) (TenWolde, 2010) (Addendum a to ASHRAE Standard-160, 2011).

As another criterion for wooden material, National Building Code of Canada determines that acceptable moisture content of the wooden material such as OSB panels shall not be more than 19% (National Building Code of Canada, 2010).

4.6. Conclusion

After reviewing several models, WUFI Pro 5.1 was chosen to simulate hygrothermal performance of various roofing systems with different indoor and outdoor climates. WUFI computes transfer of through conduction, enthalpy flow, shortwave solar radiation and long wave thermal radiation emission. Moisture transport includes processes accounting for vapor diffusion, surface diffusion and capillary conduction. WUFI has been previously validated with experimental data. WUFI has a comprehensive material and climate database which are imbedded in the model. As a limitation, WUFI does not account for air convection and movement in the roofing assembly.

WUFI consider all of precipitation as rain and ignores potential effect of snow. We developed an algorithm to predict the effect of snow accumulation on the hygrothermal performance of roofs. In this algorithm, we assumed surface temperature and relative humidity of roofs to be 0℃ and 100%, respectively, when the roof is covered with snow. Otherwise, surface temperature and relative humidity are calculated by surface energy and moisture balance equations. We carried out a sensitivity analysis for predicting total moisture content of the roof with assuming different temperatures underneath the snow (ranging from -20℃ to 0℃.

For evaluating hygrothermal performance of roofs, we used following three criteria:

- Accumulation of total water content over the time
- Risk of mold growth based on ASHRAE Standard 160
- Moisture content in wooden material based on National Building Code of Canada (max 19% by mass)

Chapter 5 Simulation cases and results

This chapter presents descriptions of different considered cases and their hygrothermal behavior for white and dark roofs. In the first half of this chapter, input data of WUFI Pro 5.1 and boundary conditions of simulation cases in different climates are discussed. In the second part, results of the simulations are presented in order to evaluate moisture performance of black and white roofs.

5.1 General description

Excessive moisture in a roofing assembly may results in destructive problems. Hence, proper design of roofs, as part of building enclosure, plays an important role in durability of roofing assembly and indoor health condition.

We designed and simulated several roofing construction scenarios for diverse climates in order to study the effect of reflectivity on moisture performance of roofs. Specifically, we studied the effect of the following three parameters on moisture transport in the white and dark roofs:

- Roofing composition
- Outdoor climate
- Indoor temperature and relative humidity

Hygrothermal behaviour of various roofing systems was investigated for a period of 5 years. WUFI 5.1 Pro simulations were carried out on hourly basis from 1st of January 2007 to 1st January 2012. In all simulation, solar absorptance of 0.4, 0.88 was used to simulate the performance of white and dark roofs, respectively. The thermal emittance for both white and dark roof was assumed to be 0.9 (typical of a non-metallic surface).

5.1.1 Roofing systems

Four prototypical systems were selected to simulate: (1) a typical roof with conventional vapor retarder, (2) a roof with smart vapor retarder, (3) a vented roof with smart vapor retarder, (4) a self-drying roof (See Figure 5-1). All of simulations were carried out for flat roofs. The first two roofing systems (typical and smart roofs) have the same compositions with different kinds of vapor retarders [see Figure 5-1 (a, b)]. For the typical roof, conventional vapor retarders were used with constant water vapor permeability. For the smart roofing systems and vented smart roofs, polyamide film (PA) with decreasing water vapor permeability with increasing relative humidity, was used as a smart vapor retarder between mineral wool and gypsum board. The water vapor diffusion resistance of smart vapor retarders changes with ambient relative humidity (See Figure 5-2).

We propose vented smart roof as a third kind of roofing systems. The composition is same as the smart roofs with an additional ventilated air space to outside air between OSB and mineral wool (Figure 5-1c). To simulate the effect of this air layer, we used an air change rate (ACH) of 6 with outdoor air for this layer.

The composition of the self-drying roof, as a fourth type of roofing systems, is shown in Figure 5-1(d). The roof is constructed by a

Polyisocyanurate insulation layer between membrane and gypsum board (discussed below). As mentioned in chapter 2, there is no need to use vapor retarder in this system to ensure potential drying out toward the inside of the building. All of materials, used to simulate various roofing types in this study, were selected from WUFI 5.1 Pro database (See Table 5-1).

Exterior membrane “sd-value” (see definition in Chapter 2) was assumed 100 m for typical, smart and vented smart roofing systems while it was assumed 1000 m for self-drying roofs since self-drying roofs must be sealed to the outside by a membrane.

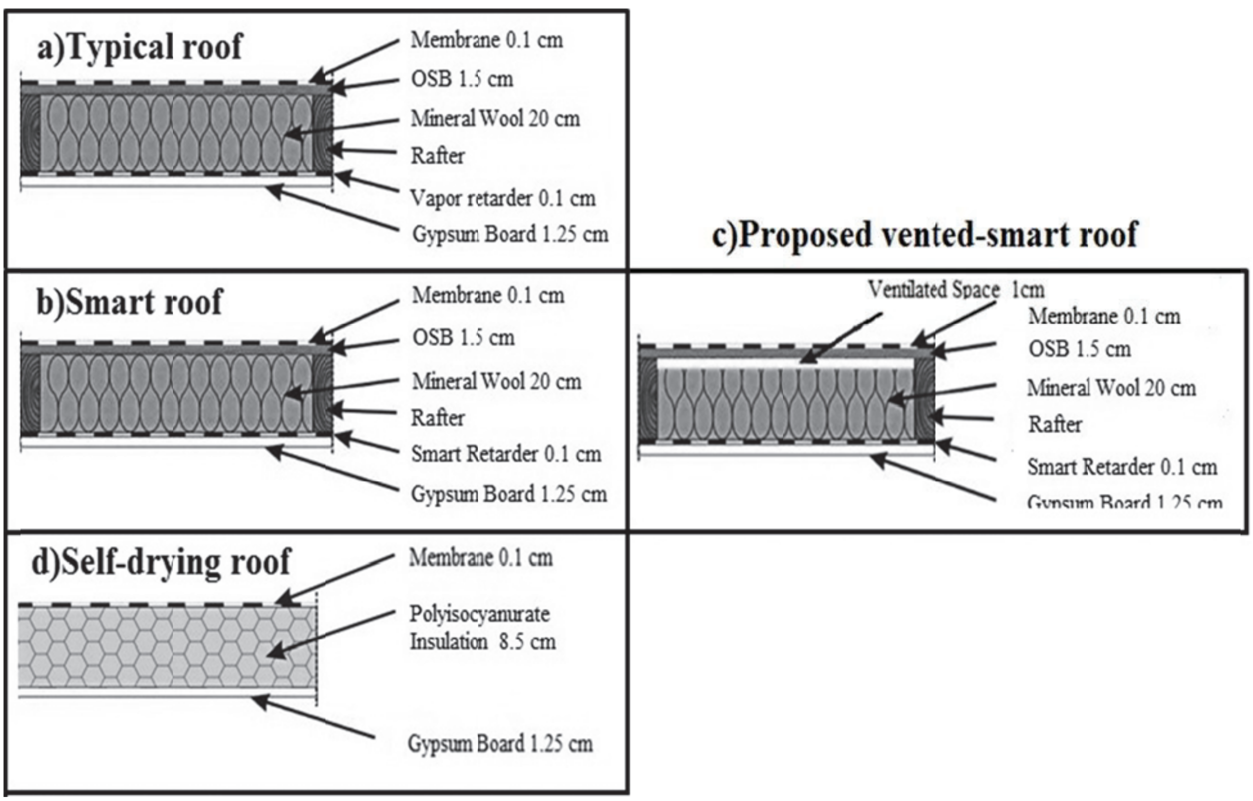


Figure 5-1.Simulated roofing compositions (Bludau, et al., 2008)

Properties / Materials	Bulk density (kg/m^3)	Porosity (m^3/m^3)	Specific heat capacity (J/kgK)	Thermal conductivity (W/mK)	Water vapor diffusion resistance factor
Exterior membrane	130	0.001	2300	2.3	100000
OSB	595	0.9	1500	0.13	165
Mineral wool	60	0.95	850	0.04	1.3
Vapor retarder	130	0.001	2300	2.3	2000
Gypsum board	850	0.65	850	0.2	8.3
PA-membrane	65	0.001	2300	2.9	0-43800
Polyisocyan-urate	26.5	0.99	1470	0.024	51.5

Table 5-1.Materials basic properties (WUFI material database)

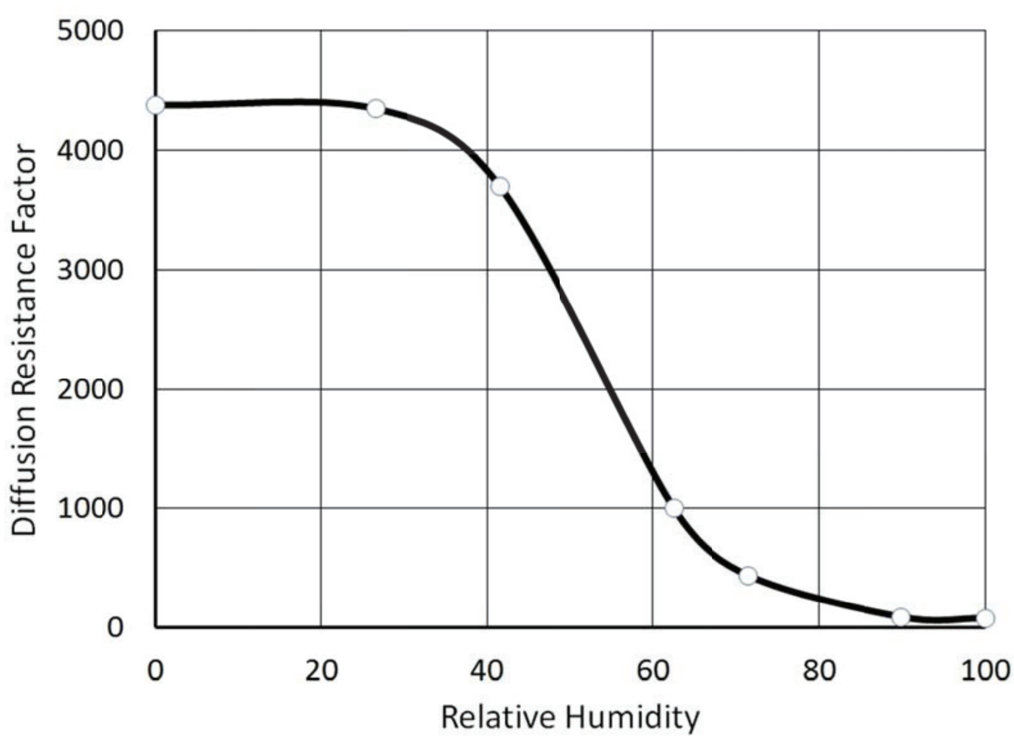


Figure 5-2.Diffusion resistance factor dependency of smart vapor retarder (PA-film) to Relative Humidity (originated from WUFI database)

5.1.2 Outdoor climates

Thirteen climate regions across U.S. and Canada were selected from WUFI 5.1 Pro climate database for simulations. These cities were selected to represent a variety of climate conditions including hot and humid, hot and dry, cold winter and hot summers, and very cold winters (see Figure 5-3)

The selected cities include Anchorage, AK and Edmonton, AB (very cold climates); Madison, WI, Montreal, QC, St. John's, NL (cold winter and humid summer); Chicago, IL and Vancouver, BC (cool and humid); Kansas City, MO, New York, NY (mixed and humid); Los Angeles, CA and Phoenix, AZ for warm and dry climates; Houston, TX as hot and humid location and Miami, FL as a very hot and humid place. Table 5-2 presents summary of climatic data for each selected cities. Among selected city, Anchorage and Edmonton have highest HDD 18 with 5872° C-day, 6124° C-day, respectively, whereas lowest HDD18 belongs to Miami with only 111° C-day (ASHRAE Standard 90.1, 2010).

Furthermore, Anchorage, Montreal and Chicago were selected to simulate the effect of snow on hygrothermal performance of both white and black roofs on residential and commercial buildings. For this purpose, typical flat roofs and smart roofs were chosen to simulate. For Anchorage and Montreal, it was assumed that roofs were covered with snow for the first 90 days of each year (Jan 1 through Mar 31). For Chicago, roofs were considered with snow for the first 60 days of the year (Jan 1 through Mar 1).

Figure 5-3.Simulated cities all across U.S and Canada (blank map (Free USA and world maps website, 2012))

City	Latitude	Longitude	ASHRAE climate zone	HDD 18 (˚C-day)	CDD50	Max T(˚C)	Min T(˚C)	Mean T(˚C)
Anchorage	61.17 N	150.02 W	7	5872	382	23.9	-29.4	0.8
Chicago	41.98 N	87.90 W	5A	3631	1634	34.4	-22.8	8.8
Edmonton	53.30 N	113.58 W	7	6124	594	28.0	-40.0	2.0
Houston	29.97 N	95.35 W	2A	888	3820	38.3	-6.1	18.8
Kansas City	39.32 N	94.72 W	4A	2996	2140	37.2	-24.4	11.2
Los Angeles	33.93 N	118.38 W	3B	810	2654	38.3	2.8	15.9
Madison	43.13 N	89.33 W	6A	4263	1327	36.1	-23.9	6.9
Miami	25.80 N	80.30 W	1A	111	5263	33.9	1.7	23.4
Montreal	45.47 N	73.75 W	6A	4603	1192	40.0	-26.0	6.8
New York	40.78 N	73.97 W	4A	2669	2019	34.4	-16.1	11.5
Phoenix	33.43 N	112.02 W	3B	750	4681	45.6	0.0	21.4
St. John’s	47.62 N	52.73 W	6A	4938	471	26.7	-22.2	3.7
Vancouver	49.18 N	123.17 W	5A	3157	853	27.2	-11.1	9.1

Table 5-2: Climatic data for simulated cities (ASHRAE Standard 90.1, 2010) and WUFI database

5.1.3 Indoor climates

The simulations were carried out for two different indoor conditions representing typical indoor conditions of residential and commercial buildings. Indoor climate of residential buildings were selected with set points based on outdoor climate. On the other hand, indoor conditions of commercial buildings (offices) were designed with flexible set points based on outdoor climate and occupancy time.

For residential buildings, indoor environmental conditions (temperature, relative humidity) were selected based on ASHRAE Standard-160. Table 4-2 shows recommended temperature set points for residential buildings. In this standard, indoor temperature is a function of outdoor temperature. In designing indoor relative humidity, indoor partial vapor pressure can be calculated by Equation 5-1 and Equation 5-2 for heating and cooling season respectively. Meanwhile, maximum relative humidity was set at 50% (Standard-160, 2009) (TenWolde & Walker, 2001).

$$\mathbf{P_i = P_O + \frac{c\,m_s}{VI}}$$ **Equation 5-1**

$$\mathbf{P_i = 0.004\frac{P_{atm}}{0.62198} + 0.4P_{OC}}$$ **Equation 5-2**

Where

P_i: Moisture design indoor vapor pressure (Pa)

P_O: Outdoor vapor pressure (Pa)

c = 4.89 x 10 5 m^2/s^2

m_s: Moisture source rate (kg/s)

V: Building volume (m^3)

I: Air exchange rate (1/h)

P_{atm}: Atmospheric pressure (pa)

P_{OC}: Cooling design outdoor vapor pressure (Pa)

For commercial buildings, indoor temperature and relative humidity set points for a typical office building with occupancy schedule of 8:00 AM to 5:00 PM (Monday to Friday) were assumed. The building was assumed unoccupied during the evenings and weekends. Table 5-3 presents heating, cooling and relative humidity set points. Since WUFI Pro 5.1 does not allow for scheduled HVAC design, we used WUFI+ (version 2.1.1.50) to create indoor climate files for commercial buildings based on Table 5-3.

	Heating		**Cooling**	
	Day times	**Night times and weekends**	**Day times**	**Night times and weekends**
Temperature˚C (˚F)	22.2(72)	15.5(60)	24.4(76)	29.4(85)
Relative humidity	50	50	50	50

Table 5-3.Indoor climate for office building

5.1.4 Initial and boundary conditions

The ASHRAE standard-160 proposes that equilibrium moisture content at 80% relative humidity (EMC80) is the highest possible moisture level that does not lead to mold growth. In this study, initial moisture content of all layers in the roofing assemblies was set to EMC80 and initial temperature of materials were assumed constant across all components at 20˚C.

5.1.5 Surface resistance coefficients

An overall surface heat conductance or surface heat resistance was used to calculate sum of heat fluxes by radiation and convection at the surfaces. The overall coefficient is the sum of convective and radiative heat transfer coefficients (see Sections 3.2.2 and 3.2.3). In all simulations, exterior and interior heat resistance coefficients were assumed 0.0526 m^2K/W and 0.125m^2K/W, respectively.

5.1.6 Validation

To validate our simulations, we simulated white self-drying roofs for 3 cities (Phoenix, Chicago and Anchorage) that were also simulated by Bludau *et al* (2008). Simulated roofing system composed of a foam insulation in center (polyisocyanurate) and sealed to the outside by a roofing membrane (sd=1000 m) and steel deck to the inside (sd=3.3 m). Solar absorptivity of black and white roofs assumed to be 0.88, 0.2, respectively. The simulations were conducted for a period of five years started from beginning of October. Figure 5-4 shows our simulation total moisture content for self-drying roofs with white surface in

Anchorage, Chicago and Phoenix. By comparing our results with results of Bludau et al (2008), we concluded that both total moisture content results were identical.

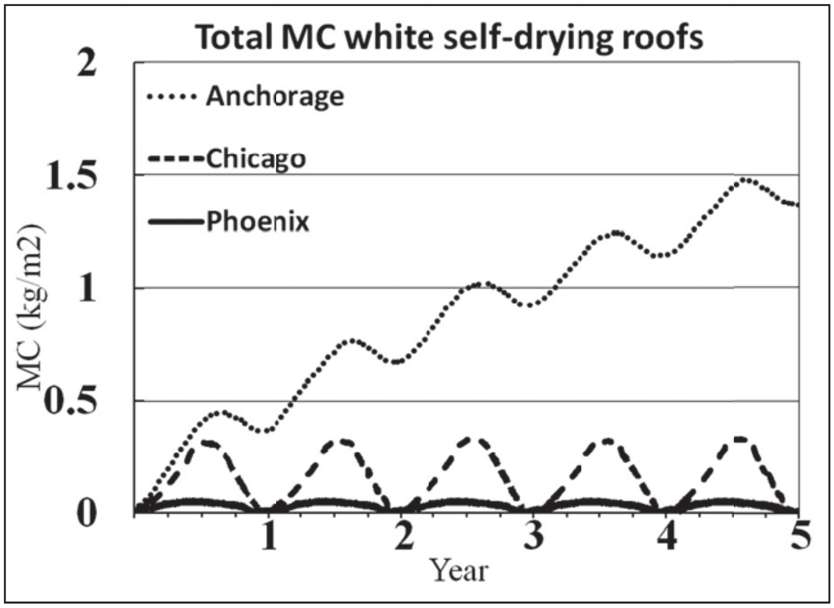


Figure 5-4.**Total moisture content of white self-drying roofs in three cities**

As a second validation, we considered a steady-state condition for indoor and outdoor climates for a given roofing system (see Figure 5-5) and compared calculated temperature and vapor pressure by WUFI with Glaser method calculated results. For outdoor climate, we assumed that the temperature and relative humidity were 0℃, 70%, respectively. The indoor temperature presumed to be 21℃ while relative humidity was 35%. Comparing Table 5-4 and Table 5-5 show that simulated temperatures in absence of moisture transport by WUFI were identical with calculated temperatures Glaser method.

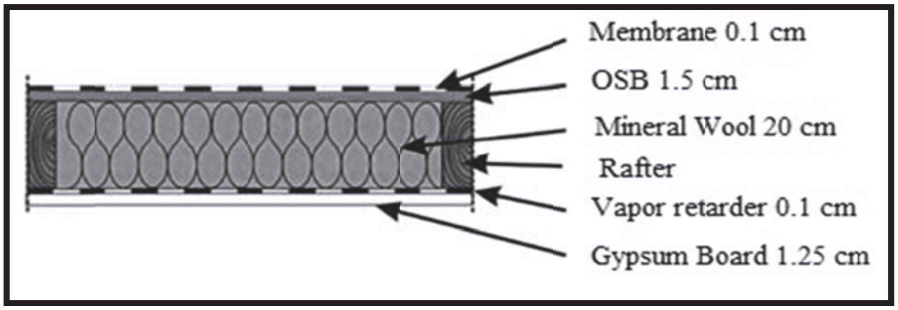


Figure 5-5.Simulated roofing composition for validation of a steady state condition

	Exterior surface	Membrane/ OSB	OSB / Wool	Wool /Vapor retarder	Vapor retarder /Gypsum	Interior surface
Temperature (℃)	0.2	0.2	0.6	20.2	20.3	20.5

Table 5-4.WUFI temperature results without moisture transport

	L (m)	k (W/mK)	l/k (m^2K/W)	T(℃)
Exterior surface			0.0526	0.2
Membrane	0.001	2.3	0.00043478	
OSB	0.015	0.13	0.11538462	0.2
Wool	0.2	0.04	5	0.6
Vapor retarder	0.001	2.3	0.00043478	20.2
Gypsum	0.0125	0.2	0.0625	20.3
Interior surface			0.125	20.5
Total			5.356354181	

Table 5-5.Calculated temperature by Glaser method without moisture transport

As mentioned before, we switched heat transport and capillary conduction off in our simulation by WUFI and compare our results with Glaser method calculated vapor pressures between layers. Comparing Table 5-6 and Table 5-7 display that distributions of vapor pressure by WUFI all across roofing assembly were same as computed vapor pressures by Glaser method between layers.

	Exterior surface	Membrane/ OSB	OSB / Wool	Wool /Vapor retarder	Vapor retarder /Gypsum	Interior surface
Vapor pressure (kPa)	4.3	7.7	8.6	8.6	8.7	8.7

Table 5-6.WUFI vapor pressure results without heat transport and capillary conduction

	Permanence (Perm)	Resistance to vapor transmission (1/Perm)	ΔP	Vapor pressure (kPa)
Exterior surface				
Membrane	11500	8.7E-05	0.000397	4.3
OSB	1.35	0.740741	3.385538	7.7
Wool	5	0.2	0.914095	8.6
Vapor retarder	100	0.01	0.045705	8.6
Gypsum	71.12014224	0.014061	0.064264	8.7
Interior surface				
Total		0.964888		

Table 5-7.Calculated vapor pressure by Glaser method

5.2 Results

We carried out parametric WUFI 5.1 Pro simulations for all roofing systems (typical, smart, smart vented and self-drying), with a white or a black surface, for different indoor and outdoor conditions. In this section, the following results are shown and discussed:

- Monthly average surface temperature
- Maximum and minimum of surface temperature
- Total moisture content of the roofing assembly
- OSB moisture content
- Risk of mold growth based on ASHRAE-160

To minimize the effect of initial conditions, we calculated surface temperature, monthly total water content and risk of mold growth for the last year of simulation. Effects of initial conditions were considered in calculation of OSB moisture content to comply with the national building code of Canada .

5.2.1 Residential buildings with typical roof compositions

Table 5-8 shows monthly-averaged surface temperatures for typical black and white roofs. Since the roof surface temperatures are only function of solar absorptance and thermal emittance, we only show surface temperature of black and white typical composition roof as representing other cases (Thermal emittance of black and white roofs were kept unchanged).

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal	Black	-7.5	-5.3	3.3	12.5	20.8	26.5	29.9	26.4	20.2	10.6	4.0	-5.0
	White	-9.2	-8.1	-0.6	7.6	15.1	20.5	23.7	21.3	16.2	8.1	2.6	-6.3
Anchorage	Black	-13.7	-8.2	-5.9	7.4	13.2	20.3	22.0	17.5	11.4	0.8	-8.3	-13.6
	White	-14.0	-9.4	-8.6	2.9	8.4	15.0	16.6	14.1	8.8	-0.5	-8.8	-13.8
Kansas City	Black	-5.0	-3.7	5.9	19.8	23.8	31.9	35.8	33.3	29.8	17.3	10.2	1.2
	White	-7.3	-7.1	1.6	14.5	18.1	25.0	29.0	26.8	24.3	13.1	7.6	-1.3
Madison	Black	-7.9	-7.2	3.1	13.5	21.9	28.9	30.7	29.2	24.8	12.2	4.9	-4.2
	White	-10.2	-10.8	-1.5	8.4	15.9	22.0	24.6	23.2	19.8	9.2	2.5	-6.0
New York	Black	1.4	2.2	10.2	17.3	25.7	30.8	30.8	29.7	23.4	16.9	7.5	0.4
	White	-0.8	-0.5	5.3	11.8	19.2	24.4	24.5	24.0	18.8	13.5	5.1	-1.5
Phoenix	Black	13.8	17.0	21.7	29.8	33.9	41.1	42.3	39.3	33.2	24.9	16.0	12.9
	White	10.3	11.9	15.5	21.8	25.4	32.7	34.5	32.4	26.9	19.6	12.1	9.7
Vancouver	Black	1.1	4.3	9.4	12.2	19.6	23.0	25.7	26.5	18.7	11.3	7.0	2.2
	White	0.2	2.7	7.3	8.2	14.1	17.3	19.0	20.2	14.4	8.5	5.7	1.4
Miami	Black	22.9	22.8	26.3	32.5	33.2	33.7	36.0	36.4	34.0	31.3	25.9	23.1
	White	19.2	18.1	20.6	26.0	27.7	28.3	29.7	30.4	28.9	26.9	21.5	19.2
Los Angeles	Black	15.2	16.4	19.3	21.3	25.7	26.0	30.6	29.6	27.7	23.6	18.4	15.0
	White	12.0	12.6	14.5	15.3	18.7	20.2	23.2	22.7	22.0	18.9	14.7	12.0
Houston	Black	9.0	10.0	19.8	26.6	32.5	35.1	36.4	36.0	31.9	26.1	22.3	14.2
	White	6.5	6.4	15.1	21.3	26.4	28.7	30.2	29.9	27.5	21.3	19.0	11.4
Saint John's	Black	-4.3	-5.7	0.6	6.5	10.9	22.2	23.1	20.3	16.2	9.6	2.8	-4.2
	White	-5.8	-8.3	-2.6	1.7	6.1	16.6	17.5	15.9	12.8	7.4	1.5	-5.5
Edmonton	Black	-14.7	-7.7	-1.8	10.7	18.7	22.9	24.9	22.3	13.0	6.1	-3.2	-11.3
	White	-15.9	-10.0	-5.8	5.3	12.6	16.3	18.4	16.9	9.2	3.6	-4.5	-12.2
Chicago	Black	-5.0	-5.0	3.8	14.7	21.4	29.2	31.3	30.1	27.4	14.9	8.0	-1.5
	White	-7.0	-8.5	-0.2	9.7	15.3	22.5	25.2	24.2	22.3	11.6	5.6	-3.5

Table 5-8.Calculated monthly outdoor surface temperature (℃) of the typical roof for residential building in the fifth year

As shown in Table 5-8, the surface of the black roof (solar reflectance of 0.88) always experienced higher temperature than the white roof (solar absorptance of 0.4). The surface temperature of roofs in Miami, Phoenix, Los Angeles and Houston were highest. While lowest surface temperature occurred in Anchorage, Edmonton and St. John's. The surface temperature differences between black and white roofs were much higher in sunny locations such as Phoenix and Miami rather than less sunny and cold locations like anchorage and St. John's.

Table 5-9 shows the maximum and minimum surface temperature of white and black typical roofs in residential buildings during the five years simulation. It should be noticed that the minimum surface temperatures for black and white roofs were almost the same, since minimum surface temperature occurs at night and roof solar reflectance has no effect on the surface temperature.

city	Maximum surface temperature (˚C)		Minimum surface temperature (˚C)	
	Black roof	**White roof**	**Black roof**	**White roof**
Montreal	69.3	49.8	-29.8	-29.8
Anchorage	52.7	34.5	-32.8	-32.8
Kansas City	72.8	50.3	-28.0	-28.1
Madison	68.6	46.2	-27.0	-27.0
New York	68.7	47.4	-20.8	-20.7
Phoenix	80.5	57.1	-5.3	-5.3
Vancouver	62.1	40.0	-15.6	-15.6
Miami	71.7	47.9	-3.3	-3.3
Los Angeles	67.3	46.8	-1.9	-1.9
Houston	72.3	50.1	-10.0	-10.0
Saint John's	63.5	41.0	-25.2	-25.2
Edmonton	59.6	39.9	-42.2	-42.2
Chicago	66.0	44.7	-26.8	-26.8

Table 5-9.Max and Min surface temperature for residential buildings with black and white typical roofs

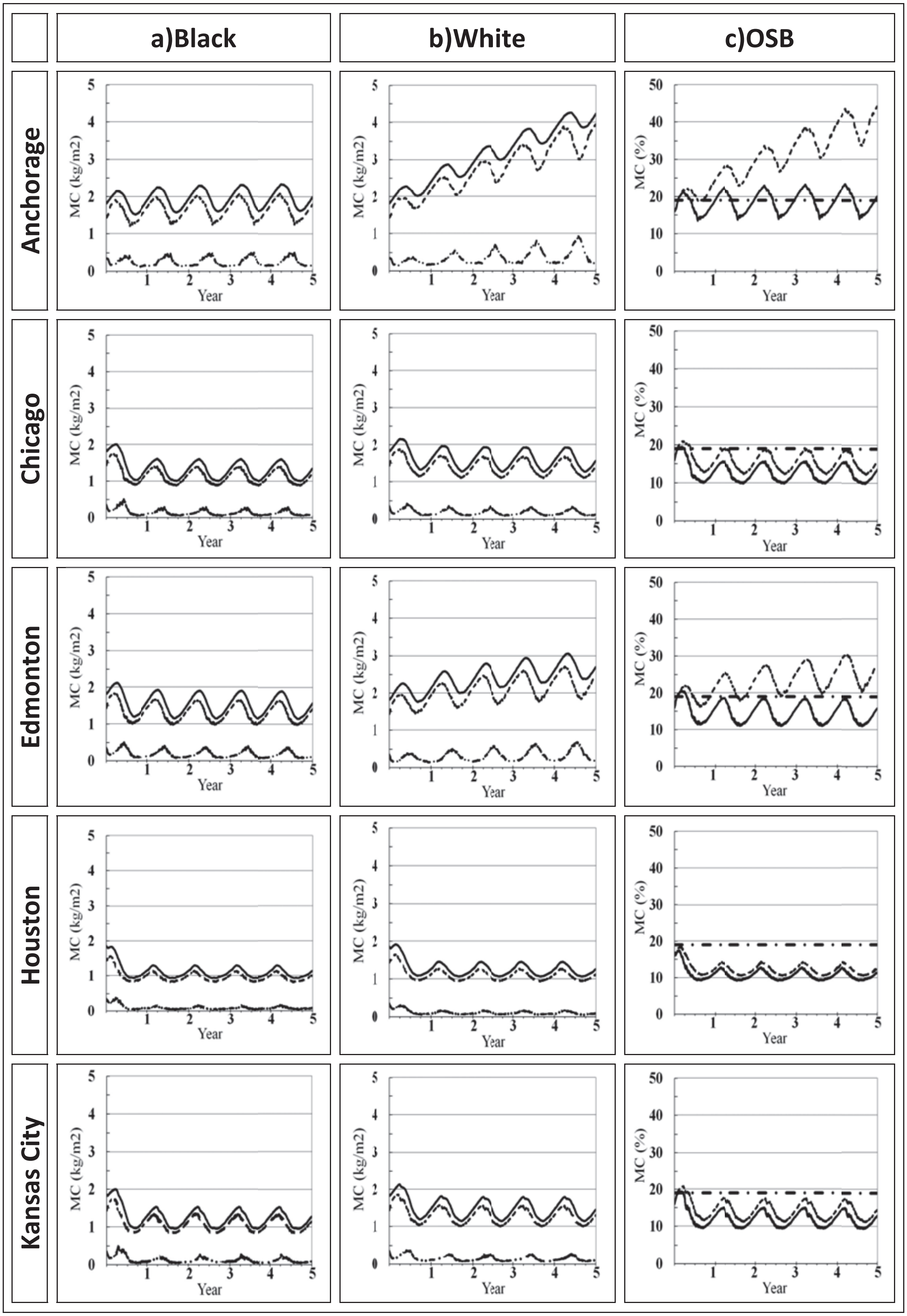
Table 5-10 compares monthly average total moisture content of black and white roofs for simulated cities in the last year of simulation (5^{th} year). The highest moisture content occurred at Anchorage. Phoenix (warm and dry) and Miami (hot and humid) had the lowest moisture content for both black and white roofs. In all locations, amount of moisture content in black roof was less than white roof.

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal	Black	1.49	1.60	1.68	1.66	1.54	1.34	1.16	1.07	1.07	1.14	1.25	1.37
	White	1.81	1.93	2.04	2.11	2.07	1.93	1.73	1.55	1.46	1.49	1.57	1.68
Anchorage	Black	2.05	2.17	2.28	2.32	2.26	2.11	1.89	1.69	1.63	1.67	1.78	1.92
	White	3.87	4.00	4.12	4.22	4.26	4.21	4.08	3.92	3.87	3.91	4.02	4.15
Kansas City	Black	1.34	1.45	1.51	1.44	1.32	1.15	1.00	0.97	0.96	1.02	1.11	1.23
	White	1.52	1.64	1.75	1.75	1.70	1.54	1.33	1.21	1.15	1.19	1.27	1.39
Madison	Black	1.44	1.54	1.61	1.59	1.46	1.24	1.09	1.03	1.02	1.09	1.19	1.31
	White	1.70	1.82	1.94	2.00	1.96	1.79	1.58	1.42	1.32	1.35	1.44	1.56
New York	Black	1.39	1.48	1.53	1.47	1.32	1.13	1.04	1.01	1.03	1.08	1.17	1.28
	White	1.60	1.71	1.80	1.82	1.74	1.57	1.41	1.31	1.27	1.29	1.37	1.48
Phoenix	Black	1.14	1.16	1.11	1.01	0.90	0.84	0.80	0.80	0.83	0.88	0.98	1.09
	White	1.27	1.31	1.32	1.24	1.12	1.00	0.92	0.90	0.92	0.97	1.08	1.19
Vancouver	Black	1.50	1.61	1.67	1.67	1.59	1.41	1.26	1.13	1.09	1.16	1.27	1.38
	White	1.92	2.02	2.10	2.14	2.13	2.02	1.89	1.73	1.63	1.65	1.72	1.81
Miami	Black	1.08	1.10	1.08	1.03	0.99	0.98	0.97	0.94	0.95	0.97	1.01	1.05
	White	1.20	1.23	1.24	1.21	1.16	1.13	1.10	1.07	1.06	1.08	1.12	1.17
Los Angeles	Black	1.18	1.21	1.20	1.16	1.10	1.06	1.01	0.98	0.98	1.00	1.06	1.12
	White	1.35	1.39	1.41	1.41	1.38	1.33	1.27	1.21	1.19	1.19	1.23	1.29
Houston	Black	1.19	1.28	1.27	1.17	1.07	0.99	0.94	0.94	0.96	0.99	1.03	1.10
	White	1.31	1.41	1.44	1.39	1.30	1.19	1.11	1.08	1.07	1.11	1.15	1.22
Saint John's	Black	1.66	1.76	1.85	1.88	1.84	1.71	1.48	1.34	1.29	1.32	1.42	1.53
	White	2.86	2.98	3.10	3.19	3.25	3.20	3.01	2.85	2.74	2.71	2.78	2.88
Edmonton	Black	1.65	1.78	1.87	1.88	1.74	1.51	1.30	1.17	1.18	1.25	1.36	1.50
	White	2.68	2.83	2.95	3.05	3.03	2.89	2.69	2.48	2.39	2.40	2.50	2.63
Chicago	Black	1.41	1.51	1.58	1.57	1.44	1.23	1.09	1.03	1.01	1.07	1.16	1.28
	White	1.63	1.75	1.86	1.92	1.89	1.73	1.54	1.38	1.29	1.30	1.38	1.50

Table 5-10.Monthly average total water content (kg/m^2) in the fifth year of simulation (typical residential roof)

Figure 5-6 illustrates moisture content of black and white roofs in different roofing layers. Columns *a* and *b* show total moisture content of black and white roof in OSB and mineral wool moisture content (kg/m^2). The moisture contents of the gypsum board and vapor retarder (not shown in the Fig 5-6) were small and negligible compared to the other those of OSB and mineral wool. Figure 5-6 shows that moisture accumulation over the simulation period for white roofs in Anchorage, Edmonton and St. John's (cities with lowest roof surface temperature) are clearly visible. On the other hand, typical black roofs show moisture accumulation only in Anchorage.

Column *c* of Figure 5-6 depicts OSB moisture content (percent by mass) for black and white roofs. National Building Code of Canada requires a maximum allowable 19% moisture content in wooden material such as OSB. Table 5-11 provides number of hours in every year of simulation period that moisture content in OSB exceeded 19%. Houston, Los Angeles, Phoenix and Miami are cities that MC in OSB layer never exceeded the 19% for both black and white roofs. OSB for both black and white roofs have some hours during the year with MC more than 19% in Montreal, Anchorage, Kansas City, Madison, Vancouver, St. John's, Edmonton and Chicago. The OSB moisture content of white roofs in Anchorage and Edmonton predominantly were above 19%. New York is the only city that OSB moisture content of white roofs exceeded 19% while that of the black roofs always stayed below this limit.


a)Black
b)White
c)OSB
Anchorage
Chicago
Edmonton
Houston
Kansas City
MC (kg/m2)
MC (%)
Year

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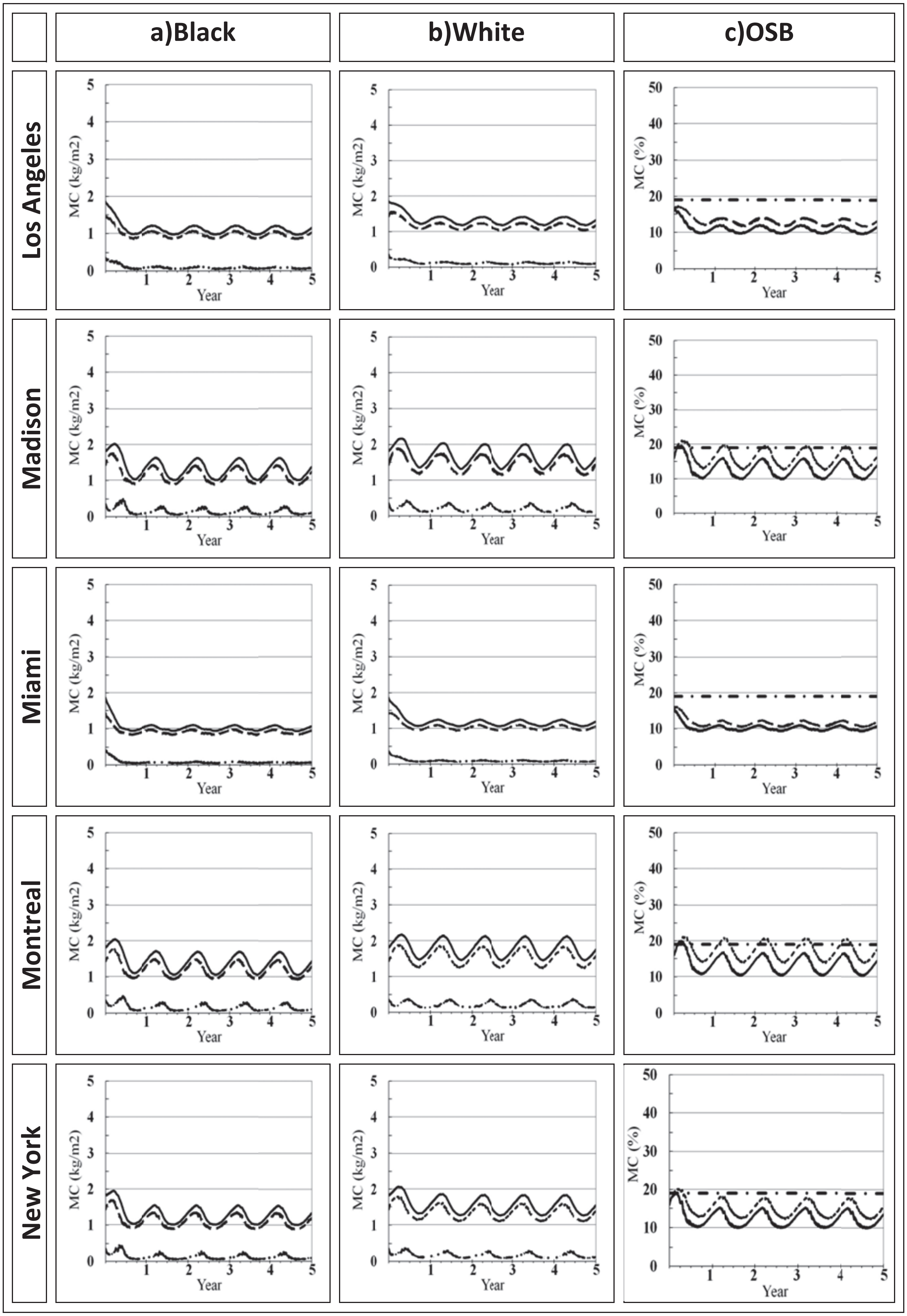

a)Black
b)White
c)OSB
Los Angeles
Madison
Miami
Montreal
New York
MC (kg/m2)
MC (%)
Year

Continued

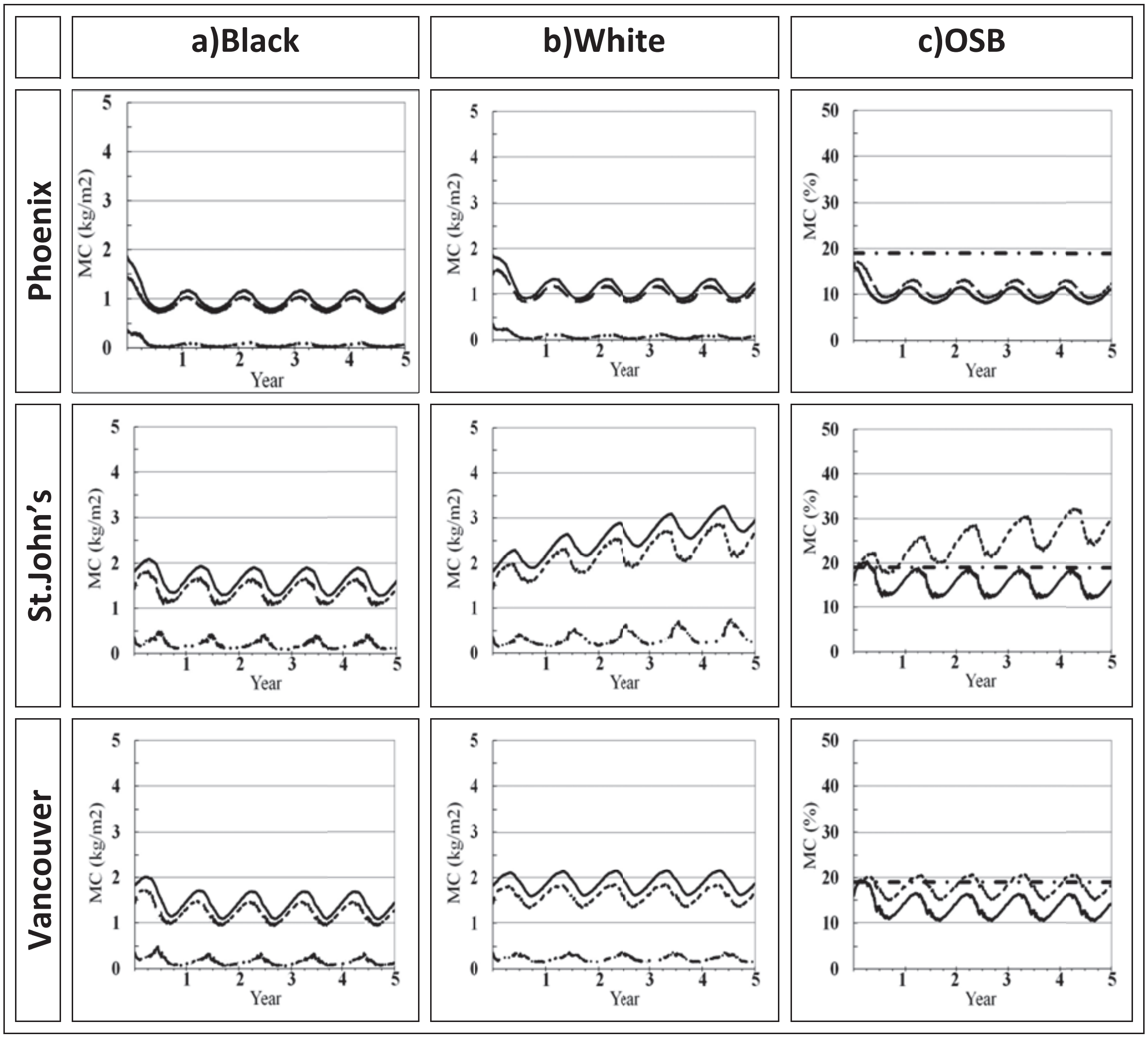


Figure 5-6. Calculated moisture content of typical roofs for residential buildings .Column a, b shows black and white roofs moisture contents (kg/m^2): total (▬▬), OSB (▪ ▪ ▪), Mineral Wool (▪ • • ▪).Column c shows OSB moisture content (%): white roof (▪ ▪ ▪), black roof (▬▬), max allowable MC (19%) (▪ • ▪)

City	Roof color	1st Year (hr.)	2nd Year (hr.)	3rd Year (hr.)	4th Year (hr.)	5th Year (hr.)
Montreal	**Black**	1144	0	0	0	0
	White	2752	2522	2460	2439	2431
Anchorage	**Black**	2735	4039	4176	4206	4228
	White	7174	8760	8760	8760	8760
Kansas City	**Black**	1004	0	0	0	0
	White	2119	0	0	0	0
Madison	**Black**	1218	0	0	0	0
	White	2886	1681	1393	1334	1312
New York	**Black**	0	0	0	0	0
	White	1876	0	0	0	0
Vancouver	**Black**	1053	0	0	0	0
	White	2825	2997	3161	3220	3232
Saint John's	**Black**	2127	0	0	0	0
	White	5269	8760	8760	8760	8760
Edmonton	**Black**	2006	0	0	0	0
	White	4696	7149	8750	8760	8760
Chicago	**Black**	1256	0	0	0	0
	White	2847	162	0	0	0

Table 5-11.Number of hours MC at OSB exceed 19% in typical residential roofs

Table 5-12 shows risk of mold growth (hours) based on ASHRAE Standard-160 criteria between layers in the last year of simulations. Because of the high water vapor resistance of vapor retarder and higher interior drying potential, relative humidity at interior side of vapor retarder never reached 80% to provide requirement for mold growth. Therefore analyzing risk of mold growth was carried out for the three layers at exterior side of the vapor retarder (see Table 5-12).

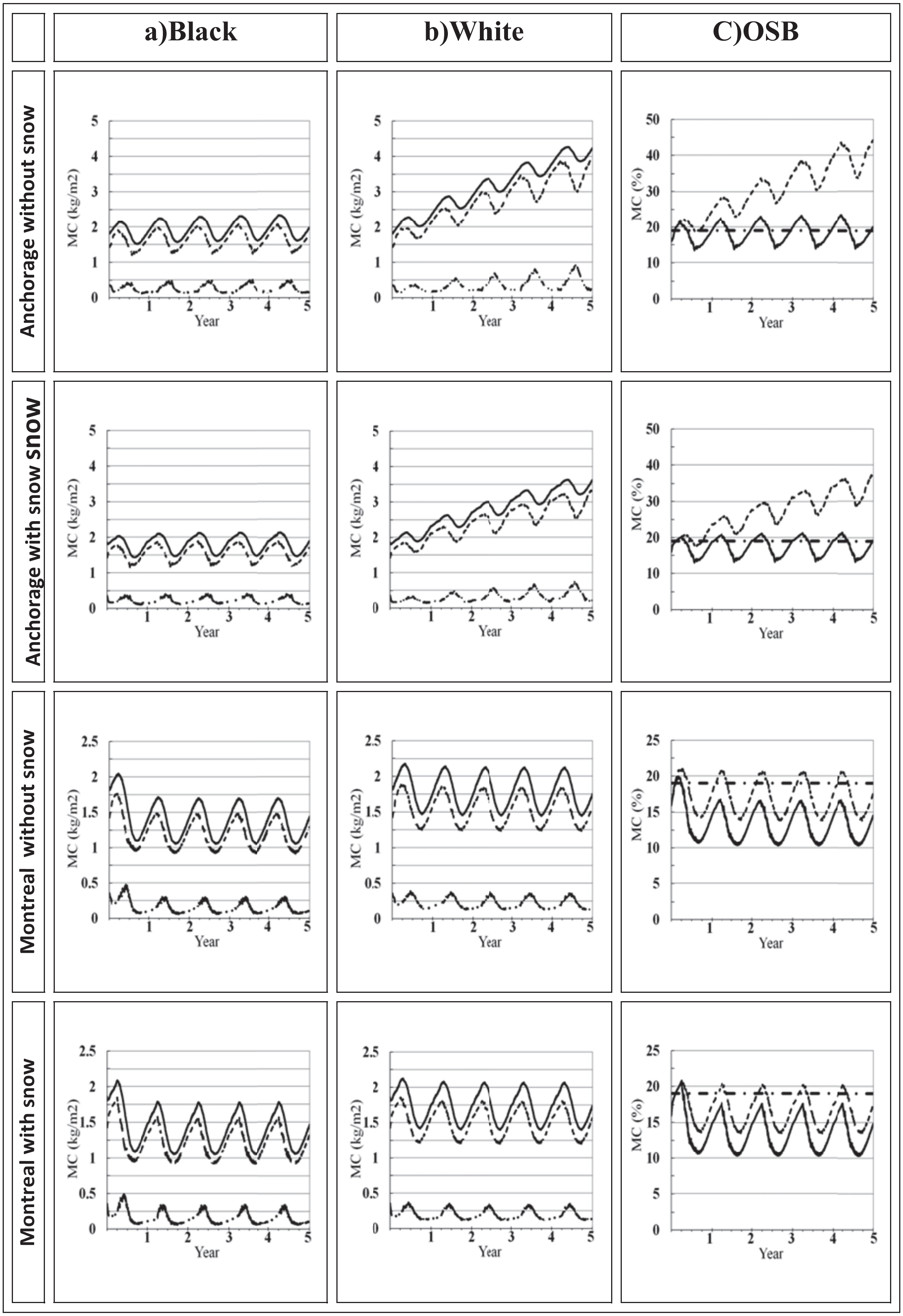
Based on Table 5-12, Phoenix, Miami, Los Angeles and Houston as hot climates are locations that both white and black roofs never experienced risk of mold growth; whereas white roofs in Anchorage, Vancouver and Edmonton have the highest risk of mold growth. In other climates, either black or white roofs have risk of mold growth at different surfaces. Exterior side of mineral wool in white roofs in all climates except hot cities experienced higher risk of mold growth than black roofs. In these climates except Kansas City, risk of mold growth at the interior side of insulation in white roofs was less than black roofs.

City	Roof color	Exterior membrane/OSB	OSB/ Mineral wool	Mineral wool/Vapor retarder
Montreal	Black	0	222	626
	White	2370	1914	0
Anchorage	Black	2447	2425	1348
	White	3853	3903	0
Kansas City	Black	0	0	0
	White	1413	1134	49
Madison	Black	0	0	615
	White	1935	1382	0
New York	Black	0	0	111
	White	1628	1176	0
Vancouver	Black	382	1064	416
	White	4531	4929	0
Saint John's	Black	1312	1110	904
	White	4146	4179	370
Edmonton	Black	1014	595	1305
	White	4297	4343	779
Chicago	Black	0	5	496
	White	1875	1358	0

Table 5-12.Risk of mold growth (Hour) for typical residential roof between layers at the exterior side of vapor retarder

Figure 5-7 summarizes the effect of snow on moisture content of black and white roofs in different components. In Anchorage and Chicago, snow helped to reduce total moisture content in both white and black roofs. Unlike the black roofs in Montreal, white roofs experienced lower amount of total moisture content after considering effect of snow. Table 5-13 shows that number of hours that OSB moisture content is more than 19% with and without considering the effect of snow. Snow on the white roofs always helped to reduce OSB moisture content. Table 5-14 compares effects of snow on monthly average water content. Confirming that the total moisture content of the black roof slightly increased in Montreal with snow on the roof while for all of other cases, snow helped to reduce moisture content of roofs.

In simulating effect of snow covering on the roof, we assumed exterior surface temperature 0° C for the period of year when roof is covered by snow. We also simulated dark and white typical roofs in Anchorage with different surface temperature (-5,-10 and -15℃). Result shows that white roofs were more sensitive to surface temperature under the snow compared to roofs (See Figure 8). For both dark and white roofs, lowest total moisture content happened when surface temperature assumed to be 0℃. Simulating both roofs with surface temperature -10℃ and -15℃ for the snow cover period showed that total moisture content were larger than the case when we simulated roofs without considering effect of the snow. Total moisture content of roofs with surface temperature -5℃ (snow period) were very close to total moisture content of roofs without snow (see Figure 5-8).


a)Black
b)White
C)OSB
Anchorage without snow
Anchorage with snow snow
Montreal without snow
Montreal with snow
MC (kg/m2)
MC (%)
Year
0
1
2
3
4
5
0.5
1.5
2.5
10
15
20
25
30
40
50

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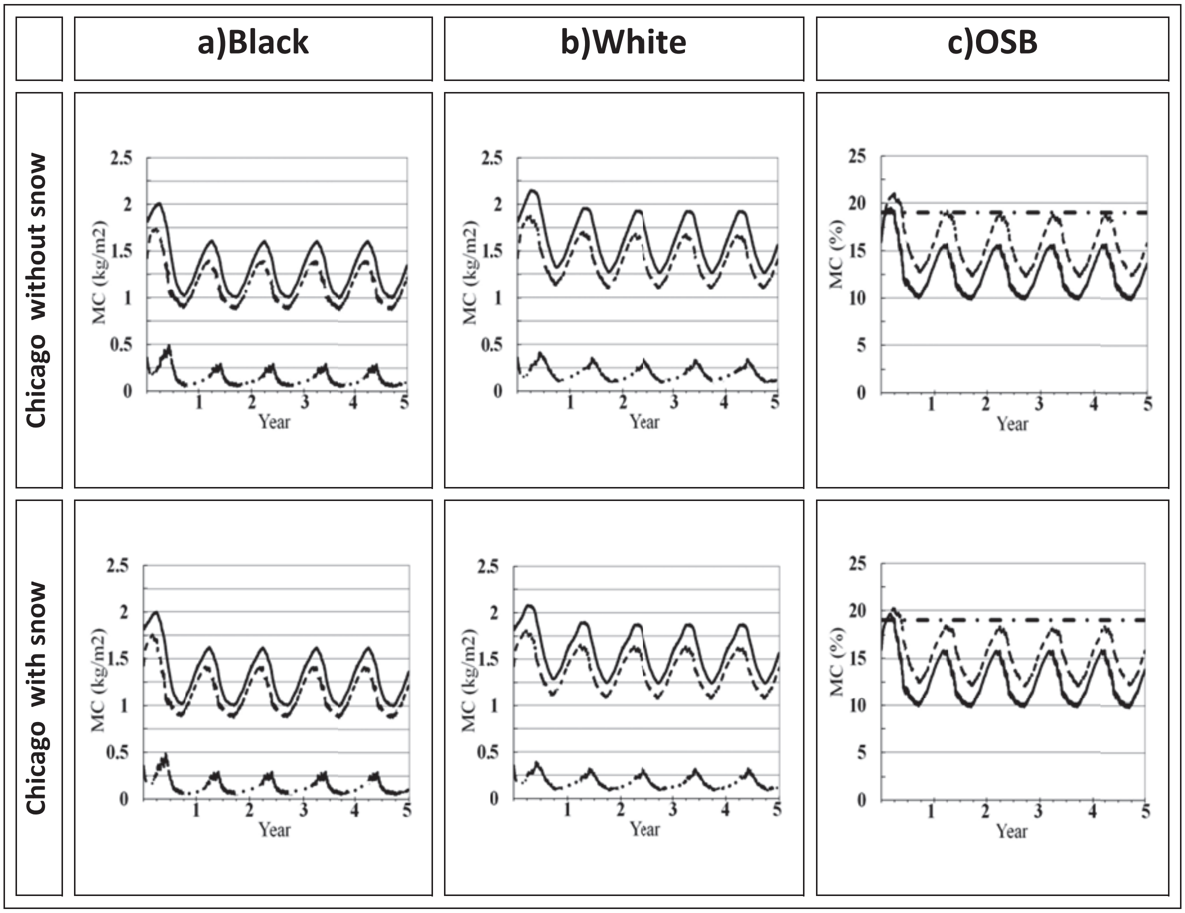


Figure 5-7.Effect of snow on moisture content residential building with typical roof composition; Column a, b shows black and white roofs moisture content (kg/m^2): total (▬), OSB (■ ■ ■), Mineral Wool (■ ◆ ◆ ■).Column c shows OSB moisture content (%): white roof (■ ■ ■), black roof (▬), max allowable MC (19%) (■ ◆ ■)

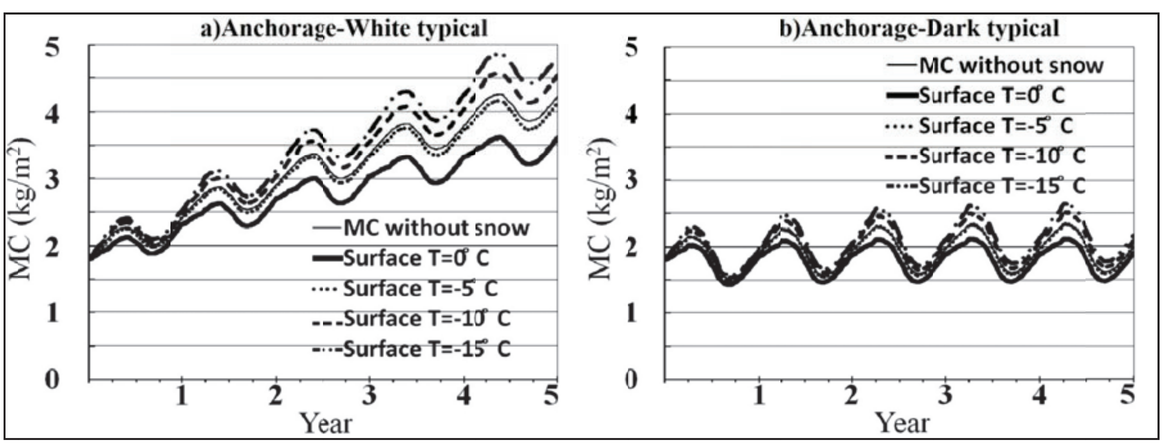


Figure 5-8.Sensitivity analysis on total moisture content of dark and white typical roofs in Anchorage

City	Roof Color	1st Year (hr.)	2nd Year (hr.)	3rd Year (hr.)	4th Year (hr.)	5th Year (hr.)
Anchorage without snow	Black	2735	4039	4176	4206	4228
	White	7174	8760	8760	8760	8760
Anchorage with Snow	Black	1821	2990	3480	3501	3507
	White	5475	8760	8760	8760	8760
Montreal without snow	Black	1144	0	0	0	0
	White	2752	2522	2460	2439	2431
Montreal with snow	Black	1571	0	0	0	0
	White	2435	2061	1913	1874	1859
Chicago without snow	Black	1256	0	0	0	0
	White	2847	162	0	0	0
Chicago with snow	Black	1197	0	0	0	0
	White	2383	0	0	0	0

Table 5-13.Effect of snow on number of hours that moisture exceed 19% at OSB (typical residential)

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal without snow	Black	1.49	1.60	1.68	1.66	1.54	1.34	1.16	1.07	1.07	1.14	1.25	1.37
	White	1.81	1.93	2.04	2.11	2.07	1.93	1.73	1.55	1.46	1.49	1.57	1.68
Montreal with snow	Black	1.50	1.60	1.70	1.75	1.60	1.37	1.16	1.07	1.07	1.15	1.26	1.39
	White	1.77	1.87	1.96	2.05	2.01	1.87	1.66	1.49	1.41	1.45	1.54	1.67
Anchorage without snow	Black	2.05	2.17	2.28	2.32	2.26	2.11	1.89	1.69	1.63	1.67	1.78	1.92
	White	3.87	4.00	4.12	4.22	4.26	4.21	4.08	3.92	3.87	3.91	4.02	4.15
Anchorage with snow	Black	1.93	2.01	2.07	2.12	2.07	1.92	1.71	1.52	1.49	1.55	1.68	1.83
	White	3.36	3.43	3.49	3.58	3.62	3.57	3.43	3.27	3.22	3.27	3.39	3.54
Chicago without snow	Black	1.41	1.51	1.58	1.57	1.44	1.23	1.09	1.03	1.01	1.07	1.16	1.28
	White	1.63	1.75	1.86	1.92	1.89	1.73	1.54	1.38	1.29	1.30	1.38	1.50
Chicago with snow	Black	1.29	1.37	1.39	1.30	1.15	0.99	0.93	0.90	0.90	0.96	1.05	1.17
	White	1.62	1.70	1.80	1.87	1.84	1.68	1.48	1.34	1.26	1.28	1.37	1.50

Table 5-14.Effect of snow on monthly average MC typical residential roof (kg/m^2)

5.2.2 Moisture behaviour of roofs in Tucson

In section 2.4.1, we reviewed some observations indicting the existence of excessive moisture in the white roofs in Tucson. We simulated hygrothermal behaviour of black and white roofs in Tucson with typical composition to compare our results with field observations. Since outdoor conditions of Tucson are not included in the WUFI database, we used TMY3 (Typical Meteorological Year) to create an outdoor climate file for Tucson. In order to assure consistency between TMY data and WUFI database, we simulated black and white roofs with both TMY and WUFI outdoor data in Phoenix and confirmed that the results were almost identical. In the simulation of black and white roofs in Tucson, we considered the same indoor condition and roofing composition as the simulation for other cities.

Our simulation shows that the moisture performances of both black and white roofs were very similar to each other and never experienced moisture accumulation during the simulation period (Figure 5-9). After stabilization of initial condition, maximum moisture content of white roofs never exceeded 1.2 kg/m^2 in comparison with 1 kg/m^2 for black roofs. Column c of Figure 5-9 shows that OSB moisture content of both black and white roofs never exceeded 19% in Tucson during the simulation period. Our simulations confirmed that moisture performances of black and white roofs are very similar in Tucson and Phoenix because of similarities in outdoor climate (nearly identical).

By our calibrated simulations, we conclude that moisture cannot condense in neither a white nor a black roof. However, if a roof is not properly design and installed, moisture can penetrate through the membrane by other mechanisms such as opening and cracks. In these circumstances in Tucson (or for that fact in any other location), one can speculate that, moisture in black roofs can dry out faster than white roofs because of higher surface temperature.

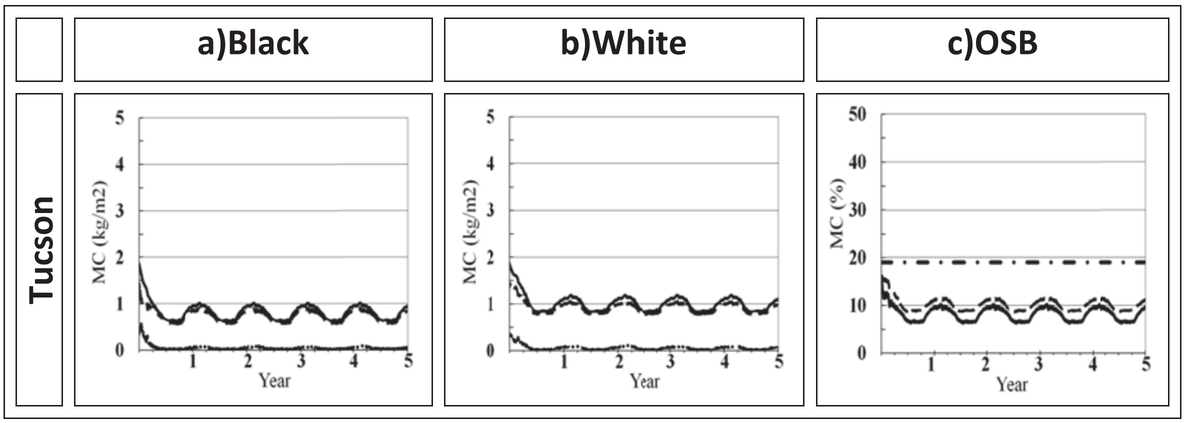


Figure 5-9.Moisture content of typical roofs for residential buildings in Tucson .Column a, b shows black and white roofs moisture contents (kg/m^2): total (▬▬), OSB (■ ■ ■), Mineral Wool (■ ◆ ◆ ■).Column c shows OSB moisture content (%): white roof (■ ■ ■), black roof (▬▬), max allowable MC (19%) (■ ◆ ■)

5.2.3 Office buildings with typical roof compositions

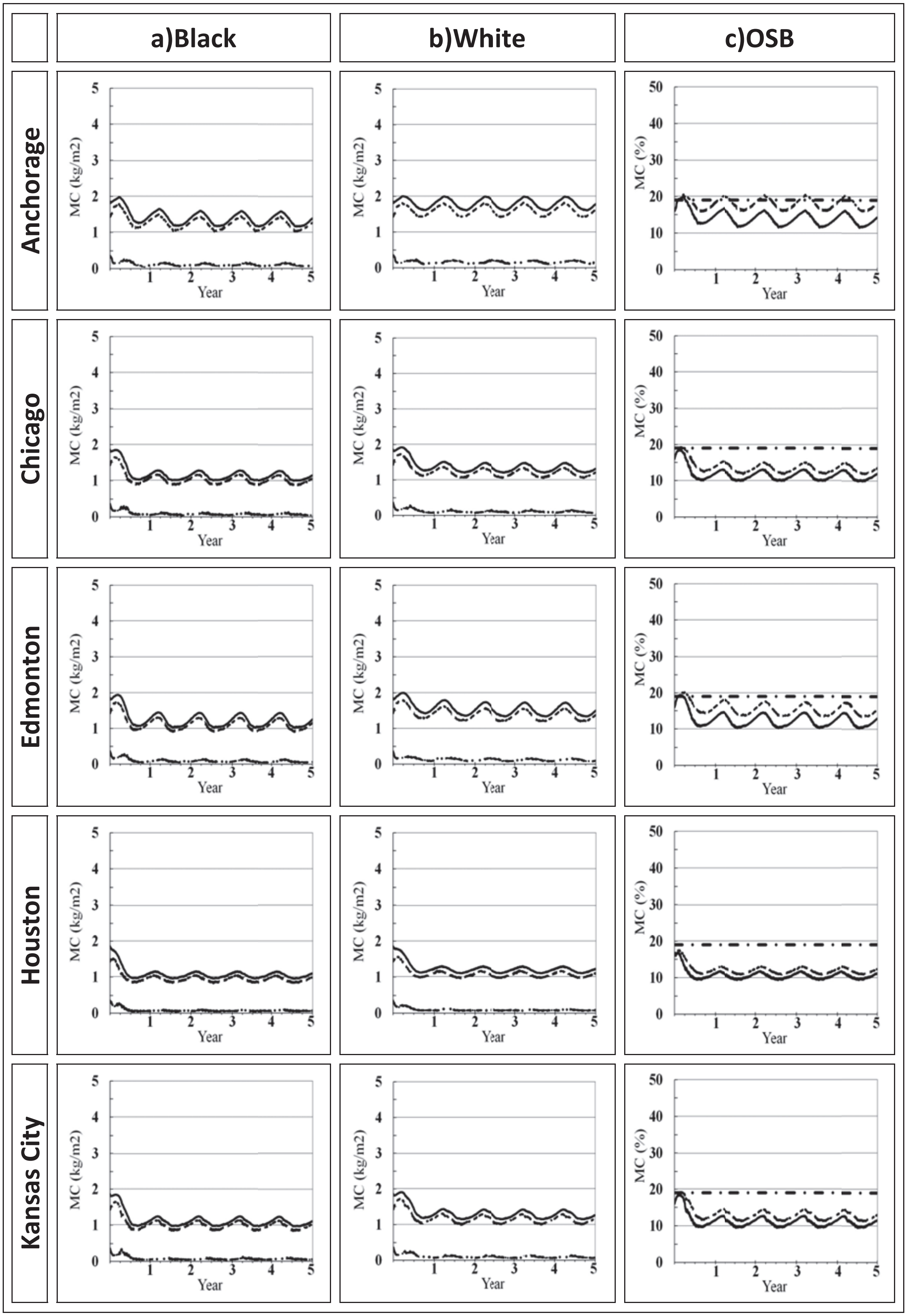
Table 5-15 presents total moisture content of typical roofs for the office buildings with black and white roofs. In moderate and cold climates, average roof moisture content of the office building were less than residential buildings whereas in hot climates such as Miami, Houston, Los Angeles and Phoenix, total moisture content of office buildings in some period of the year were slightly greater than residential ones. Compared with residential buildings, typical roofing assemblies on office buildings always experienced lower total moisture content because of lower relative humidity level and higher temperature during the summer.

Figure 5-10 compares the effect of roof solar absorptance on moisture content of typical roofing assembly in office buildings. Office buildings with either black or white typical roofs never experienced moisture accumulation over the simulation period, even for the very cold climate of Anchorage.

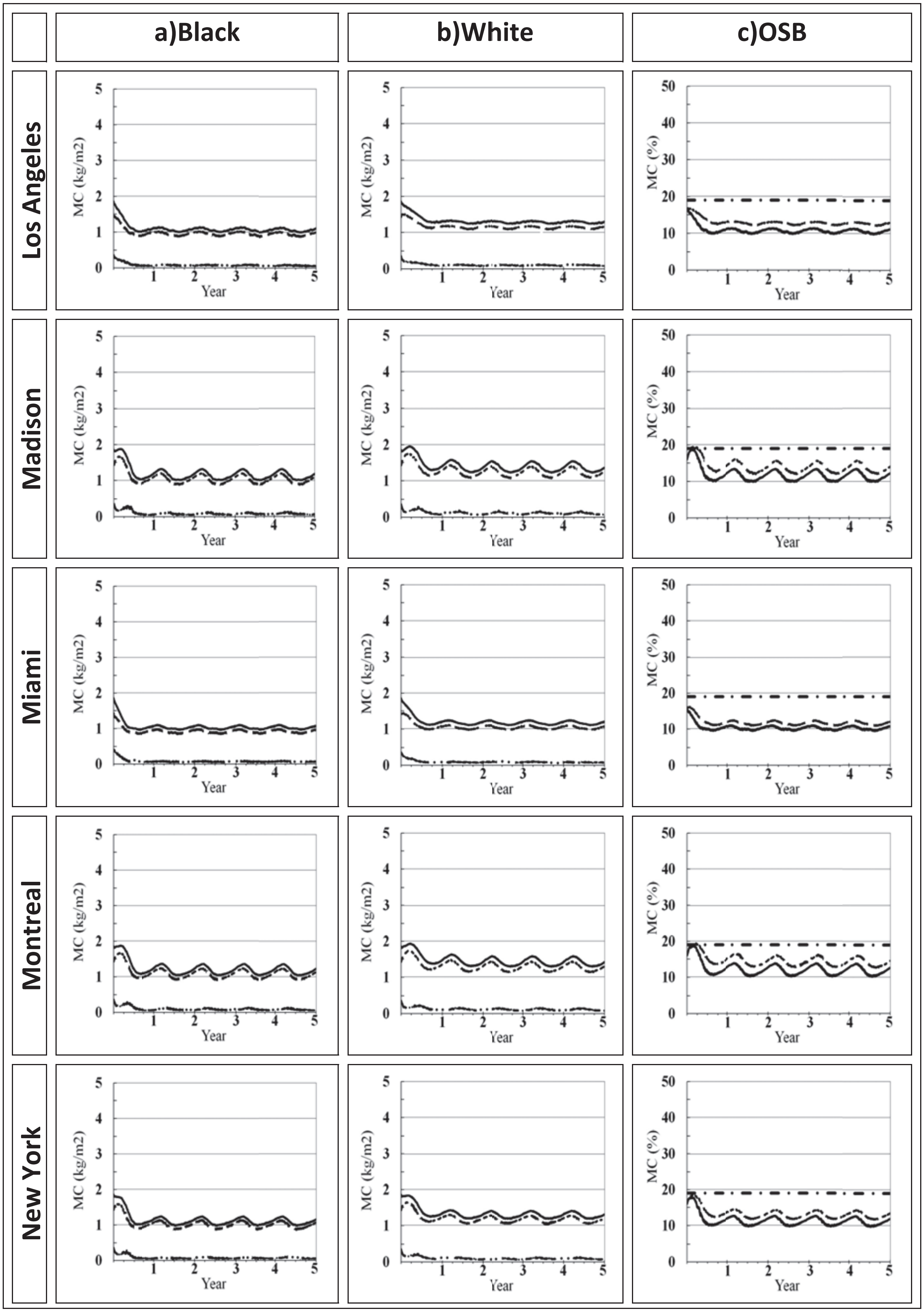
Montreal, Kansas City, Madison, Chicago and St. John's are locations that OSB moisture content of black roofs never surpassed 19% while white roofs in these cities exceeded this limit for some periods during the first year of simulation. On the other hand, both black and white roofs in Edmonton and Anchorage have many numbers of hours when OSB moisture content exceeded 19%. OSB moisture content of both black and white roofs always remained below 19% in Houston, Los Angeles, Miami, New York, Phoenix and Vancouver (Table 5-16).

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal	**Black**	1.27	1.32	1.35	1.3	1.2	1.1	1.05	1.05	1.07	1.1	1.14	1.2
	White	1.46	1.52	1.57	1.56	1.50	1.42	1.35	1.31	1.31	1.31	1.34	1.39
Anchorage	**Black**	1.44	1.51	1.57	1.55	1.45	1.33	1.22	1.17	1.18	1.20	1.26	1.35
	White	1.83	1.90	1.96	1.97	1.93	1.84	1.74	1.66	1.62	1.61	1.66	1.74
Kansas City	**Black**	1.15	1.21	1.23	1.17	1.10	1.04	0.98	0.98	0.98	1.01	1.04	1.09
	White	1.30	1.37	1.41	1.39	1.35	1.29	1.19	1.16	1.15	1.17	1.19	1.24
Madison	**Black**	1.22	1.29	1.31	1.25	1.15	1.06	1.02	1.02	1.02	1.06	1.09	1.15
	White	1.40	1.48	1.53	1.52	1.46	1.37	1.29	1.25	1.23	1.25	1.28	1.33
New York	**Black**	1.18	1.22	1.22	1.16	1.07	1.01	0.99	1.01	1.02	1.06	1.08	1.13
	White	1.34	1.38	1.40	1.38	1.33	1.26	1.21	1.20	1.20	1.22	1.24	1.28
Phoenix	**Black**	1.01	1.01	0.97	0.91	0.85	0.83	0.84	0.89	0.91	0.90	0.93	0.98
	White	1.12	1.14	1.12	1.08	1.02	0.96	0.94	0.99	1.02	1.01	1.04	1.08
Vancouver	**Black**	1.26	1.30	1.31	1.29	1.23	1.13	1.09	1.05	1.07	1.10	1.15	1.21
	White	1.45	1.49	1.50	1.49	1.47	1.41	1.38	1.34	1.33	1.35	1.38	1.42
Miami	**Black**	1.08	1.09	1.06	1.02	1.00	1.00	0.99	0.97	0.98	1.01	1.04	1.06
	White	1.22	1.23	1.23	1.21	1.17	1.15	1.14	1.11	1.11	1.13	1.16	1.19
Los Angeles	**Black**	1.11	1.12	1.12	1.09	1.05	1.05	1.02	1.01	1.02	1.04	1.07	1.09
	White	1.29	1.30	1.32	1.31	1.30	1.29	1.27	1.25	1.25	1.25	1.27	1.28
Houston	**Black**	1.12	1.14	1.13	1.08	1.03	0.99	0.96	0.96	0.99	1.01	1.04	1.08
	White	1.24	1.27	1.28	1.26	1.22	1.16	1.12	1.11	1.11	1.14	1.17	1.21
Saint John's	**Black**	1.31	1.36	1.39	1.37	1.31	1.23	1.14	1.11	1.13	1.15	1.18	1.24
	White	1.58	1.64	1.68	1.70	1.68	1.63	1.55	1.49	1.47	1.46	1.47	1.51
Edmonton	**Black**	1.31	1.39	1.43	1.38	1.25	1.10	1.04	1.04	1.05	1.07	1.13	1.21
	White	1.55	1.64	1.70	1.71	1.63	1.52	1.43	1.38	1.35	1.34	1.38	1.46
Chicago	**Black**	1.19	1.25	1.27	1.23	1.15	1.05	1.02	1.01	1.02	1.04	1.08	1.13
	White	1.35	1.42	1.47	1.46	1.42	1.33	1.27	1.23	1.21	1.22	1.24	1.29

Table 5-15.Monthly average total water content (kg/m^2) in the fifth year of simulation (typical office roof)


a)Black
b)White
c)OSB
Anchorage
Chicago
Edmonton
Houston
Kansas City
MC (kg/m2)
MC (%)
Year

Continued


a)Black
b)White
c)OSB
Los Angeles
Madison
Miami
Montreal
New York
MC (kg/m2)
MC (%)
Year

Continued

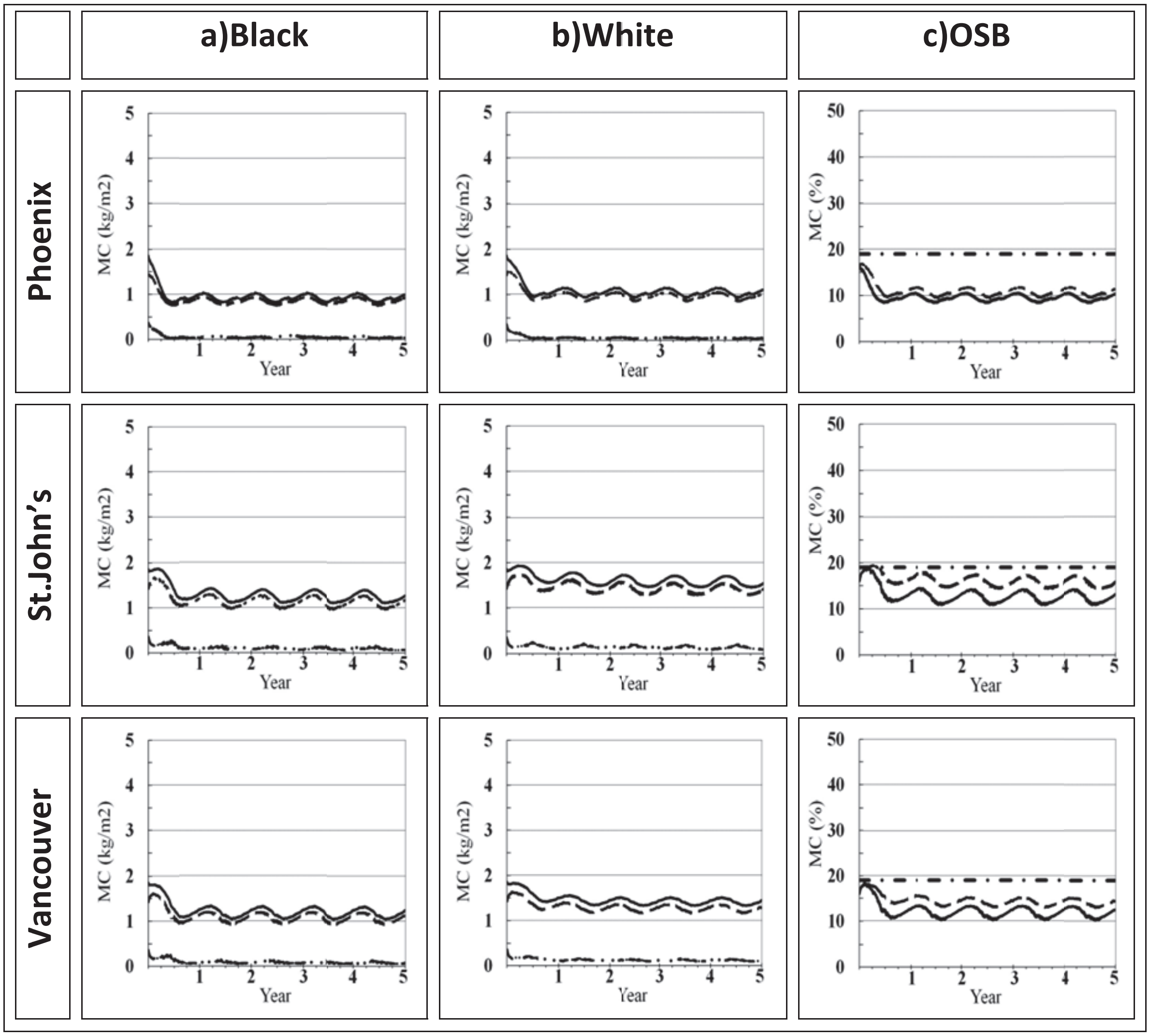


Figure 5-10.Moisture content of typical roofs for office buildings .Column a, b shows black and white roofs moisture content (kg/m^2): total (▬), OSB (■ ■ ■), Mineral Wool (■ ◆ ◆ ■).Column c shows OSB moisture content (%): white roofs (■ ■ ■), black roofs (▬), max allowable MC (19%) (■ ◆ ■)

City	Roof color	1st Year (hr.)	2nd Year (hr.)	3rd Year (hr.)	4th Year (hr.)	5th Year (hr.)
Montreal	Black	0	0	0	0	0
	White	1166	0	0	0	0
Anchorage	Black	1571	0	0	0	0
	White	2711	2803	2757	2715	2703
Kansas City	Black	0	0	0	0	0
	White	662	0	0	0	0
Madison	Black	0	0	0	0	0
	White	1415	0	0	0	0
Saint John's	Black	0	0	0	0	0
	White	1869	0	0	0	0
Edmonton	Black	946	0	0	0	0
	White	2272	0	0	0	0
Chicago	Black	0	0	0	0	0
	White	1069	0	0	0	0

Table 5-16.Number of hours MC at OSB exceed 19% in typical office roof

Office buildings with a typical black roof performed without the risk of mold growth in all layers in all thirteen simulated cities. For white roofs, however, there was risk of mold growth in Anchorage, St. John’s and Edmonton at exterior side of insulation (Table 5-17).

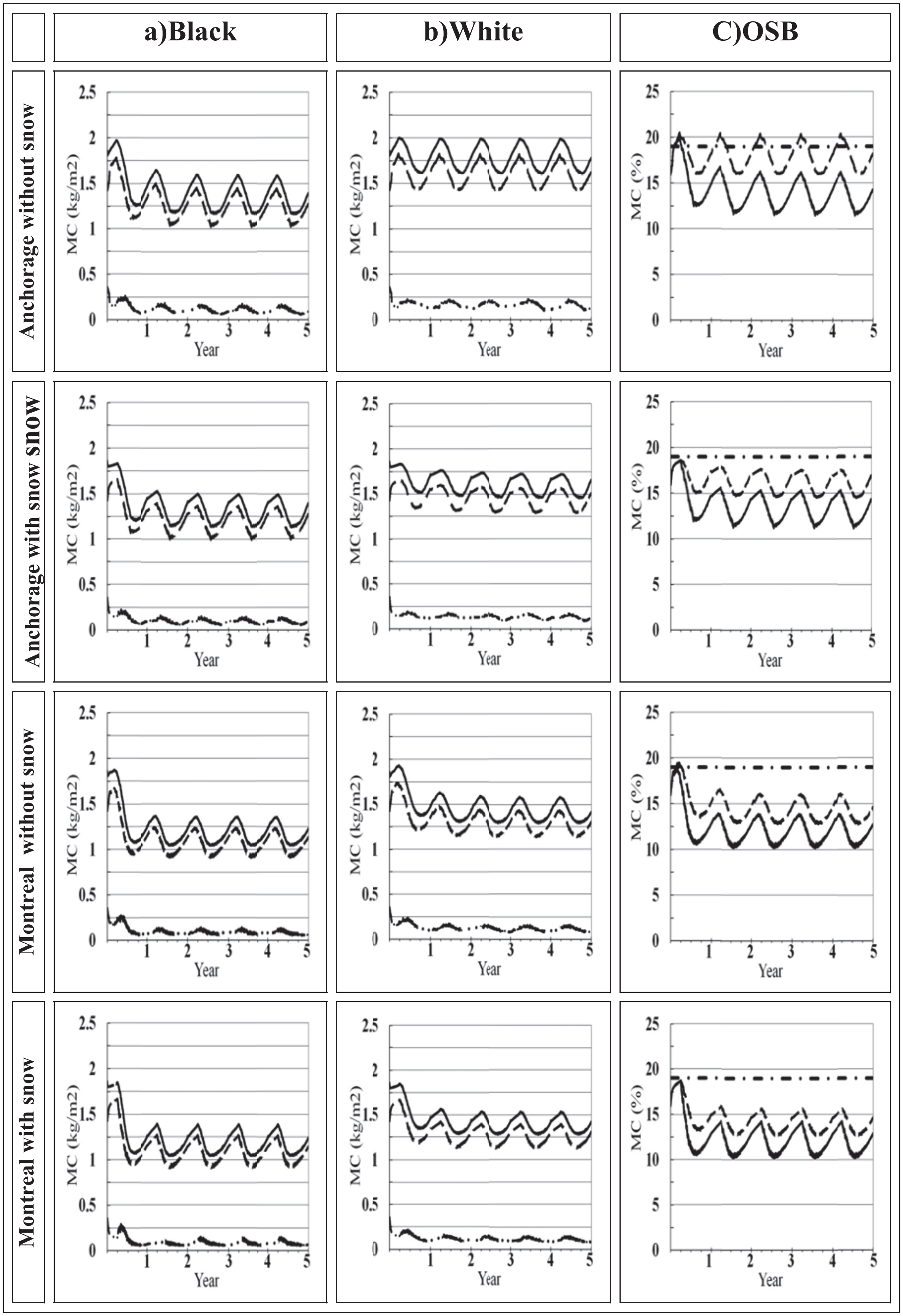
Figure 5-11 shows that the total moisture content of both black and white roofs decreased with snow on the roof in Anchorage, Montreal and Chicago. The reduction of moisture content in the white roof in Anchorage was significantly higher compared to black ones. Furthermore, simulation results for Anchorage, Montreal and Chicago with snow on the roof showed that moisture content in OSB never exceeded 19% for both black and white roofs. This results in a lower risk of condensation when the surface temperature is assumed 0oC with snow on the roof (column c of Figure 5-11 and Table 5-19).

City	Roof color	Exterior membrane/OSB	OSB/ Mineral wool
Anchorage	Black	0	0
	White	3849	2527
Saint John's	Black	0	0
	White	1061	401
Edmonton	Black	0	0
	White	1074	416

Table 5-17.Risk of mold growth (Hour) for typical office roof

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal without snow	Black	1.27	1.32	1.35	1.30	1.20	1.10	1.05	1.05	1.07	1.10	1.14	1.20
	White	1.46	1.52	1.57	1.56	1.50	1.42	1.35	1.31	1.31	1.31	1.34	1.39
Montreal with snow	Black	1.27	1.31	1.36	1.35	1.22	1.10	1.05	1.05	1.07	1.10	1.14	1.21
	White	1.44	1.47	1.50	1.52	1.46	1.38	1.32	1.29	1.29	1.30	1.33	1.38
Anchorage without snow	Black	1.44	1.51	1.57	1.55	1.45	1.33	1.22	1.17	1.18	1.20	1.26	1.35
	White	1.83	1.90	1.96	1.97	1.93	1.84	1.74	1.66	1.62	1.61	1.66	1.74
Anchorage with snow	Black	1.41	1.45	1.48	1.47	1.38	1.27	1.17	1.15	1.16	1.19	1.26	1.35
	White	1.67	1.69	1.71	1.72	1.68	1.62	1.53	1.48	1.47	1.47	1.53	1.62
Chicago without snow	Black	1.19	1.25	1.27	1.23	1.15	1.05	1.02	1.01	1.02	1.04	1.08	1.13
	White	1.35	1.42	1.47	1.46	1.42	1.33	1.27	1.23	1.21	1.22	1.24	1.29
Chicago with snow	Black	1.20	1.25	1.27	1.24	1.14	1.04	1.01	1.01	1.02	1.05	1.08	1.13
	White	1.34	1.38	1.42	1.42	1.38	1.30	1.24	1.22	1.20	1.22	1.24	1.29

Table 5-18.Effect of snow on monthly average MC typical office roof (kg/m^2)


a)Black
b)White
C)OSB
Anchorage without snow
Anchorage with snow snow
Montreal without snow
Montreal with snow
MC (kg/m2)
MC (%)
Year
0
0.5
1
1.5
2
2.5
5
10
15
20
25
1
2
3
4
5

Continued

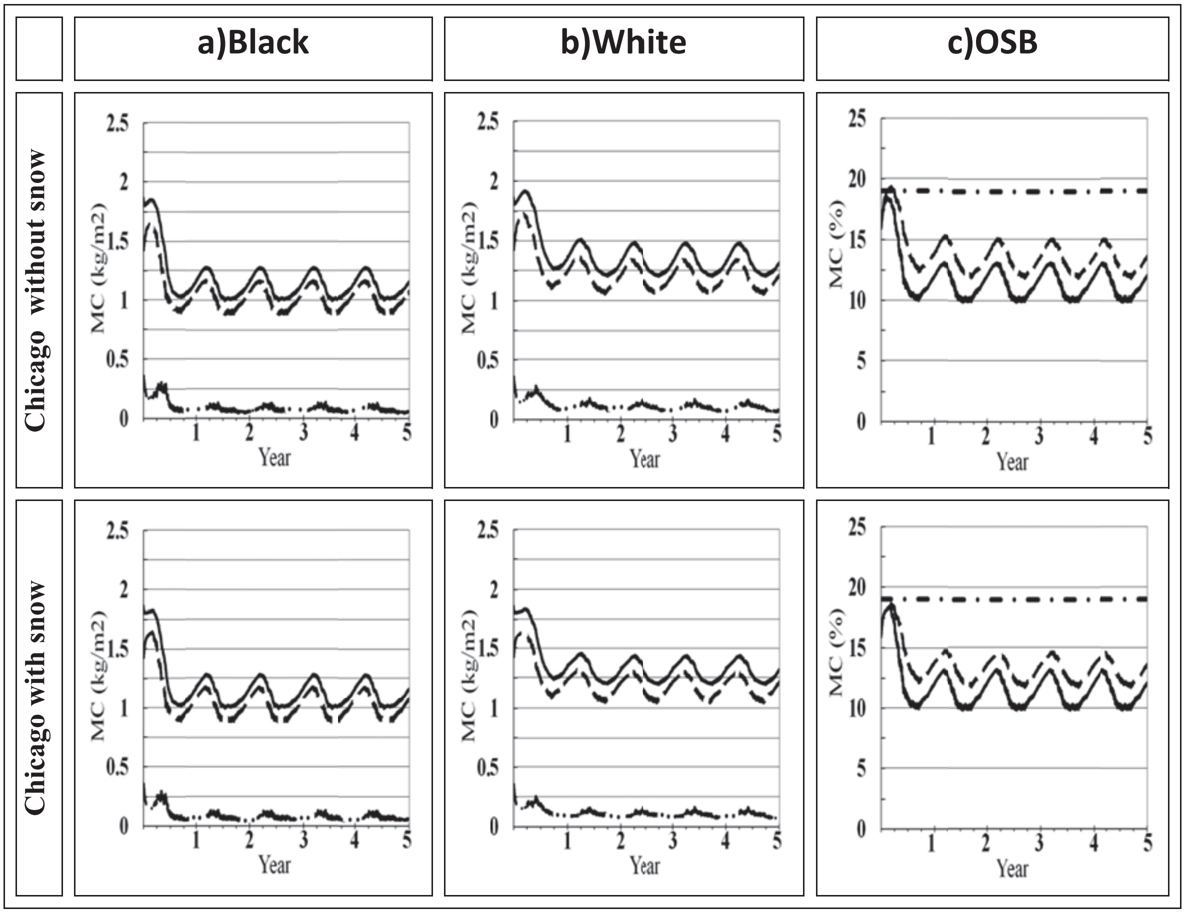


Figure 5-11.Effect of snow on the moisture content of office building with typical roof composition; Column a, b shows black and white roofs moisture content (kg/m^2): total (▬▬), OSB (▬ ▬ ▬), Mineral Wool (▬ • • ▬).Column c shows OSB moisture content (%): white roofs (▬ ▬ ▬), black roofs (▬▬), max allowable MC (19%) (▬ • ▬)

City	Roof color	1st Year (hr.)	2nd Year (hr.)	3rd Year (hr.)	4th Year (hr.)	5th Year (hr.)
Anchorage without snow	Black	1571	0	0	0	0
	White	2711	2803	2757	2715	2703
Anchorage snow	Black	0	0	0	0	0
	White	0	0	0	0	0
Montreal without snow	Black	0	0	0	0	0
	White	1166	0	0	0	0
Montreal with snow	Black	0	0	0	0	0
	White	0	0	0	0	0
Chicago without snow	Black	0	0	0	0	0
	White	1069	0	0	0	0
Chicago with snow	Black	0	0	0	0	0
	White	0	0	0	0	0

Table 5-19.Effect of snow on number of hours that moisture exceed 19% at OSB (typical office)

Result of simulations in the selected cities showed that roofs in office buildings always had better hygrothermal performances with lower total moisture content compared to residential buildings. In our simulations, interior temperature and relative humidity were the only parameters that distinguish residential and office buildings. Interior climate of residential buildings were selected based on ASHRAE Standard-160 with set points for temperature and relative humidity independent from occupancy schedules. While the interior temperature and relative humidity set points in office buildings were varied by occupancy schedules for heating and cooling.

Figure 5-9 shows yearly interior temperature and relative humidity for residential and office buildings in four cities. We selected Anchorage, St. John's and Edmonton where roofs experienced risk of moisture accumulation for residential buildings. In addition to above mentioned cities, interior condition of white and black roofs also in Montreal as a cold and humid climate were investigated. Figure 5-9 displays that the relative humidity in the office buildings is lower than the residential buildings. With the lower relative humidity inside the office building, the rate of moisture transfer between inside and outside was reduced in winter. As a result, roofs for office buildings had better hygrothermal performance with lower moisture build up in heating season. On the other hand in the summer time, higher inside temperature of office buildings increased the drying out potential in the roofing assembly.

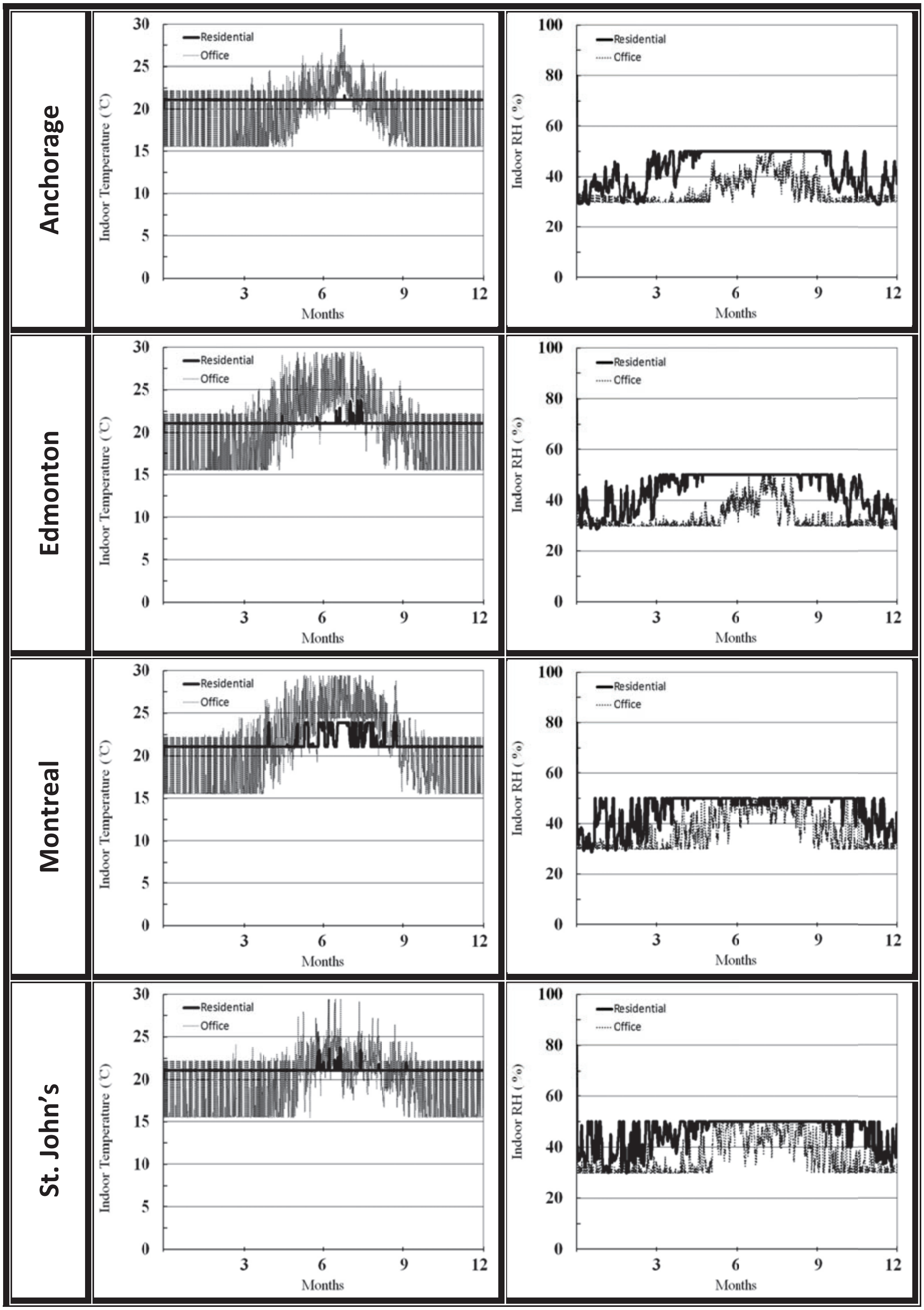


Figure 5-12.Indoor T, RH for residential and office buildings with typical composition roof

5.2.4 Residential buildings with smart roofs

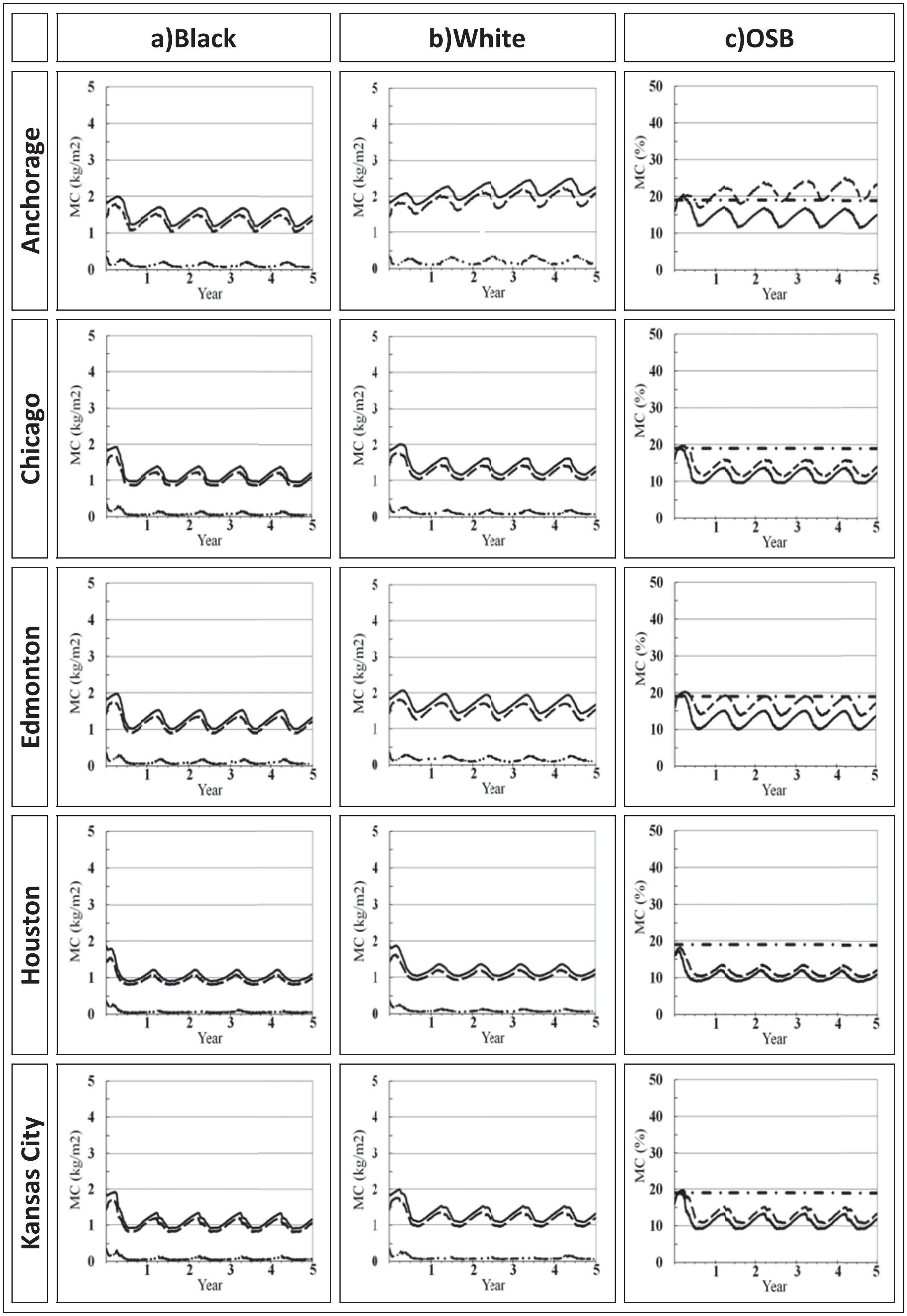
Average monthly moisture contents in the fifth year of simulations for black and white roofs with smart vapor retarders for residential buildings are shown in Table 5-20. Similar to residential buildings with typical roofs, white smart roofs had the highest total moisture content in Anchorage, St. John’s and Edmonton (cities with lowest roof surface temperature). In contrast, black roofs in Phoenix, Miami and Houston experienced the lowest total moisture content (cities with highest roof surface temperature). In all climates, the moisture content was lowest during the summer as the roofs dry in hotter summer months. Table 5-20 and Figure 5-13 show that residential smart roofs experienced lower total moisture content in comparisons to residential typical roofs. This difference is much visible in cold climates such as Anchorage, Edmonton and St. John’s.

Figure 5-13 compares moisture behaviour of black and white smart roofs in the mineral wool insulation and OSB. Anchorage is the only climate that white roofs with smart vapor retarders experience moisture accumulation over the time. OSB moisture content of white roofs in Anchorage also stay above 19% most of the time. Differences in total moisture content of black and white roofs are only noticeable in climates such as Anchorage, St. John’s and Edmonton.

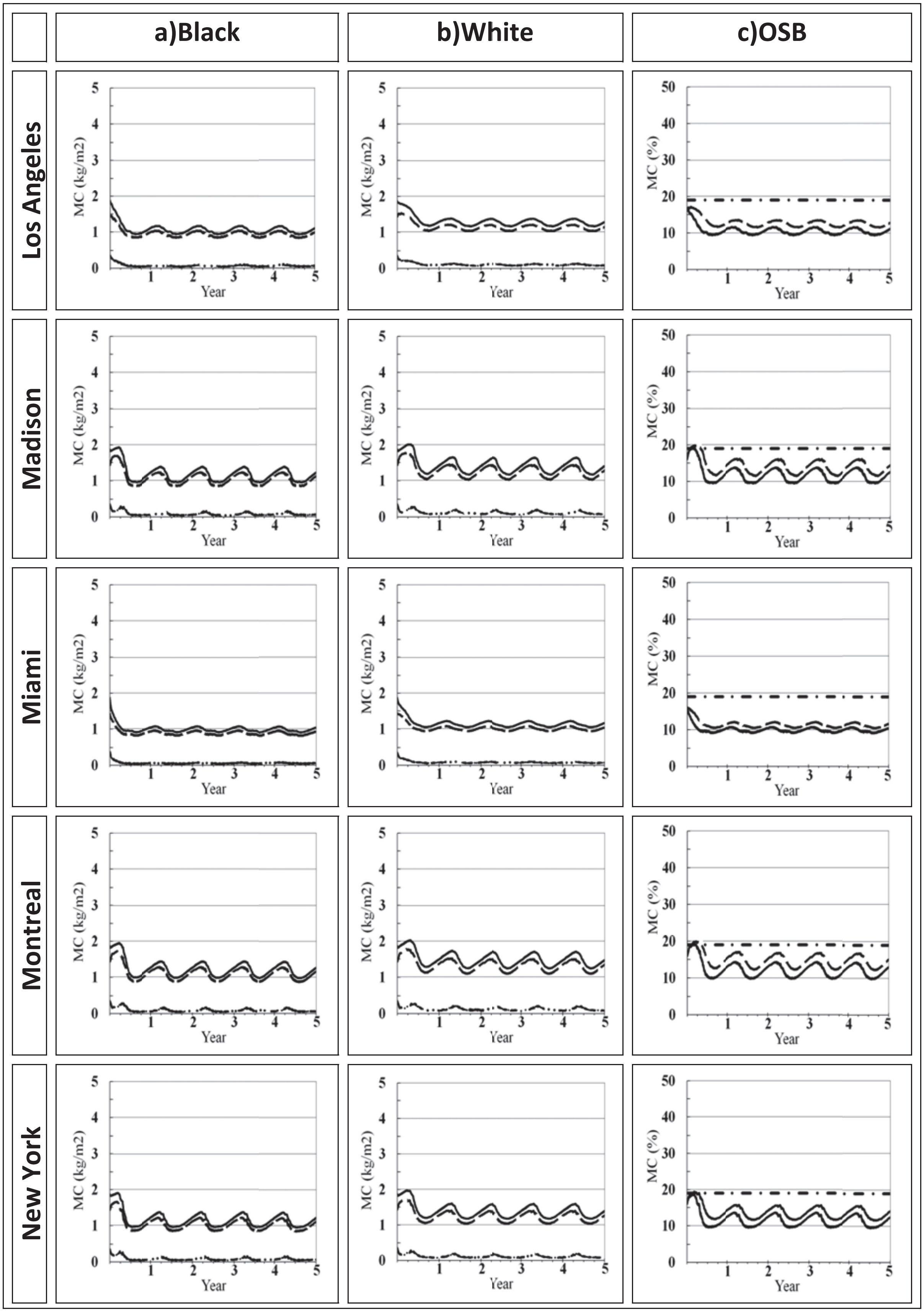
As for OSB moisture content, Houston, Miami, Los Angeles and Phoenix are the only cities that both black and white roofs experienced OSB moisture content less than 19% in the simulation period. On the contrary, Anchorage, Edmonton, Montreal and St. John’s are locations where both roofs had some days with OSB moisture content more than 19%. In other cities, white roofs only experienced some periods with OSB moisture content more than 19%. Table 5-21 shows number of hours in a year that moisture content exceeded the 19% in the OSB.

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal	Black	1.30	1.37	1.42	1.41	1.28	1.09	1.00	0.99	1.01	1.08	1.16	1.23
	White	1.51	1.58	1.64	1.69	1.67	1.52	1.35	1.26	1.25	1.30	1.37	1.44
Anchorage	Black	1.51	1.58	1.64	1.67	1.64	1.48	1.29	1.20	1.23	1.29	1.36	1.44
	White	2.26	2.33	2.39	2.45	2.49	2.43	2.26	2.07	2.05	2.09	2.15	2.22
Kansas City	Black	1.21	1.27	1.32	1.23	1.14	1.00	0.92	0.92	0.93	0.98	1.06	1.13
	White	1.35	1.42	1.49	1.49	1.46	1.31	1.14	1.10	1.09	1.13	1.20	1.28
Madison	Black	1.26	1.32	1.37	1.35	1.21	1.02	0.97	0.96	0.97	1.03	1.11	1.19
	White	1.44	1.51	1.58	1.63	1.60	1.40	1.26	1.20	1.17	1.22	1.29	1.37
New York	Black	1.26	1.32	1.36	1.30	1.11	0.99	0.96	0.97	0.99	1.04	1.11	1.18
	White	1.43	1.49	1.56	1.58	1.50	1.32	1.22	1.18	1.18	1.22	1.28	1.35
Phoenix	Black	1.07	1.10	1.05	0.95	0.87	0.83	0.79	0.78	0.80	0.85	0.94	1.02
	White	1.18	1.22	1.24	1.18	1.09	1.00	0.92	0.91	0.92	0.96	1.04	1.12
Vancouver	Black	1.33	1.40	1.46	1.47	1.38	1.14	1.07	1.00	1.01	1.08	1.17	1.25
	White	1.60	1.67	1.74	1.78	1.78	1.65	1.53	1.39	1.35	1.39	1.46	1.53
Miami	Black	1.05	1.07	1.04	0.98	0.95	0.95	0.94	0.91	0.92	0.95	0.99	1.03
	White	1.18	1.21	1.22	1.18	1.14	1.11	1.09	1.06	1.05	1.07	1.10	1.14
Los Angeles	Black	1.13	1.16	1.16	1.11	1.03	1.01	0.96	0.94	0.95	0.98	1.02	1.08
	White	1.31	1.34	1.36	1.37	1.34	1.29	1.23	1.18	1.17	1.17	1.21	1.25
Houston	Black	1.13	1.20	1.18	1.08	0.99	0.93	0.91	0.91	0.93	0.96	1.00	1.06
	White	1.25	1.32	1.35	1.31	1.22	1.13	1.07	1.05	1.06	1.09	1.13	1.18
Saint John's	Black	1.39	1.45	1.51	1.54	1.51	1.31	1.12	1.08	1.11	1.16	1.24	1.32
	White	1.81	1.88	1.94	2.01	2.05	1.98	1.75	1.64	1.59	1.61	1.67	1.74
Edmonton	Black	1.37	1.44	1.50	1.51	1.37	1.15	1.04	1.02	1.06	1.13	1.21	1.29
	White	1.71	1.79	1.86	1.92	1.91	1.78	1.59	1.45	1.45	1.49	1.56	1.63
Chicago	Black	1.25	1.31	1.36	1.35	1.22	1.02	0.97	0.97	0.97	1.02	1.10	1.18
	White	1.42	1.49	1.56	1.60	1.59	1.40	1.26	1.20	1.17	1.20	1.27	1.35

Table 5-20.Monthly average total water content (kg/m^2) in the fifth year of simulation (smart residential roof)


a)Black
b)White
c)OSB
Anchorage
Chicago
Edmonton
Houston
Kansas City
MC (kg/m2)
MC (%)
Year

Continued


a)Black
b)White
c)OSB
Los Angeles
Madison
Miami
Montreal
New York
MC (kg/m2)
MC (%)
Year

Continued

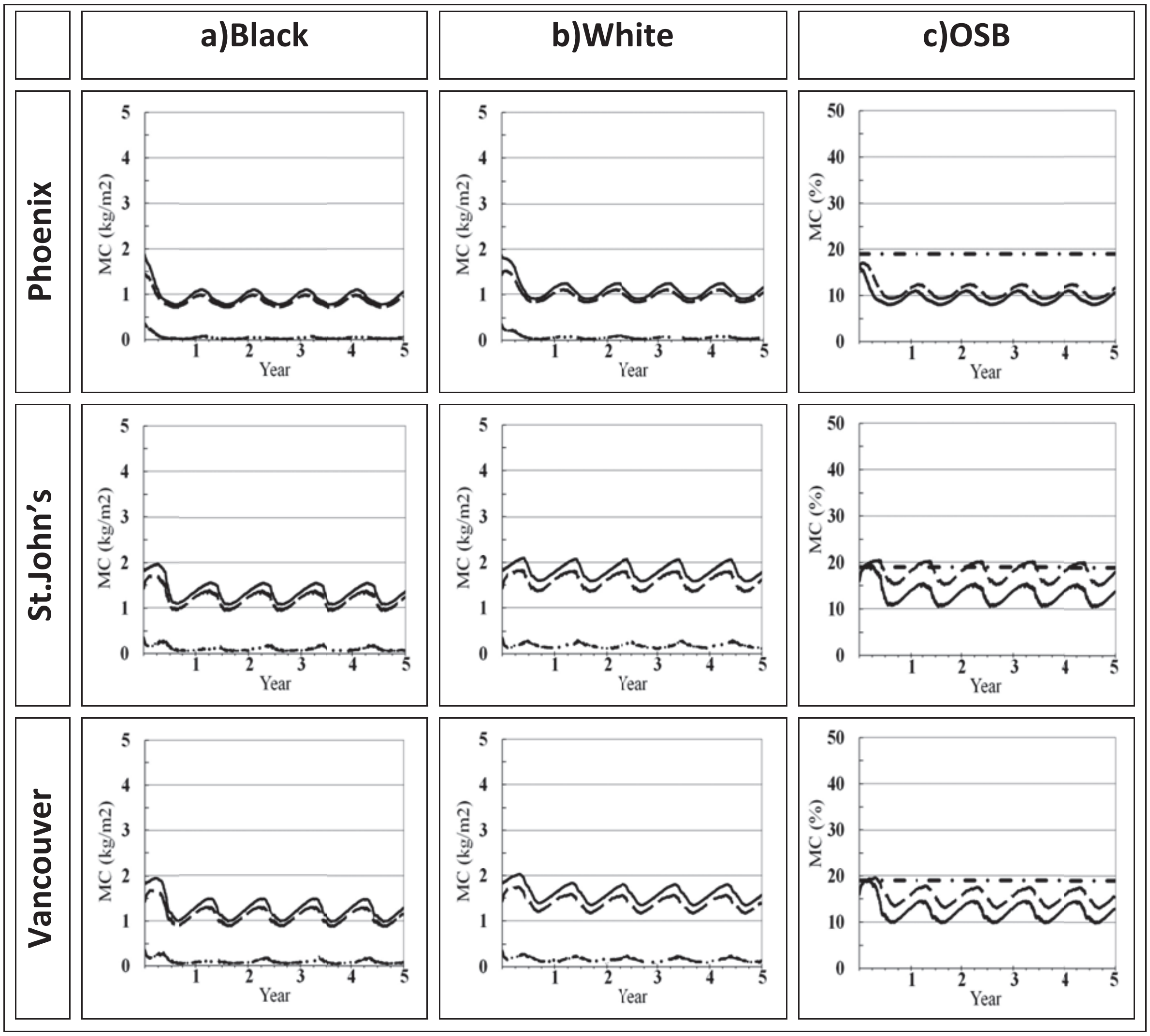


Figure 5-13.Moisture content of smart roofs for residential buildings .Column a, b shows black and white roofs moisture content (kg/m^2): total (▬▬), OSB (■ ■ ■), Mineral Wool (■ ◆ ◆ ■).Column c shows OSB moisture content (%): white roof (■ ■ ■), black roof (▬▬), max allowable MC (19%) (■ ◆ ■)

City	Roof color	1st Year (hr.)	2nd Year (hr.)	3rd Year (hr.)	4th Year (hr.)	5th Year (hr.)
Montreal	Black	472	0	0	0	0
	White	1952	0	0	0	0
Anchorage	Black	2050	0	0	0	0
	White	4742	6804	7708	8722	8760
Kansas City	Black	0	0	0	0	0
	White	1467	0	0	0	0
Madison	Black	0	0	0	0	0
	White	2180	0	0	0	0
New York	Black	0	0	0	0	0
	White	1044	0	0	0	0
Vancouver	Black	0	0	0	0	0
	White	2106	0	0	0	0
Saint John's	Black	1197	0	0	0	0
	White	3115	2990	2959	2950	2945
Edmonton	Black	1587	0	0	0	0
	White	2749	1319	233	145	127
Chicago	Black	0	0	0	0	0
	White	2070	0	0	0	0

Table 5-21.Number of hours MC at OSB exceed 19% in smart residential roofs based on national building code of Canada

Risk of mold growth for smart roofs with residential indoor climate is depicted in Table 5-22. Kansas City, New York, Phoenix, Miami, Los Angeles and Houston were cities without risk of mold growth for both black and white roofs at surfaces between different material layers. On the other hand, Anchorage was the only city that both black and white roofs had risk of mold growth in the exterior side of mineral wool. In other cities, white roofs only experienced risk of mold while black roofs perform very well against mold growth. In contrast to typical roofs with residential indoor climate, the interior side of mineral wool never experienced risk of mold growth in smart residential roofs.

City	Roof color	Exterior membrane/OSB	OSB/ Mineral wool
Montreal	Black	0	0
	White	1106	664
Anchorage	Black	778	352
	White	3854	3914
Madison	Black	0	0
	White	0	443
Vancouver	Black	0	0
	White	2604	2080
Saint John's	Black	0	0
	White	2313	1745
Edmonton	Black	0	0
	White	1978	1328
Chicago	Black	0	0
	White	0	81

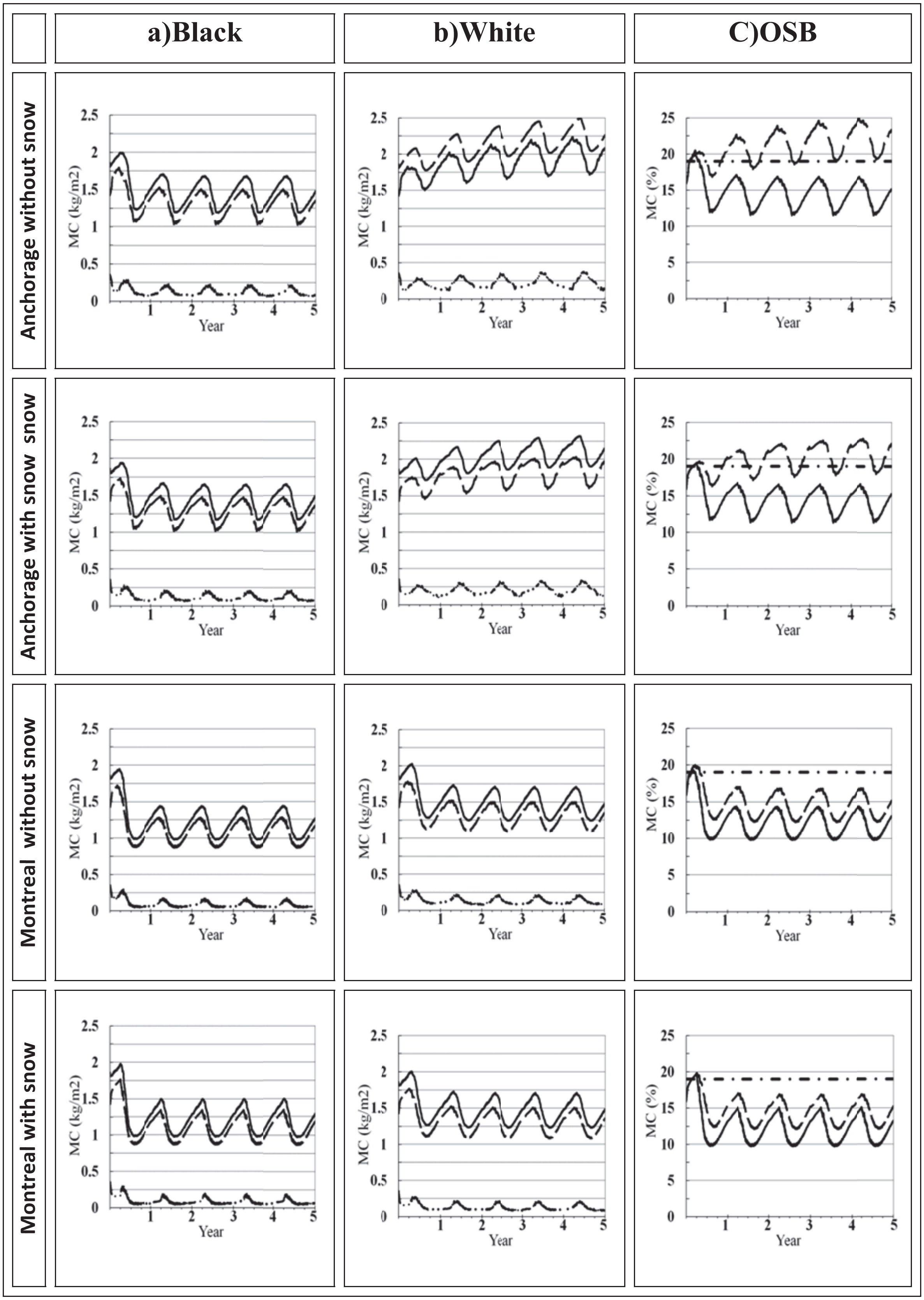
Table 5-22.Risk of mold growth (Hour) for smart residential roofs based on ASHRAE-160

Effect of snow accumulation on the roof was evaluated based on mentioned algorithm in sections 4.4. Table 5-23 shows average moisture content of black and white roofs. The simulations indicated that the snow has only significant influenced on the performance of white roofs in Anchorage; the effect of snow on other roofs and other cities was minimal. Figure 5-14, indeed, confirms that snow helped to reduce moisture content of white roofs in Anchorage however the OSB moisture content is still greater than the allowable maximum limit (19%) for most of the year.

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal without snow	**Black**	1.30	1.37	1.42	1.41	1.28	1.09	1.00	0.99	1.01	1.08	1.16	1.23
	White	1.51	1.58	1.64	1.69	1.67	1.52	1.35	1.26	1.25	1.30	1.37	1.44
Montreal with snow	**Black**	1.31	1.38	1.44	1.47	1.29	1.08	1.00	0.99	1.01	1.08	1.17	1.25
	White	1.50	1.57	1.63	1.69	1.66	1.51	1.34	1.25	1.24	1.29	1.37	1.44
Anchorage without snow	**Black**	1.51	1.58	1.64	1.67	1.64	1.48	1.29	1.20	1.23	1.29	1.36	1.44
	White	2.26	2.33	2.39	2.45	2.49	2.43	2.26	2.07	2.05	2.09	2.15	2.22
Anchorage with snow	**Black**	1.50	1.56	1.60	1.64	1.61	1.45	1.26	1.18	1.22	1.29	1.37	1.44
	White	2.14	2.18	2.22	2.27	2.31	2.26	2.10	1.93	1.91	1.96	2.03	2.10
Chicago without snow	**Black**	1.25	1.31	1.36	1.35	1.22	1.02	0.97	0.97	0.97	1.02	1.10	1.18
	White	1.42	1.49	1.56	1.60	1.59	1.40	1.26	1.20	1.17	1.20	1.27	1.35
Chicago with snow	**Black**	1.26	1.32	1.38	1.36	1.22	1.02	0.97	0.97	0.97	1.02	1.10	1.19
	White	1.43	1.47	1.54	1.59	1.58	1.39	1.25	1.19	1.16	1.20	1.27	1.35

Table 5-23.Effect of snow on monthly average MC smart residential roof (kg/m^2)

Table 5-24 shows that snow on the white roofs in the three simulated cities always helped to decrease the numbers of hours that OSB has moisture content more than 19%. This reduction is more evident in Anchorage as a very cold climate. On the contrary, OSB moisture content of black roofs in Montreal and Chicago slightly increased after applying effect of snow. Anchorage is the only city that OSB layer under a black roof experienced lower moisture content after considering the effect of snow.


a)Black
b)White
C)OSB
Anchorage without snow
Anchorage with snow snow
Montreal without snow
Montreal with snow
MC (kg/m2)
MC (%)
Year

Continued

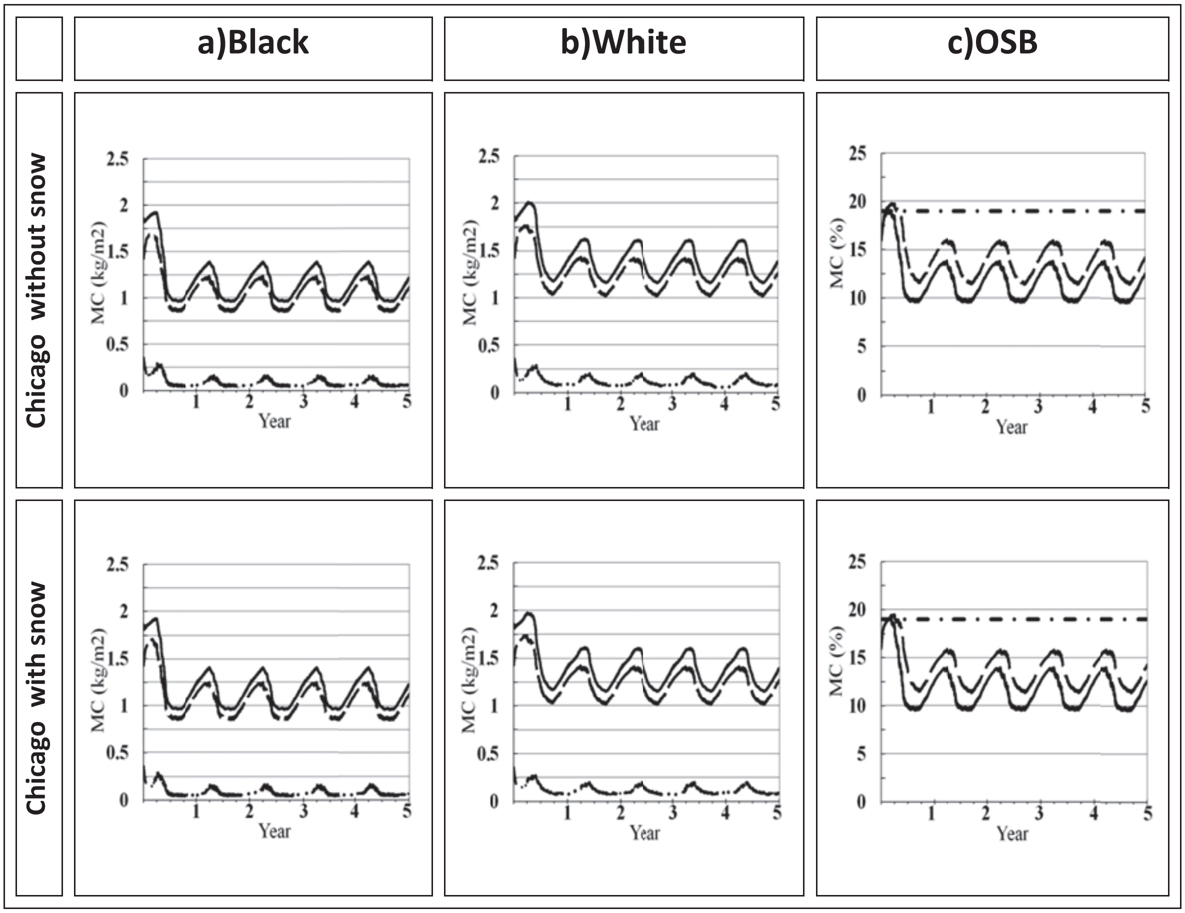


Figure 5-14.Effect of snow on the moisture content of residential building with smart roof composition; Column a, b shows black and white roofs moisture content (kg/m^2): total (▬▬), OSB (▬ ▬ ▬),Mineral Wool (▬ • • ▬). Column c shows OSB moisture content (%): white roofs (▬ ▬ ▬), black roofs (▬▬), max allowable MC (19%) (▬ • ▬)

City	Roof color	1st Year (hr.)	2nd Year (hr.)	3rd Year (hr.)	4th Year (hr.)	5th Year (hr.)
Anchorage without snow	Black	2050	0	0	0	0
	White	4742	6804	7708	8722	8760
Anchorage snow	Black	917	0	0	0	0
	White	3474	6230	6583	6770	6863
Montreal without snow	Black	472	0	0	0	0
	White	1952	0	0	0	0
Montreal with snow	Black	1099	0	0	0	0
	White	1619	0	0	0	0
Chicago without snow	Black	0	0	0	0	0
	White	2070	0	0	0	0
Chicago with snow	Black	352	0	0	0	0
	White	1080	0	0	0	0

Table 5-24.Effect of snow on number of hours that moisture exceed 19% at OSB (smart residential)

5.2.5 Office buildings with smart roofs

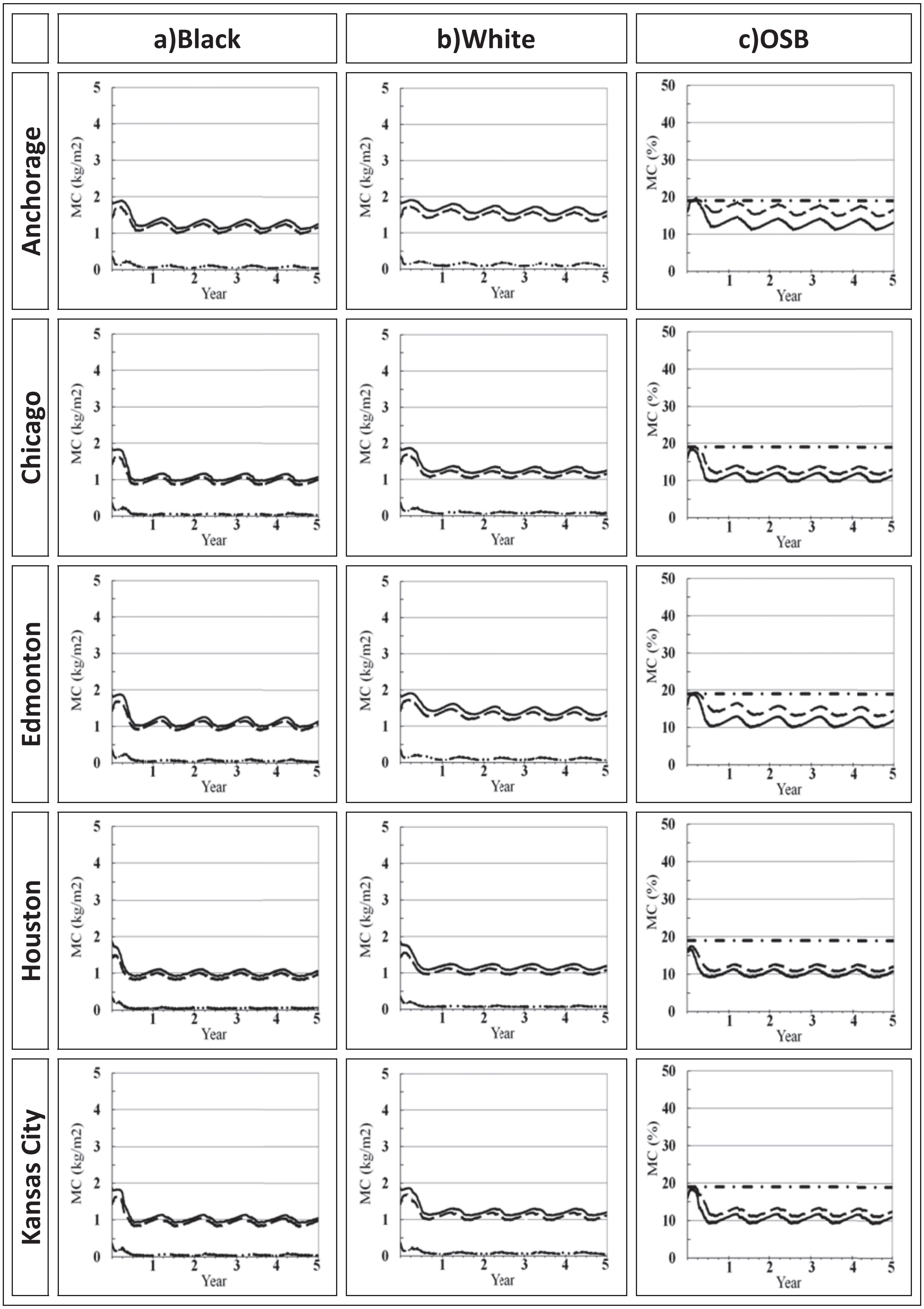
Monthly average moisture contents of black and white smart roofs on office buildings are shown in Table 5-25. Similar to previous cases with typical roof composition, white roofs in Anchorage, St. John’s and Edmonton experienced highest total moisture content among all cases whereas minimum of total moisture content occurred in black roofs in hot climates such as Phoenix, Houston and Miami.

Neither black nor white smart office roofs experienced moisture accumulation over the simulation period even for very cold cities such as Anchorage and St. John’s (similar to office buildings with typical roofs). Moisture content of both white and black roofs with smart vapor retarder on office buildings always remained below 2 kg/m^2 .

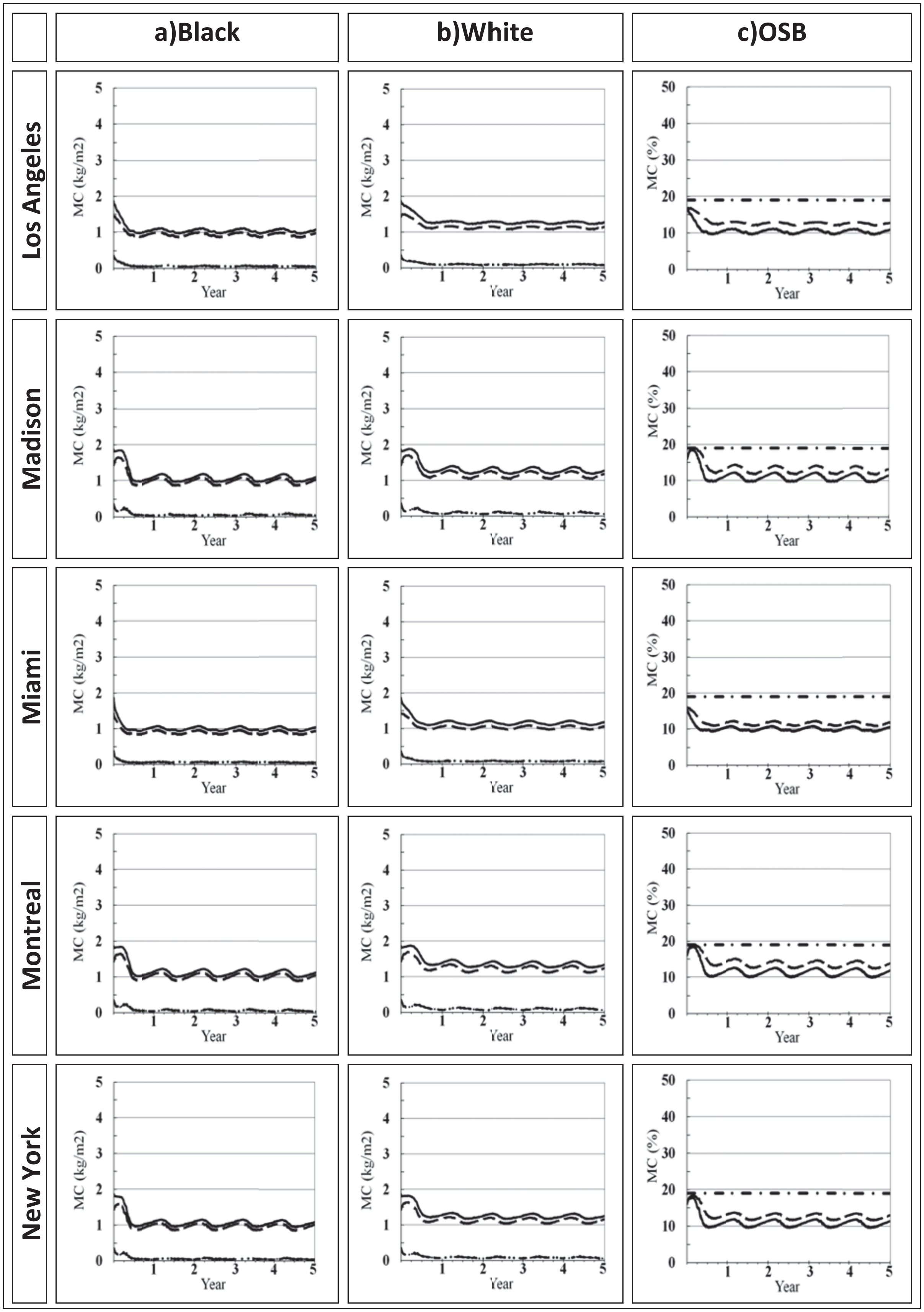
When compared with typical roofs, smart roofs experienced lower total moisture content because of higher inward drying potential by using smart vapor retarders. Distribution of moisture contents in different components (mineral wool and OSB) and total moisture content are shown in Figure 5-15.

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal	**Black**	1.16	1.20	1.22	1.20	1.13	1.05	1.01	1.01	1.03	1.06	1.09	1.12
	White	1.36	1.39	1.42	1.43	1.40	1.35	1.30	1.27	1.27	1.28	1.29	1.32
Anchorage	**Black**	1.29	1.33	1.36	1.36	1.31	1.24	1.16	1.13	1.14	1.16	1.19	1.24
	White	1.62	1.66	1.69	1.70	1.68	1.64	1.57	1.52	1.51	1.50	1.53	1.57
Kansas City	**Black**	1.07	1.11	1.13	1.09	1.05	0.99	0.93	0.94	0.95	0.98	1.00	1.04
	White	1.22	1.26	1.29	1.29	1.27	1.23	1.14	1.13	1.12	1.14	1.16	1.18
Madison	**Black**	1.12	1.16	1.18	1.16	1.09	1.00	0.98	0.98	0.99	1.02	1.04	1.08
	White	1.30	1.34	1.37	1.37	1.35	1.28	1.22	1.20	1.19	1.21	1.23	1.26
New York	**Black**	1.11	1.14	1.14	1.11	1.04	0.98	0.96	0.98	0.99	1.03	1.05	1.07
	White	1.27	1.29	1.31	1.31	1.28	1.22	1.18	1.18	1.18	1.20	1.21	1.24
Phoenix	**Black**	0.97	0.98	0.96	0.91	0.86	0.83	0.83	0.87	0.89	0.88	0.91	0.94
	White	1.08	1.09	1.09	1.07	1.02	0.97	0.95	0.98	1.00	1.00	1.02	1.05
Vancouver	**Black**	1.16	1.19	1.21	1.21	1.17	1.08	1.04	1.01	1.03	1.05	1.09	1.13
	White	1.39	1.41	1.42	1.42	1.41	1.37	1.35	1.32	1.31	1.32	1.34	1.36
Miami	**Black**	1.06	1.07	1.04	0.99	0.96	0.97	0.96	0.94	0.95	0.98	1.01	1.03
	White	1.20	1.21	1.21	1.19	1.16	1.14	1.12	1.10	1.10	1.11	1.14	1.17
Los Angeles	**Black**	1.08	1.10	1.10	1.07	1.02	1.02	0.98	0.97	0.99	1.01	1.04	1.06
	White	1.27	1.29	1.30	1.29	1.29	1.28	1.26	1.23	1.23	1.23	1.25	1.26
Houston	**Black**	1.08	1.10	1.09	1.05	0.99	0.95	0.93	0.93	0.96	0.98	1.01	1.05
	White	1.21	1.22	1.24	1.23	1.19	1.14	1.10	1.09	1.10	1.12	1.15	1.18
Saint John's	**Black**	1.20	1.23	1.26	1.26	1.22	1.15	1.08	1.06	1.08	1.10	1.13	1.16
	White	1.46	1.49	1.52	1.53	1.53	1.50	1.43	1.40	1.39	1.39	1.40	1.42
Edmonton	**Black**	1.17	1.22	1.25	1.24	1.16	1.06	1.01	1.01	1.02	1.04	1.07	1.12
	White	1.42	1.47	1.51	1.51	1.48	1.41	1.36	1.32	1.31	1.31	1.33	1.37
Chicago	**Black**	1.11	1.14	1.16	1.15	1.09	0.99	0.98	0.98	0.99	1.01	1.03	1.07
	White	1.27	1.31	1.33	1.34	1.33	1.26	1.21	1.19	1.18	1.19	1.21	1.23

Table 5-25. Calculated monthly average total water content (kg/m^2) in the fifth year of simulation (smart office roof)


a)Black
b)White
c)OSB
Anchorage
Chicago
Edmonton
Houston
Kansas City
MC (kg/m2)
MC (%)
Year

Continued


a)Black
b)White
c)OSB
Los Angeles
Madison
Miami
Montreal
New York
MC (kg/m2)
MC (%)
Year

Continued

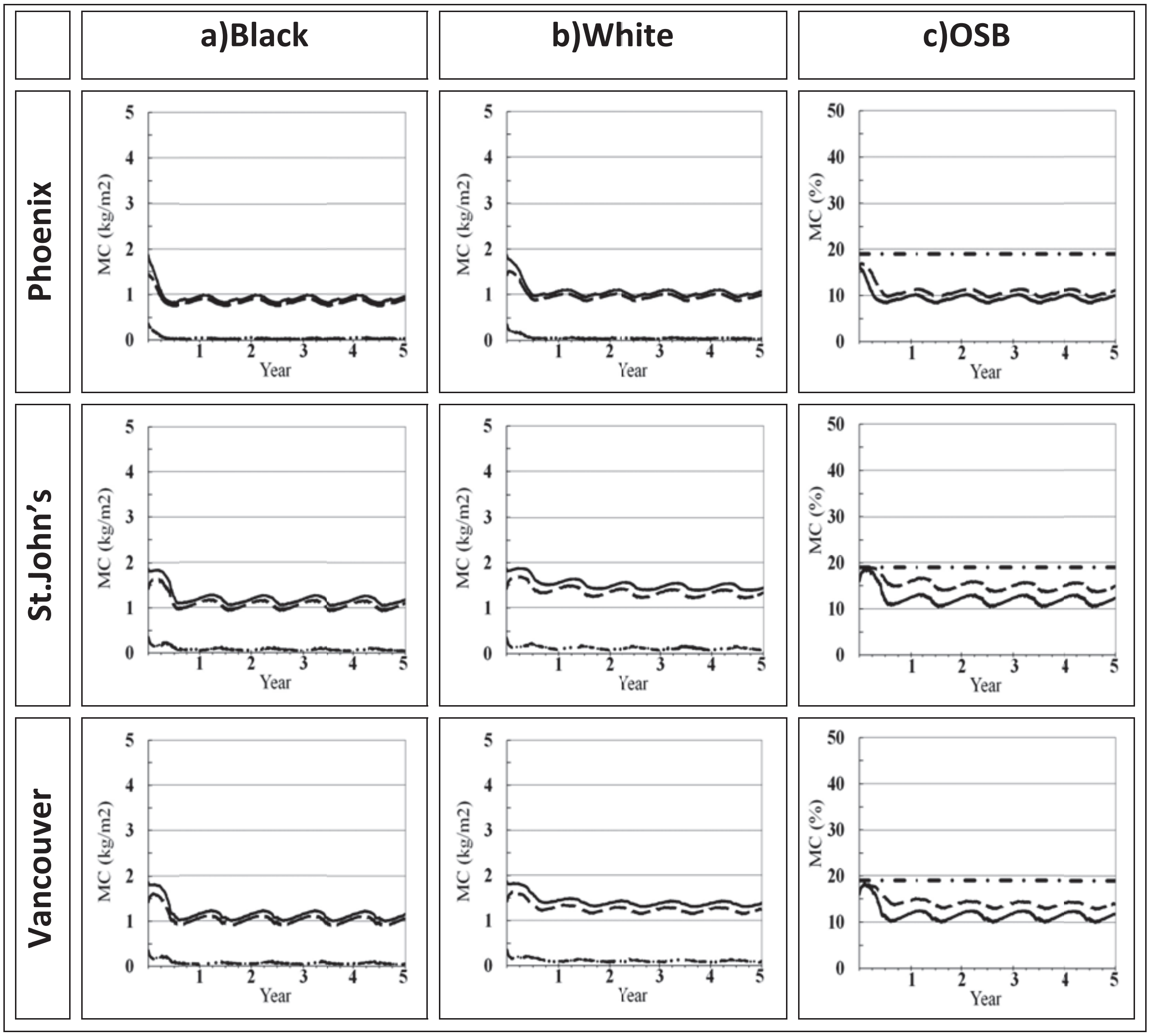


Figure 5-15.Moisture content of smart roofs for office buildings .Column a, b shows black and white roofs moisture content (kg/m^2): total (▬▬), OSB (▪ ▪ ▪), Mineral Wool (▪ • • ▪).Column c shows OSB moisture content (%): white roof (▪ ▪ ▪), black roof (▬▬), max allowable MC (19%) (▪ • ▪)

City	Roof color	1st Year (hr.)
Montreal	Black	0
	White	56
Anchorage	Black	714
	White	1545
Madison	Black	0
	White	370
Saint John's	Black	0
	White	1
Edmonton	Black	0
	White	1290

Table 5-26.Number of hours MC at OSB exceed 19% in smart office roofs

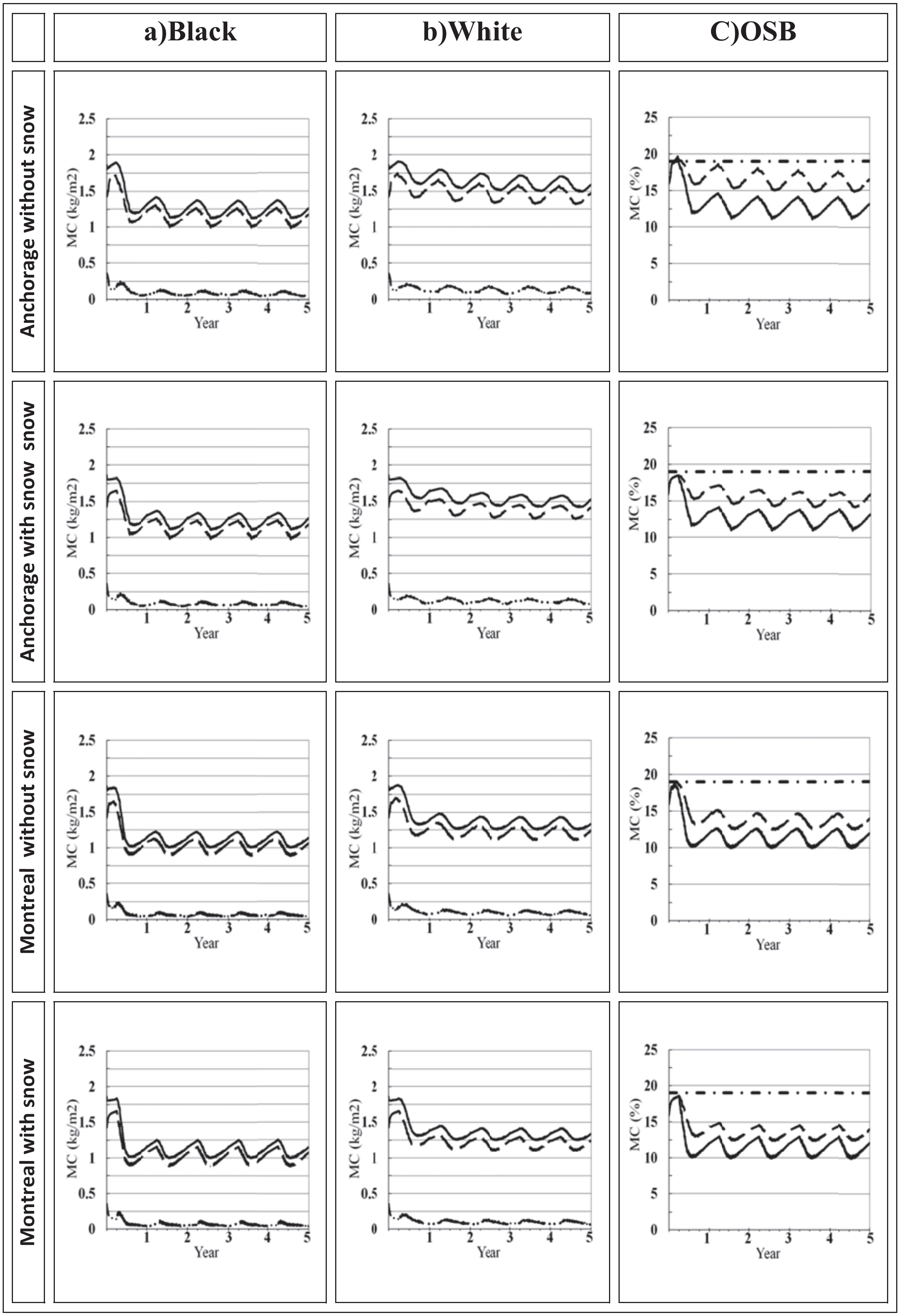
Figure 5-15 shows that the OSB moisture content of Smart roofs on an office with white surfaces in Montreal, Anchorage, Madison, St. John's and Edmonton exceeded 19% over the five year simulation while black roofs exceeded this limit only in Anchorage. It should be noticed that OSB moisture content for both black and white roofs exceeded 19% only in the first year of simulation for above mentioned locations. Table 5-26 provides the number of hours that OSB experienced moisture content more than 19%. White roofs in Montreal and St. John's only have a few hours with OSB moisture content of more than allowable limit.

Regarding the risk of mold growth, both black and white smart roofs on office buildings performed very well against mold growth except white roofs in Anchorage. Roofs with white surfaces in Anchorage in the fifth year of simulation experienced 1531 hours risk of mold growth between exterior membrane and OSB and 658 hours between OSB and mineral wool. In all other cases, risks of mold growth were zero in the roofing assemblies during the simulation period.

Table 5-27 compares effect of snow on monthly average moisture content of office smart roofs for three cities during the fifth year of simulation period. Snow helped in reduction of moisture content only in Anchorage for white roofs while in the other cases, effect of snow is not considerable on total moisture content of office smart roofs. Figure 5-16 displays moisture content of mineral wool, OSB and total moisture content with and without snow on the roof. Without the effect of snow, both black and white roof in Anchorage and white roof in Montreal experienced some number of hours with OSB moisture content more than 19% (Table 5-28). With the effect of snow, OSB moisture content never exceeded the allowable limit in these locations.

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal without snow	**Black**	1.16	1.20	1.22	1.20	1.13	1.05	1.01	1.01	1.03	1.06	1.09	1.12
	White	1.36	1.39	1.42	1.43	1.40	1.35	1.30	1.27	1.27	1.28	1.29	1.32
Montreal with snow	**Black**	1.17	1.20	1.23	1.23	1.14	1.04	1.01	1.01	1.03	1.06	1.09	1.13
	White	1.35	1.37	1.40	1.41	1.38	1.33	1.28	1.26	1.26	1.27	1.29	1.32
Anchorage without snow	**Black**	1.29	1.33	1.36	1.36	1.31	1.24	1.16	1.13	1.14	1.16	1.19	1.24
	White	1.62	1.66	1.69	1.70	1.68	1.64	1.57	1.52	1.51	1.50	1.53	1.57
Anchorage with snow	**Black**	1.28	1.30	1.33	1.33	1.28	1.21	1.14	1.12	1.13	1.15	1.19	1.24
	White	1.54	1.56	1.57	1.58	1.56	1.53	1.47	1.44	1.43	1.43	1.46	1.51
Chicago without snow	**Black**	1.11	1.14	1.16	1.15	1.09	0.99	0.98	0.98	0.99	1.01	1.03	1.07
	White	1.27	1.31	1.33	1.34	1.33	1.26	1.21	1.19	1.18	1.19	1.21	1.23
Chicago with snow	**Black**	1.11	1.14	1.17	1.15	1.09	0.99	0.97	0.98	0.99	1.01	1.04	1.07
	White	1.27	1.29	1.32	1.33	1.31	1.25	1.20	1.19	1.18	1.19	1.21	1.23

Table 5-27.Effect of snow on monthly average MC smart residential roof (kg/m^2)


a)Black
b)White
C)OSB
Anchorage without snow
Anchorage with snow snow
Montreal without snow
Montreal with snow
MC (kg/m2)
MC (%)
Year

Continued

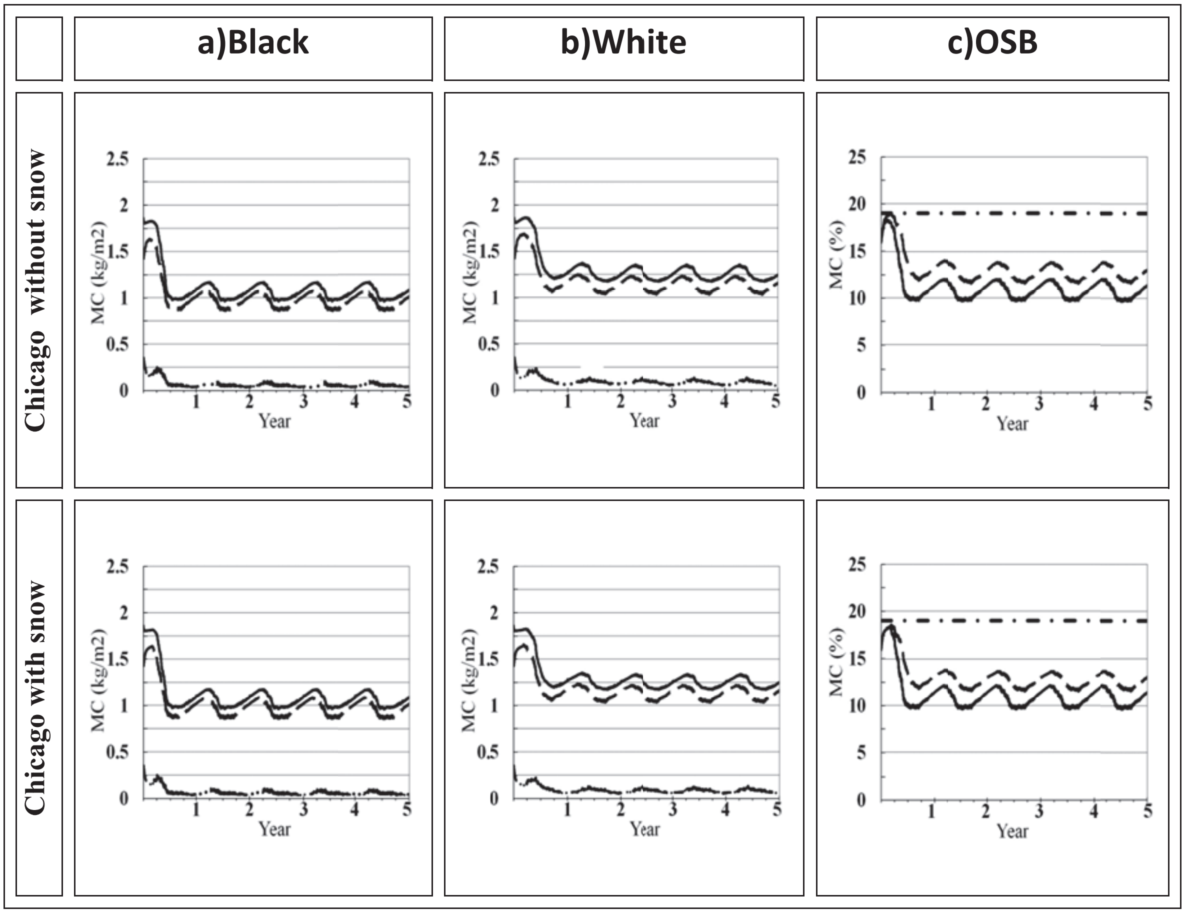


Figure 5-16.Effect of snow on the moisture content of office building with smart roof composition; Column a, b shows black and white roofs moisture content (kg/m^2): total (▬), OSB (▪ ▪ ▪), Mineral Wool (▪ ◆ ◆ ▪).Column c shows OSB moisture content (%): white roofs (▪ ▪ ▪), black roofs (▬), max allowable MC (19%) (▪ ◆ ▪)

City	Roof color	1st Year (hr.)
Anchorage without snow	**Black**	714
	White	1545
Anchorage with snow	**Black**	0
	White	0
Montreal without snow	**Black**	0
	White	56
Montreal with snow	**Black**	0
	White	0
Chicago without snow	**Black**	0
	White	0
Chicago with snow	**Black**	0
	White	0

Table 5-28.Effect of snow on number of hours that moisture exceed 19% at OSB (smart office)

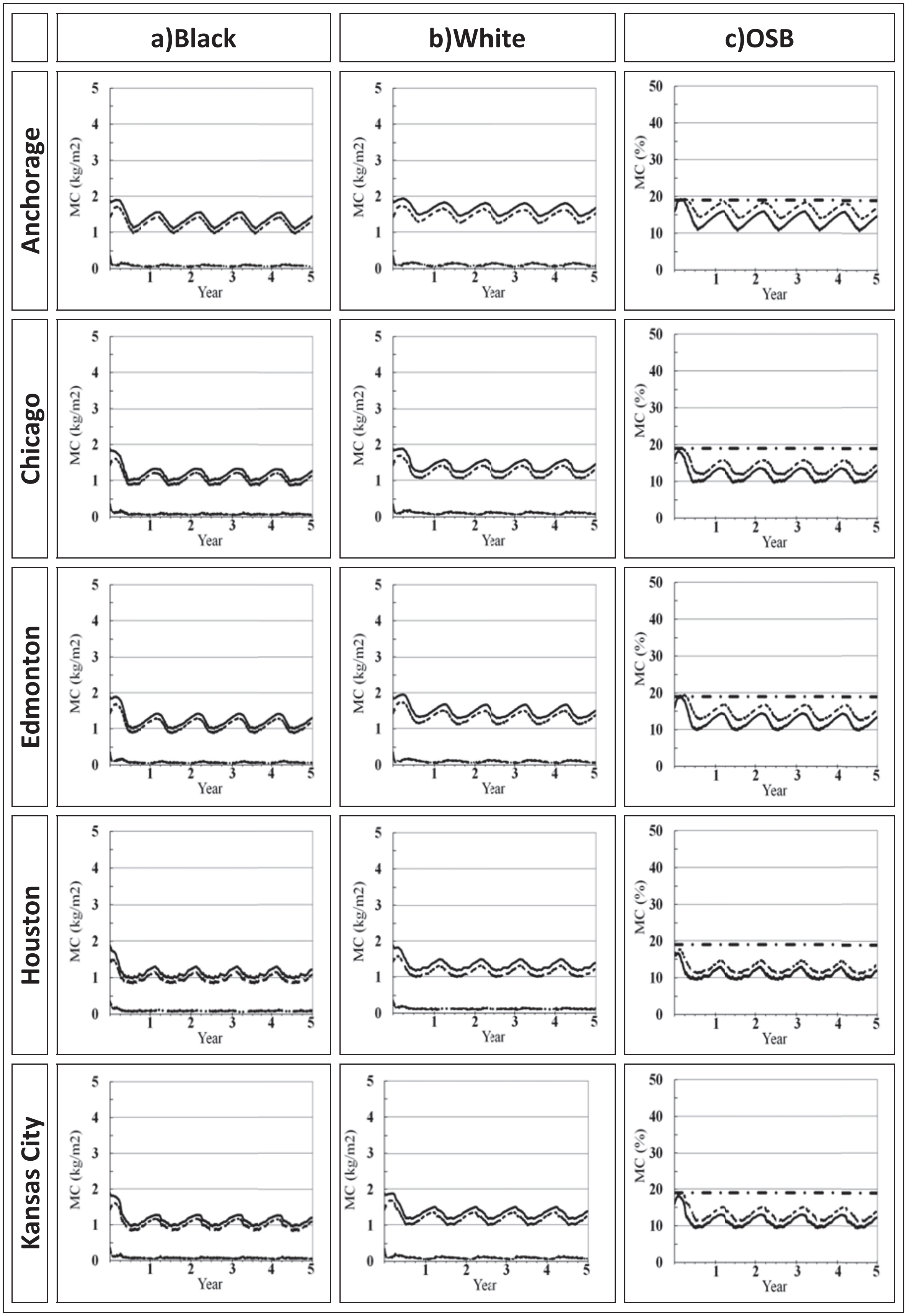
5.2.6 Residential buildings with vented smart roofs

In previous roofing systems, white roofs experienced moisture accumulation in very cold and cold climates (e.g. Anchorage, Edmonton and St. John's). In order to eliminate or reduce moisture accumulation problem, we added a vented air layer with thickness of 10 mm between OSB and insulation of a smart roof. Table 5-29 shows monthly average of total water contents of this roof in different locations. In comparison with smart roofs without air layer, monthly average total water content of vented smart roofs in Anchorage, St. John's and Edmonton were lower for either white of black roofs.

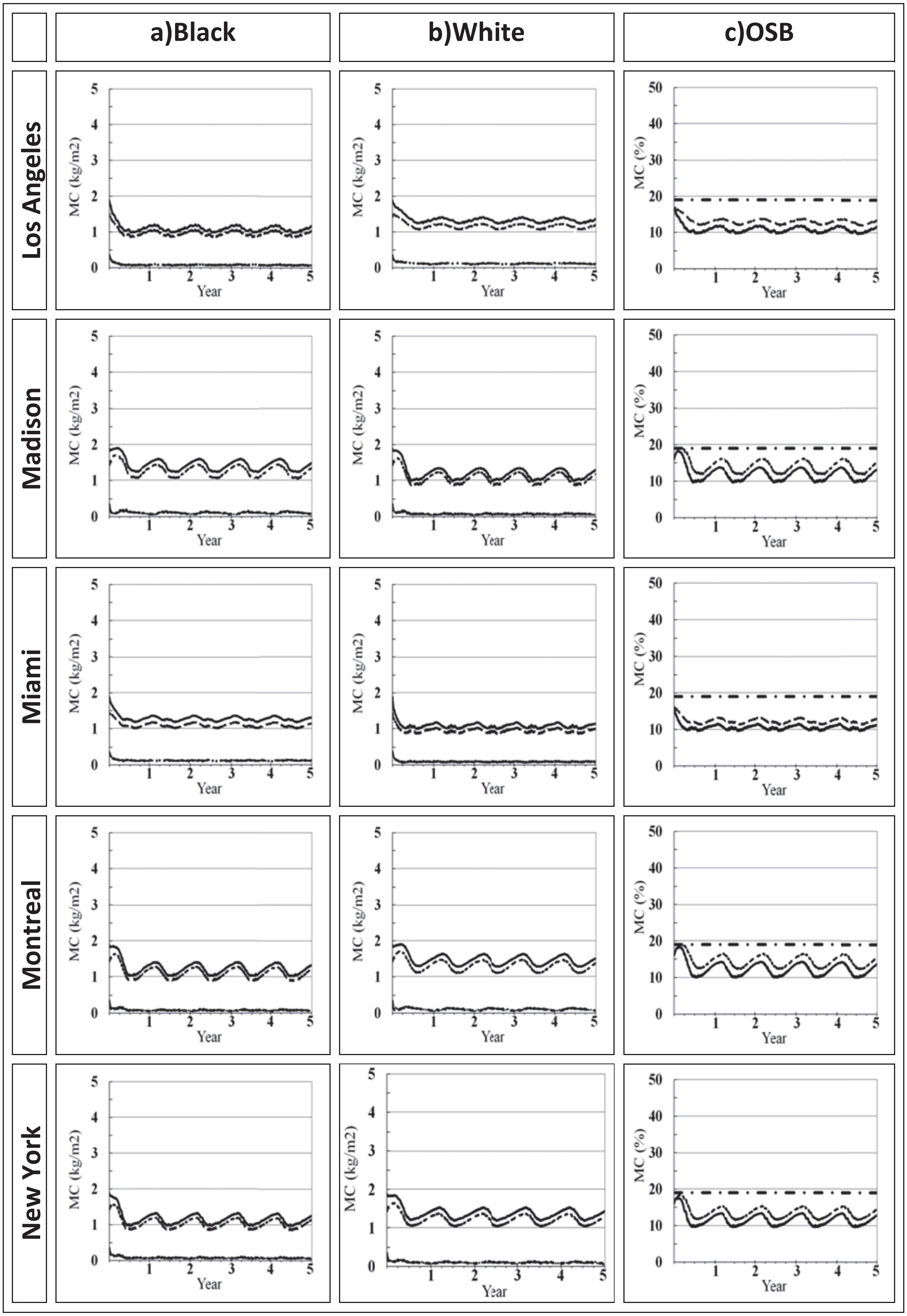
Figure 5-17 depicts distribution of moisture in the vented smart roofing assembly in different locations for white and black roofs. The first two columns of Figure 5-17 (*a*, *b*) shows that both colors vented smart roof never experienced moisture accumulation problem even in the very cold climates such as Anchorage and St. John's. Third column of Figure 5-17 (column c) also shows that OSB moisture content of both white and black smart roofs with an air layer never exceed 19% in the last four years of simulation period. In the first year of simulation because of transitional effect of initial condition, black roofs only in Anchorage have some number of hours with moisture content more than 19%. White roofs, in addition to Anchorage, exceeded this limit in Montreal, Edmonton, Madison and St. John's. Number of hours that moisture content in OSB was more than 19% in the first year is shown in Table 5-30. Comparing OSB moisture content of smart roofs with and without air layer showed that OSB layer of vented smart roofs always experienced lower moisture content.

City	Roof color	January	February	March	April	May	June	July	August	September	October	November	December
Montreal	Black	1.35	1.39	1.39	1.30	1.16	1.04	1.03	1.06	1.10	1.17	1.24	1.30
	White	1.54	1.59	1.62	1.61	1.51	1.38	1.30	1.29	1.31	1.37	1.43	1.48
Anchorage	Black	1.48	1.53	1.55	1.49	1.36	1.23	1.14	1.14	1.21	1.27	1.34	1.41
	White	1.70	1.76	1.79	1.79	1.74	1.64	1.52	1.46	1.48	1.52	1.58	1.64
Kansas City	Black	1.24	1.27	1.26	1.15	1.08	1.01	0.99	1.00	1.01	1.07	1.12	1.19
	White	1.41	1.46	1.49	1.44	1.38	1.28	1.19	1.19	1.19	1.24	1.29	1.36
Madison	Black	1.31	1.33	1.32	1.24	1.10	1.01	1.02	1.03	1.05	1.13	1.20	1.26
	White	1.51	1.56	1.59	1.57	1.47	1.32	1.26	1.25	1.25	1.32	1.39	1.45
New York	Black	1.28	1.31	1.29	1.18	1.04	0.99	0.99	1.03	1.06	1.12	1.17	1.23
	White	1.45	1.49	1.51	1.47	1.36	1.24	1.19	1.22	1.25	1.30	1.35	1.40
Phoenix	Black	1.05	1.03	0.96	0.88	0.80	0.76	0.79	0.88	0.90	0.89	0.96	1.04
	White	1.17	1.17	1.12	1.04	0.94	0.89	0.92	0.99	1.02	1.00	1.06	1.15
Vancouver	Black	1.45	1.50	1.52	1.45	1.29	1.10	1.06	1.03	1.08	1.16	1.27	1.36
	White	1.64	1.69	1.73	1.73	1.66	1.50	1.41	1.33	1.33	1.40	1.49	1.56
Miami	Black	1.16	1.14	1.08	1.03	1.04	1.07	1.04	1.01	1.04	1.09	1.11	1.13
	White	1.35	1.35	1.32	1.26	1.24	1.26	1.23	1.19	1.21	1.25	1.28	1.31
Los Angeles	Black	1.17	1.19	1.17	1.10	1.04	1.05	1.00	1.00	1.04	1.07	1.11	1.14
	White	1.36	1.39	1.40	1.38	1.35	1.32	1.27	1.25	1.26	1.28	1.31	1.33
Houston	Black	1.26	1.29	1.21	1.10	1.03	1.02	1.00	1.02	1.07	1.07	1.10	1.21
	White	1.43	1.48	1.46	1.38	1.28	1.22	1.19	1.20	1.23	1.26	1.29	1.37
Saint John's	Black	1.44	1.47	1.47	1.43	1.32	1.18	1.09	1.10	1.16	1.22	1.31	1.38
	White	1.67	1.72	1.76	1.77	1.75	1.65	1.50	1.44	1.45	1.48	1.55	1.61
Edmonton	Black	1.34	1.40	1.40	1.34	1.17	1.04	1.02	1.05	1.09	1.13	1.20	1.28
	White	1.54	1.60	1.65	1.66	1.55	1.40	1.32	1.30	1.32	1.35	1.40	1.47
Chicago	Black	1.30	1.32	1.31	1.26	1.12	1.00	1.02	1.04	1.05	1.11	1.17	1.25
	White	1.48	1.52	1.56	1.55	1.47	1.31	1.26	1.25	1.25	1.29	1.35	1.42

Table 5-29.Monthly average total water content (kg/m^2) in the fifth year of simulation (vented smart residential roof)


a)Black
b)White
c)OSB
Anchorage
Chicago
Edmonton
Houston
Kansas City
MC (kg/m2)
MC (%)
Year

Continued


a)Black
b)White
c)OSB
Los Angeles
Madison
Miami
Montreal
New York
MC (kg/m2)
MC (%)
Year

Continued

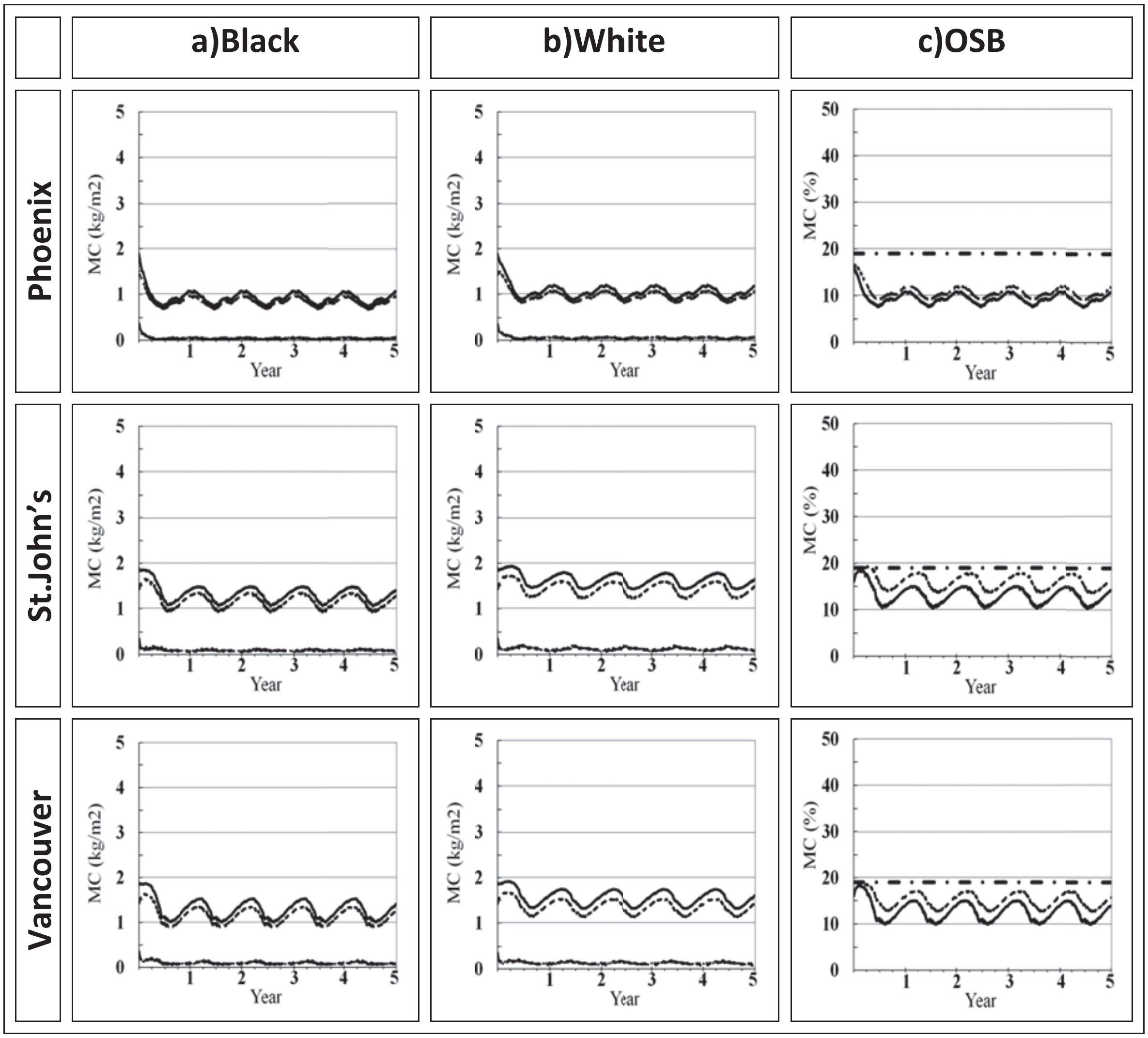


Figure 5-17.Moisture content of vented smart roofs for residential buildings .Column a, b shows black and white roofs moisture content (kg/m^2): total (▬▬), OSB (▪ ▪ ▪), Mineral Wool (▪ ◆ ◆ ▪).Column c shows OSB moisture content (%): white roof (▪ ▪ ▪), black roof (▬▬), max allowable MC (19%) (▪ ◆ ▪)

Risks of mold growth in the vented smart roofs are only limited to white roofs in Anchorage, Vancouver, St. John's and Edmonton. However, air gap helped to decreased risk of mold in these cities compared to smart roofs. In comparison to smart roofs without air gap, using a vented air layer between OSB and insulation significantly helped to eliminate risk of mold growth in white roofs in cities such as Montreal, Madison and Chicago. Using vented smart roofs also helped to eliminate risk of mold growth for black roofs in Anchorage. Table 5-31 shows number of hours that vented smart roof experience risk of mold growth. It should be mentioned that in contrast to smart roofs without air layer in residential buildings, vented smart roofs never have risk of mold growth between OSB and membrane layers.

City	Roof color	1st Year (hr.)
Montreal	Black	0
	White	265
Anchorage	Black	717
	White	1661
Madison	Black	0
	White	472
Saint John's	Black	0
	White	1421
Edmonton	Black	0
	White	1408

Table 5-30.Number of hours MC at OSB exceed 19% in vented smart residential roofs

City	Roof Color	OSB/Air gap	Air gap/Mineral wool
Anchorage	Black	0	0
	White	601	332
Vancouver	Black	0	0
	White	1592	1510
Saint John's	Black	0	0
	White	449	393
Edmonton	Black	0	0
	White	60	0

Table 5-31.Risk of mold growth (Hour) for vented smart roofs (last year)

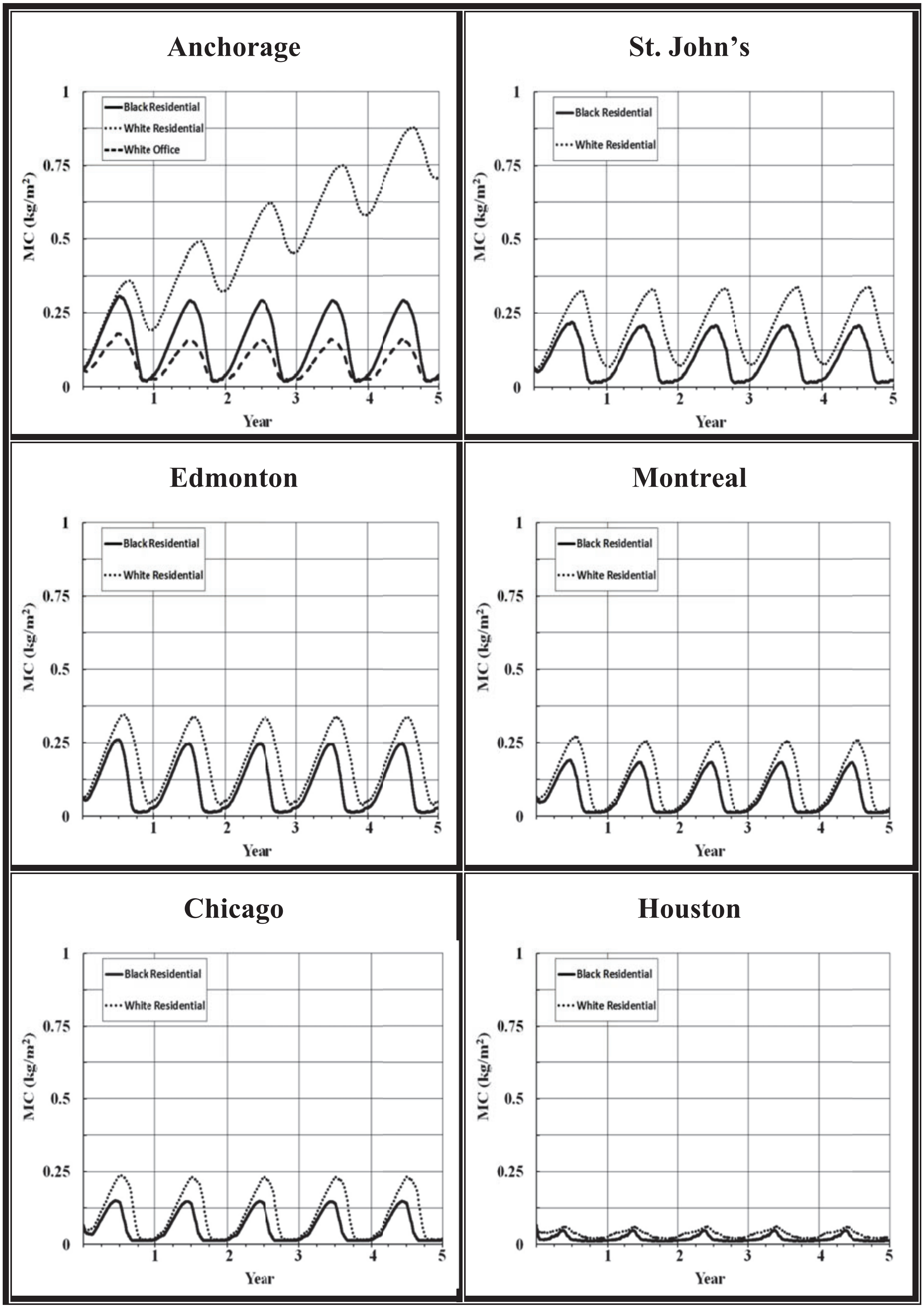
We concluded that white vented roofs with smart vapor retarder in residential buildings have better hygrothermal performances than typical and smart roofs in those climates where moisture accumulation is a problem such as Anchorage, St. John's, and Edmonton.

5.2.7 Self-drying roofs

Self-drying roof, as shown in Figure 5-1, is the fourth roofing system that we simulated. In previous sections, we demonstrated that the similar roofs on an office building performed better than on a residential building. Here, we initially simulated the effect of self-drying roof for residential buildings and only if the total moisture content was accumulated over the time, the simulations were carried out for office buildings.

Figure 5-18 compares total moisture content of self-drying roofs with black and white surfaces. Self-drying black roofs never experienced moisture accumulation problem during the simulation period and total moisture content were always below 0.5 kg/m^2. Self-drying white roofs on residential building only experienced accumulation of moisture in Anchorage. Simulation of white surface roofs on office building showed no moisture accumulation problem and the total moisture content were even lower than black residential roofs.

In hot climates such as Phoenix, Houston, Los Angeles and Miami, there was no considerable difference in total moisture content between black and white self-drying roofs. In other locations, despite difference between the moisture of white and black surfaces, their moisture content were still below 0.5 kg/m^2.


Anchorage
Black Residential
White Residential
White Office
MC (kg/m²)
Year
St. John's
Black Residential
White Residential
MC (kg/m²)
Year
Edmonton
Black Residential
White Residential
MC (kg/m²)
Year
Montreal
Black Residential
White Residential
MC (kg/m²)
Year
Chicago
Black Residential
White Residential
MC (kg/m²)
Year
Houston
Black Residential
White Residential
MC (kg/m²)
Year

Continued

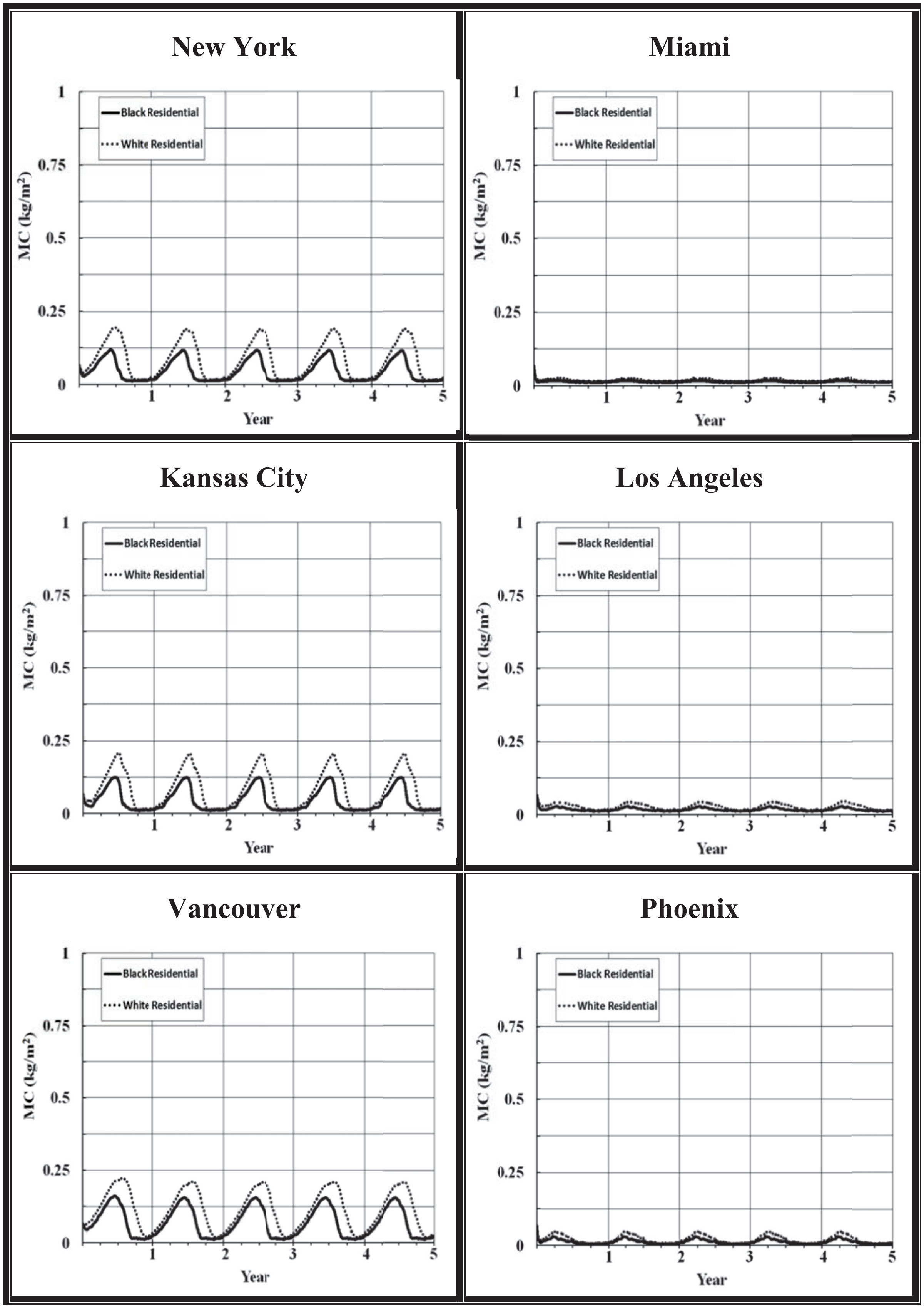


Figure 5-18.Total moisture content of self-drying roofs with black and white surfaces in different cities

Figure 5-18 shows that white self-drying roofs in Anchorage as a very cold climate with residential interior climate experience moisture accumulation while total moisture content of white roofs in Edmonton as another very cold climate never exceed 0.4 kg/m^2. Comparing outdoor climate conditions showed that there is higher drying potential in Edmonton than Anchorage during last six months because of higher average outdoor temperature. It should be noted that higher outdoor temperature in Edmonton was the reason that white self-drying roofs never experience accumulation of moisture in the roofing assembly. Figure 5-19 shows outdoor temperature variation for Edmonton and Anchorage during one year.

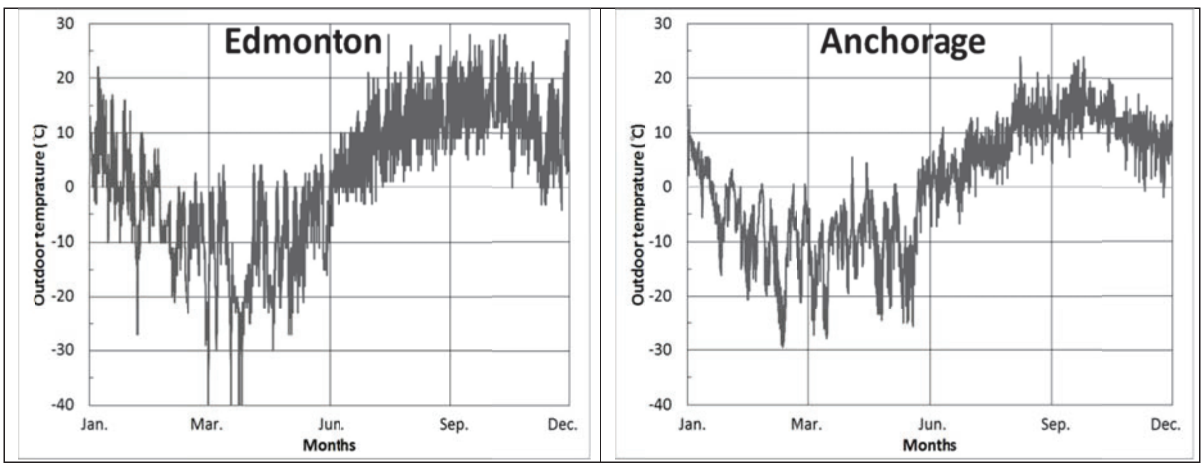


Figure 5-19.Outdoor temperature of Edmonton and Anchorage as very cold climates

Chapter 6 Summary, conclusion and future work

The objective of the thesis was to evaluate hygrothermal performance of cool and traditional roofs in different climates for residential and commercial buildings. For this purpose, different roofing systems with white and black surfaces were analyzed in several cities (each representing a climate region) across North America.

We proposed smart vented roofs with an air gap between insulation and OSB layer along with using smart vapor retarders. In addition to smart vented roofs, hygrothermal performance of the following three roofing systems also were studied: : (1) typical flat roofing composition with conventional vapor retarder, (2) smart roof with flexible vapor retarder permeability, (3) self-drying roof without any vapor retarder. Indoor climate (temperature and relative humidity) of residential buildings was selected according to the ASHRAE Standard-160 with set points for cooling, heating and RH based on outdoor climate. Indoor conditions of office buildings with different set points for cooling and heating seasons were selected based on outdoor climate and occupancy schedules (office hour from 8:00 AM to 5:00 PM). The climate regions included: Anchorage and Edmonton (very cold climates); Madison, Montreal and St. John's (cold and humid); Chicago and Vancouver (cool and humid); Kansas City and New York (mixed and humid); Los Angeles, Phoenix (warm and dry); Houston (hot and humid) and Miami, (hot and humid).

WUFI 5.1 Pro was used to simulate heat and moisture transfer through the roofing assembly. The simulations were conducted for five years with solar absorption of 0.88 for black roofs and 0.4 for aged white roofs. Since WUFI does not take into account the effect of snow on moisture behaviour of roof, we developed an algorithm to estimate the influence of snow on hygrothermal performance of black and white roofs in three different cities. Montreal and Anchorage were simulated with three months of snow on the roof and Chicago for two months.

Results showed that black roofs always experienced lower moisture content compared to white roofs. However, moisture performances of white roofs were very similar to black roofs in hot climates such as Phoenix, Houston, Los Angeles and Miami. In these areas, all of four roofing systems can be used with white surfaces without any problems either in residential or office buildings.

We also simulated typical roofing composition in Tucson with residential indoor climate to compare with the field observation reports. In the winter of 2004-2005, various field observations in Tucson indicated the existence of excessive moisture in the white roofs. However, our calibrated simulations showed that both white and black roofs perform without any problem. We concluded that moisture in fields observations can be penetrated by opening and crack underneath the membrane. In these circumstances, white roofs did not have potential to dry out the penetrated moisture because of lower surface temperature compared to black roofs.

In residential buildings, typical flat composition roofs with a white surface experienced moisture accumulation in Anchorage, Edmonton and St. John’s. By using smart roofs or self-drying roofs, risk of moisture accumulation was reduced and only occurred in Anchorage. Vented smart roofs (our proposed roofing system) in residential buildings, with a ventilated air space between OSB and insulation, never experienced moisture accumulation problem among simulated cities even in Anchorage as a very cold climate.

In residential buildings, OSB moisture content of typical roofing system without considering effect of snow for both white and black roofs exceeded 19% by mass in Montreal, Kansas City, Madison, Vancouver and Chicago, Anchorage, Edmonton and St. John’s. Meanwhile, OSB moisture contents of smart roofs were more than 19% for both colors in Montreal, Anchorage, St. John’s and Edmonton. In other cities, OSB moisture content of black roofs remained below 19%. Smart white roofs only experienced OSB moisture content more than 19% in Kansas City, New York, Madison, Vancouver and Chicago. By using vented smart roofs, Anchorage is the only city that OSB moisture content was more than 19% for both color roofs. Only white vented smart roofs have some number of hours with OSB moisture content more than 19% in Montreal, Madison, St. John’s and Edmonton while it is remained below 19% for black surfaces.

Considering effect of snow accumulation of roofs, black roofs with typical composition in Montreal and smart composition in Montreal and Chicago showed higher number of hours with OSB moisture content more than

19%. In the other snow simulation cases, snow helped to reduce number of hours that OSB moisture content was more than 19%.

Regarding the risk of mold growth in residential buildings, both white and black roofs with typical and smart composition systems never experienced risk of mold growth in hot cities such as: Phoenix, Houston, Los Angeles and Miami. In other locations except Kansas City, there was risk of mold growth with typical roofing system for both roof colors. In Kansas City, only typical white roofs experienced risk of mold. Smart roofs on residential buildings showed risk of mold growth only in Anchorage for both roof colors. White smart roofs had risk of mold growth in Montreal, Madison, Vancouver, St. John's, Edmonton and Chicago. It should be noted that typical composition roofs with black color experienced higher risk of mold growth underneath the insulation than white roofs in Montreal, Anchorage, Madison, New York, Vancouver, St. John's, Edmonton and Chicago. Vented smart roofs had the best performance against mold growth for both roof colors for various simulated scenarios. Risk of mold growth for white vented roofs with smart vapor retarder were only limited to Anchorage, St. John's and Edmonton while black surfaces never experienced risk of mold growth in the simulated cities. White self-drying roofs in residential buildings experienced moisture accumulation problem only in Anchorage as a very cold climate. In other cities, self-drying roofs showed better performance for both colors with moisture content less than 0.5 kg/m^2.

For office buildings, none of roofing systems in the selected climates experienced moisture accumulation over the simulation period and roof total moisture content always stayed below 2 kg/m^2. Without considering effect of snow, white typical roofs had OSB moisture content more than 19% in Montreal, Anchorage, Kansas City, Madison, Saint John's, Edmonton, Chicago. OSB moisture content of white smart roofs in Montreal, Anchorage, Madison, Saint John's and Edmonton were greater than 19%. Simulating the effect of snow in three cities (Montreal, St. John’s and Chicago), the total moisture content never exceeded 19% for both color of roofs. White typical office roofs experienced risk of mold growth in Anchorage, St. John’s and Edmonton although white office smart roofs only had risk of mold growth in Anchorage. White self-drying roofs in Anchorage simulated with office indoor condition showed acceptable moisture performance but not for residential buildings.

In Table 6-1, we summarized effect of reflectivity on hygrothermal behaviour of various roofing compositions in the simulated cities all across North America. Risk of moisture accumulation, number of hours with OSB moisture content more than 19% and number of hours with risk of mold growth are shown in this table.

Since we only simulated hygrothermal behaviour of flat roofs with determined indoor condition with solar absorptivity 0.4 for aged white roof and 0.88 for dark roofs. We propose to investigate moisture performance of sloped roofs with and without attics. Furthermore, moisture performance of cool and dark roofs should be evaluated with different indoor condition and solar absorptivity’s.

		Residential						Office			
		Typical		Smart		Smart-vented		Typical		Smart	
		Black	White	Black	White	Black	White	Black	White	Black	White
Anchorage	Accumulation	✓	✓		✓						
	MC OSB	**	****	**	***	*	**	**	**	*	**
	Mold	**	***	*	***		*		***		**
St. John’s	Accumulation		✓								
	MC OSB	**	****	**	***		**		**		*
	Mold	**	***		**		*		**		
Edmonton	Accumulation		✓								
	MC OSB	**	***	**	**		**	*	**		**
	Mold	**	***		**		*		**		
Montreal	Accumulation										
	MC OSB	**	**	*	**				**		*
	Mold	*	**		**						
Madison	Accumulation										
	MC OSB	**	**		**				**		*
	Mold	*	**		*						
Chicago	Accumulation										
	MC OSB	**	**		**				**		
	Mold	*	**		*						
Vancouver	Accumulation										
	MC OSB	**	**		**						
	Mold	**	***		***						
Kansas City	Accumulation										
	MC OSB	**	**		**				*		
	Mold		**								
New York	Accumulation										
	MC OSB		**		**						
	Mold	*	**								
Houston	Accumulation										
	MC OSB										
	Mold										
Los Angeles	Accumulation										
	MC OSB										
	Mold										
Phoenix	Accumulation										
	MC OSB										
	Mold										
Miami	Accumulation										
	MC OSB										
	Mold										

Table 6-1.Summary of hygrothermal performances of various roofing compositions for the simulated cities. Blank cells show conditions with no risk of moisture accumulation and mold.
Keys:
✓ Risk of moisture accumulation.
Number of hours that moisture content in the OSB exceeds 19% and number of hours with risk of mold growth based on ASHRAE Standard 160: * < 1000 hours, ** 1000-3000 hours, * 3000-5000 hours, **** > 5000 hours**

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