Thermal Performance of Closed-Cell Foam Insulation Board Under Different Temperature Conditions

by

Gurpreet Singh Jagdev
Bachelor of Technology, Guru Nanak Dev Engineering College, 2012

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Supervisory Committee

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Abstract

Thermal performance of an insulation material is influenced by the in-service temperature condition. Unlike most other insulation materials, thermal resistance (R-value) of polyisocyanurate (polyiso) foam insulation with 'captive blowing agent' varies non-linearly with temperature. Building designers consider constant R-value of different insulating materials for building design and energy calculations, and hygrothermal simulation software packages, such as WUFI, consider linear temperature dependent R-value profiles, even for polyiso. However, neither the linear temperature dependent thermal resistance nor the constant thermal resistance value of polyiso represents the actual thermal performance of the building envelope. This thesis aims to quantify the impact of in-service boundary temperature conditions in Canadian climates on the thermal resistance of polyiso foam insulation board used in EPDM and PVC roof constructions. Hygrothermal simulations were performed using WUFI® Pro, which considers real climate data and hygrothermal properties of constituent roof components for evaluating moisture and temperature conditions in roof constructions. Based on heating degree days (HDD), ten different cities were selected between climate Zone 4 (HDD<3000) to Zone 8 (HDD≥7000). The thermal resistance measurements were conducted using heat flow meter apparatus on four polyiso insulation boards (two new and two aged) of different sizes [thickness - new: 1inch (25mm) and 2 inch (51mm); aged: 2 inch (51mm) and 3 inch (76mm)] at five mean temperatures -4°C (25°F), 4.5°C (40°F), 10°C (50°F), 24°C (75°F), 43°C (110°F) and at a temperature differential of 28°C (50°F). The measured thermal resistance data of the four samples at different mean temperatures were normalized with calculated thermal resistance of each sample at 22°C (72°F). The normalized R-value variation was calculated using in-service boundary temperature conditions determined from hygrothermal simulations and considering linearly varied thermal resistance with temperature, for the selected ten Canadian cities.

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I would also like to thank Peter Klinger (Technical Director) and Wendy Fraser (Technical Manager) from Canadian Roofing Contractors Association (CRCA) who were involved in this research project and provided valuable technical assistance at regular intervals throughout research. Moreover, I would also like to thank Matthew Walker for providing assistance with sample preparation and laboratory activities.

Finally, I must express my very profound gratitude to my parents, to my spouse, and entire family for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Dedication

I would like to dedicate my thesis to my beloved grandparents

Chapter 1 Research Overview

Sharp increase of energy price, warning of fuel shortages, need for clean energy, concerns about greenhouse gas (GHG) emissions and impacts of climate change are the factors influencing our public opinion and policy makers. The discussion of making a better place to live is leading researchers to find efficient ways to utilize energy resources and subsequently minimizing the emission of GHGs. The fractional reduction in energy consumption in buildings could significantly decrease the emission of GHGs. Considering building sector alone, the building envelope components and construction account for significant energy consumption and consequential generation of GHGs. In 2014, Canada generated 12,678.2 petajoules of primary energy supply out of it only 71.9% was available for secondary energy use. However, Canada's residential sector made use of 17.1% of the available secondary energy supply [1]. In 2015, 60.2% of Canada's total energy consumption of commercial and industrial buildings is used for heating and cooling spaces, which contributed to 64.6% of the sectors greenhouse gas emissions [2]. Thus, it is essential to consider measures to reduce energy consumption in building sector.

In Canada, increased thermal insulation use is becoming more critical in new building constructions due to the need for energy efficient buildings. Insulation maintains the interior temperature conditions and thereby reducing the electricity demands of buildings. This electricity is generated by the combustion of fossil fuels, which leads to GHG emissions. The factors like exterior temperature, interior temperature of buildings, insulation type, and hygrothermal properties of building materials influence the thermal performance of building envelope. Moreover, environmental factors like extreme cold temperatures, wind velocity, wind direction, and rain have significant impacts on thermal performance of building envelope. However, the overall thermal performance of building envelope depends to a great extent on the thermal resistance (R-value) of the insulation used in the building envelope construction. The role of insulation is thus very significant in terms of reducing the heat flow from the interior to exterior particularly in cold climates.

Insulations that have air or gas (i.e. 'captive blowing agent') trapped in foam pockets are known as cellular foam insulations [3]. A cellular foam insulation with 'captive blowing agent' (e.g. polyurethane, polyisocyanurate (polyiso) etc.) has higher thermal resistance value as compared to other available insulations, except few advanced insulation materials like Aerogel and Vacuum Insulation Panels (VIPs). The thermal resistance of gases (blowing agent) used in manufacturing of foam insulations is higher than air. However, at lower temperature (i.e. usually lower than 10°C) the blowing agent starts to condense and is eventually replaced by air, thus reducing the thermal resistance of the foam insulation, unlike other conventional insulations.

Hygrothermal performance assessment and energy calculation software/tools employ a constant R-value, measured at a mean temperature close to ambient laboratory temperature, to describe the thermal resistance of roof insulations. In actual environmental conditions, the thermal resistance of polyiso foam board insulation in a roof configuration can fall significantly below the mean temperature at which R-value of the insulation was determined in the laboratory thus creating a significant discrepancy between laboratory determined R-value and in-situ R-value.

Thermal insulation is expected to be durable and long-lasting for the designated lifetime of a building. However, insulations are exposed to cyclic loading of temperature and moisture conditions, thus influencing the thermal performance of insulation. The thermal resistance due to aging of polyiso insulation over a period of time decrease at a faster rate than extruded polystyrene insulation [4]. The non-linear temperature dependency behaviour of polyiso insulation is influencing researchers to explore different techniques to make building envelope more energy efficient.

Chapter 2 Literature Review

Heat transfer from warmer to cooler surface occurs due to temperature gradient and by conduction, convection, and radiation or combination of these three. Conduction is defined as heat flow through solid materials or stationary fluids with direct molecular contact. Convection heat transfer occur through motion of molecules. Lastly, radiation heat transfer is due to electromagnetic radiation and does not require a medium to pass through, thus can happen in vacuum.

The function of insulation considering three modes of heat transfer is to minimize convective and radiation transfer and introduce a minimum of solid conduction [5]. Fourier's law of heat conduction states that the time rate of heat transfer is proportional to the temperature gradient across the system through which heat flows and can be written as [4].

$$dQ = -\lambda \frac{\partial T}{\partial X} . dA . dT$$ ……………………..Equation 1 Fourier's Law of Heat Conductance

Where, Q: heat flux, $\partial T/\partial X$: temperature gradient across a material layer, A: surface area, t: time, and λ: thermal conductivity.

Thermal conductivity is time rate of heat flow through a unit area of homogenous material in a direction perpendicular to isothermal planes, induced by a unit temperature gradient. It is expressed in units (W/m. K) [6]. Thermal resistance (R-value) is defined as the temperature difference between two surfaces that induces a unit heat flow through a unit area due to temperature gradient between two defined surfaces of material or construction under steady state conditions [6]. Thermal resistance is expressed in imperial, and metric units as "($ft^2.^0F.hr$)/Btu", and ($m^2 \times K$)/W respectively; R-value represents imperial units and RSI value is metric unit equivalent such that R-value is approximately 5.678 times RSI value. The thermal conductivity is dependent on the material density, porosity, moisture content, and mean temperature [7].

Faced polyiso is a closed-cell rigid foam board insulation, where foam is sandwiched between paper (organic) or fiberglass facers (inorganic) [8]. Moreover, foil faced polyiso foam insulation is also available for cavity wall, stud wall or interior basement construction. Polyiso has the highest thermal resistance per inch thickness among insulations used for mass constructions [9]. The reason behind better thermal resistance is primarily due to the low thermal conductivity of the gas used as blowing agent during manufacturing of the foam insulation [10]. Moreover, foil faced polyiso foam insulation is also available for cavity wall, stud wall or interior basement construction.

The resistance of an insulation is a function of temperature. Fiberglass batts, expanded polystyrene (EPS), and extruded polystyrene insulations (XPS) perform better at low temperatures than high temperatures [11]. However, some foam insulations like polyurethane and polyiso have reduced thermal resistance at mean reference temperature below 10^0C and higher than 22˚C. The blowing agent present in polyiso insulation cells begins to condense at temperature lower than 10^0C, thus decreasing the thermal resistance value. The literature data shows that blowing agent condensation (and loss of insulation value) occurs in the temperature range between 5° to 12°C (41° to 54°F) for foams made with blowing agents like CFC-11, HCFC-141b, and HCFC-22 (Formacel® S) [12].

A technical report published in 2010 acknowledged temperature dependent R-value of polyiso, testing 15 samples ranged in age from 4 to 13 months, collected from different manufacturers across USA, of 2 in. (51mm) thickness using ASTM C-518 at mean temperatures of 25, 40, 75 & 110°F) with 50°F temperature differential [13]**.** In 2015, another published study conducted similar testing on seven new samples of polyiso insulation, 2 inch (51 mm) thick, manufactured by six manufacturers in USA. The comparison of experimental data of both studies reveals almost similar R-value data. However, later study recommended designers to consider specific climate conditions for determining in–service R-value of polyiso foam insulation, and specify a thickness of insulation rather than R-value at one mean temperature [14].

Research report published in 2013 adopted similar testing method; tested 16 samples, 2 in. (51 mm), collected from four manufacturers and five manufacturing facilities. The results suggest decrease in thermal performance as the temperature deviate from mean reference temperature of 75^0F (23.9˚C), the mean temperature used for label R-value tests [9]. The relationship between temperature and R-value is non-linear so the mean temperature R-value tests cannot easily be used to predict in-service performance. Study suggested using thicker layers of polyiso insulation for better performance, and hybrid insulation approach for cold climate conditions [9].

Thermal resistance of polyiso insulation materials is influenced by temperature variations of the exterior environmental conditions. The manufacturers and literature published values are representing laboratory testing conditions. The actual temperature variations in real climate conditions immensely influence the performance of thermal insulation. ASTM C518 [15] and

ASTM C1058 [16] recommend R-value test to be conducted at different mean temperatures with a temperature differential of 27.8˚C (50˚F) across the material surfaces. It also signifies the importance of evaluating R-value at different mean temperature and different temperature differential, to get close to real in-service temperature conditions.

Thermal resistance of polyiso insulation materials are influenced by temperature variations of the exterior environment and aging of insulation. The manufacturers and literature published values are representing laboratory testing conditions. The actual temperature and humidity variations in real climate conditions immensely influence the performance of thermal insulation. ASTM C518 and ASTM C1058 recommends R-value test to be conducted at different mean temperatures with a 27.8°C (50°F) temperature differential across the material surfaces. The standard also signifies the importance of evaluating R-value at different mean temperature and different temperature differential, to get close to real in-service temperature conditions. Moreover, literature publications suggested laboratory aging techniques for foam insulations. Singh et. al. (2007) compares the two methods, ASTM C 1303-07 and CAN/ULC-S770-03 for their suitability for use as standard test methods for accelerated aging by the polyiso and XPS insulation industry for their boardstock products [17]. However, this paper considers obsolete accelerated aging test method CAN/CGSB-51.5-92, using elevated temperatures for accelerated aging (28 days at 100˚C for PUR/PIR, phenolic and SPF, and 70˚C for XPS) [3].

2.1 Research Objective

This research aims to investigate the effect of in-service boundary temperature on the thermal performance of polyiso foam insulation used in different low-slope roof assemblies in Canadian climates.

2.2 Organization of Thesis

This thesis focuses on thermal performance of polyisocyanurate (polyiso) foam insulation under different Canadian climates. The first chapter provides an introduction to the properties of polyiso and the significance of this insulation to the research field. In chapter 2, a review of material properties is provided, including discussion on how to improve thermal performance of polyiso insulation and advancements made in this field. In chapter 3, experimental work and hygrothermal simulations methodology is explained. In chapter 4, results obtained from experimental work and hygrothermal simulation are presented and analyzed. In chapter 5, a summery of the work in this thesis and closing remarks –including suggestions for future work are provided.

Chapter 3 Research Methodology

The thermal performance of the polyiso insulation in roof constructions under different climatic conditions is dependent on the system composition, thermal and moisture characteristics of involving materials. Temperature data is difficult, time consuming and expensive to collect from field constructions. However, similar information can be easily derived through numerical simulations of hygrothermal response of building envelopes.

Hygrothermal simulations and laboratory thermal conductivity measurements were taken to determine possible extreme in-situ boundary temperature conditions for building envelopes with polyiso foam insulation rigid board in various Canadian climates. WUFI® Pro hygrothermal simulation software was used to establish in-service boundary temperature conditions to which polyiso foam insulation would be exposed in extreme Canadian climatic conditions. WUFI® is an acronym for Wärme Und Feuchte Instationär – which when translated, means heat and moisture transiency [18]. WUFI® Pro is the standard program for evaluating temperature conditions in building envelopes under real climate conditions considering built-in moisture, driving rain, solar radiation, long-wave radiation, capillary transport, and summer condensation [19].

Thermal conductivity of closed-cell foam insulations changes with mean temperature. In order to identify the effect of temperature, new and aged polyiso foam board insulation samples were tested in the laboratory at different mean temperatures, using a standard heat flow meter apparatus.

This research work reviews literature and experimental data defining the temperature dependency of thermal resistance of polyiso foam board insulation. Furthermore, hygrothermal simulations were used to predict in-service boundary temperature across roof insulation under different Canadian climate zones. The analysis between experimental data and hygrothermal simulations was used to predict the extent to which R-value decline from room mean temperature R-value at 22°C. Figure 1 demonstrates research methodology flow chart and details mentioned above.

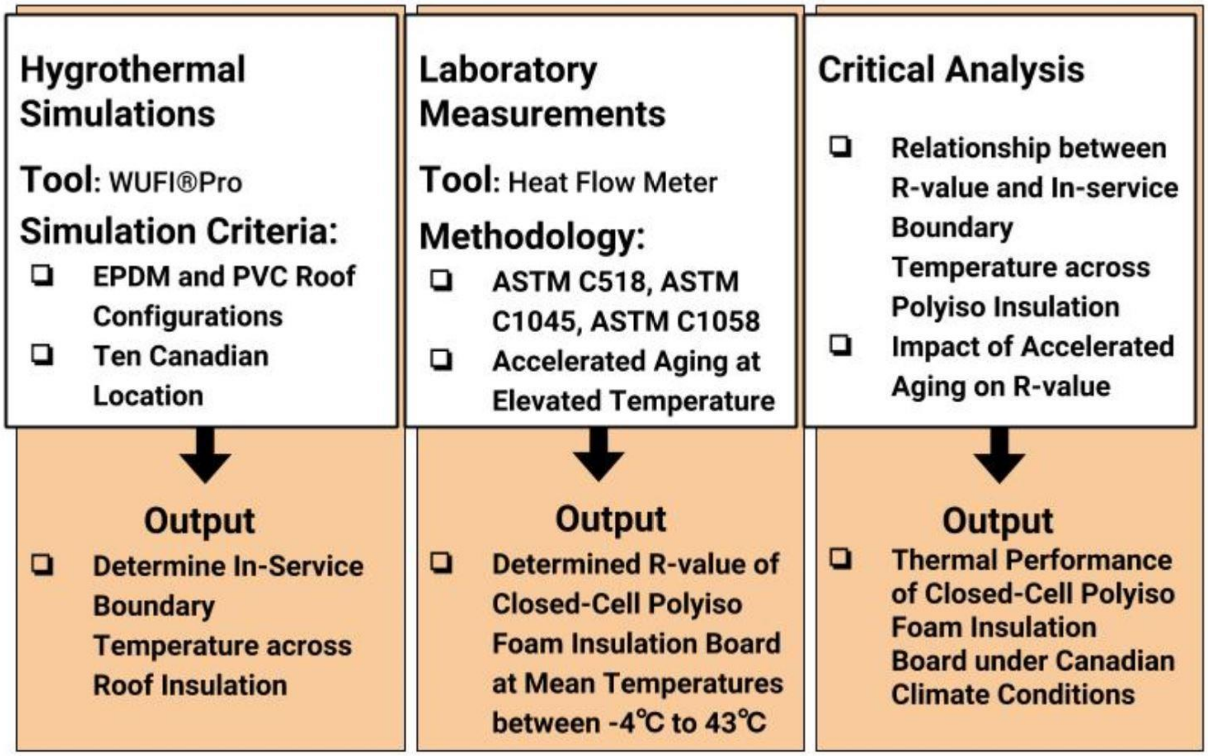

Figure 1 Flow chart showing research methodology

3.1 Canadian Climate Zones

According to National Energy Building Code (NECB 2015), Canadian climate is divided into six different climate zones. See Table 1, each zone represents specific climate conditions from moderate cold to severe cold based on heating degree days.

Table 1 Canadian climate zones based on heating degree days (NECB 2015) [20]

Climate Zones (NECB 2015)	Heating Degree Days
4	<3000
5	3000-3999
6	4000-4999
7A	5000-5999
7B	6000-6999
8	≥7000

Heating degree days, termed as HDD are the number of days when a day's average temperature is below 65°F (18°C); the temperature below which buildings need to be heated [21]. Base temperature (T_b) or inside temperature usually taken as 65°F (18° C). Average temperature (T_a) is the average of hourly temperatures is calculated as

$$T_a = \frac{T_{max} + T_{min}}{2} \text{ and, } HDD = (T_b - T_a) \text{ ...Equation 2 Heating Degree Day (HDD) Calculation}$$

where, T_{max} = Maximum temperature in a single day

T_{min} = Minimum temperature in a single day

T_a = Average hourly temperature below 65°F (18°C), and

T_b = Base temperature or inside temperature usually taken as 65°F (18°C)

Table 2 shows selected ten Canadian cities and corresponding outdoor temperature conditions reported in WUFI® Pro software database.

Table 2 Climate data for selected Canadian locations [19]

City (Province)	HDD	Climate Zone	Max T(°C)	Min T(°C)	Mean T(°C)
Vancouver (BC)	2825	4	27.2	-11.1	9.1
Toronto (ON)	3520	5	32.8	-23.3	6.7
Saint John (NB)	4570	6	26.7	-22.2	3.7
Calgary (AB)	5000	6	30.6	-36.7	2.5
Edmonton (AB)	5120	7A	28.0	-36.0	1.9
Saskatoon (SK)	5700	7A	34.9	-38.1	2.3
Fort McMurray (AB)	6250	7B	34.8	-37.2	1.2
Whitehorse (YT)	6580	7B	28.9	-48.9	-1.0
Yellowknife (NT)	8170	8	27.8	-42.8	-4.5
Inuvik (NT)	9600	8	28.0	-47.2	-9.2

3.2 Low Slope Roof Configurations

Selection of roof configuration is very critical for the overall performance. Roof assemblies are divided into two categories: a) low slope roofs, and b) steep slop roofing assemblies [22]. Based on type of membranes used in low slope roof assemblies EPDM (Figure 2) and PVC membrane roof (Figure 3) were selected for hygrothermal simulations. See Appendix A for detailed material properties of EPDM and PVC membrane roofs.

I. EPDM membrane roof: It is composed of 1.52-mm thick EPDM membrane, a 12.5-mm thick oriented strand board (OSB), a 114.3-mm thick polyiso insulation, a 1-mm thick vapour retarder, a 15-mm thick plywood board and a 0.8-mm thick perforated metal deck with a total RSI-value of 5.03 m²K/W (R-28.56).

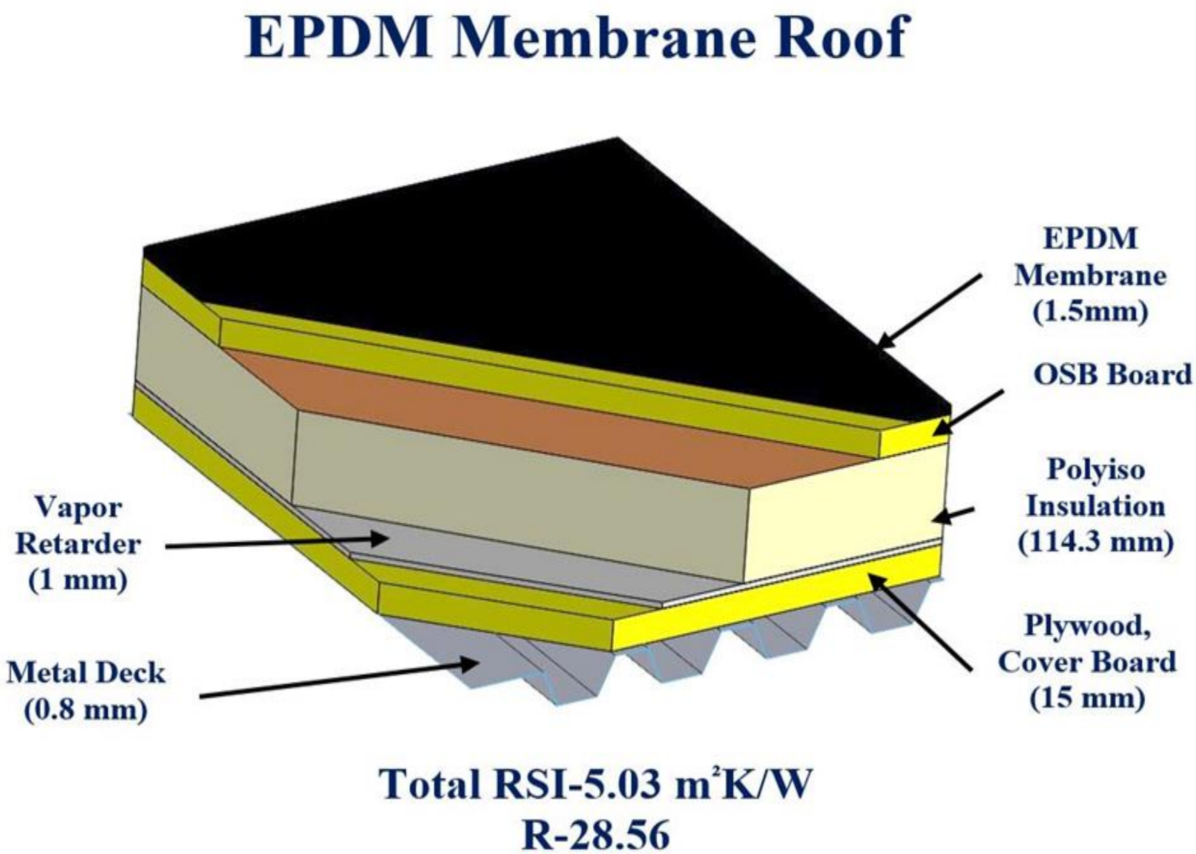

Figure 2 EPDM membrane roof Edited for demonstration; copyright CRCA Roofing Specifications Manual 2011 [22]

II. PVC membrane roof: It is composed of 1.52-mm thick PVC membrane, a 12.5-mm thick oriented strand board (OSB), a 114.3-mm thick polyiso insulation, a 1-mm thick vapour retarder, a 15-mm thick plywood board and a 0.8-mm thick perforated metal deck with a total RSI-value of 5.03 m²K/W (R-28.56).

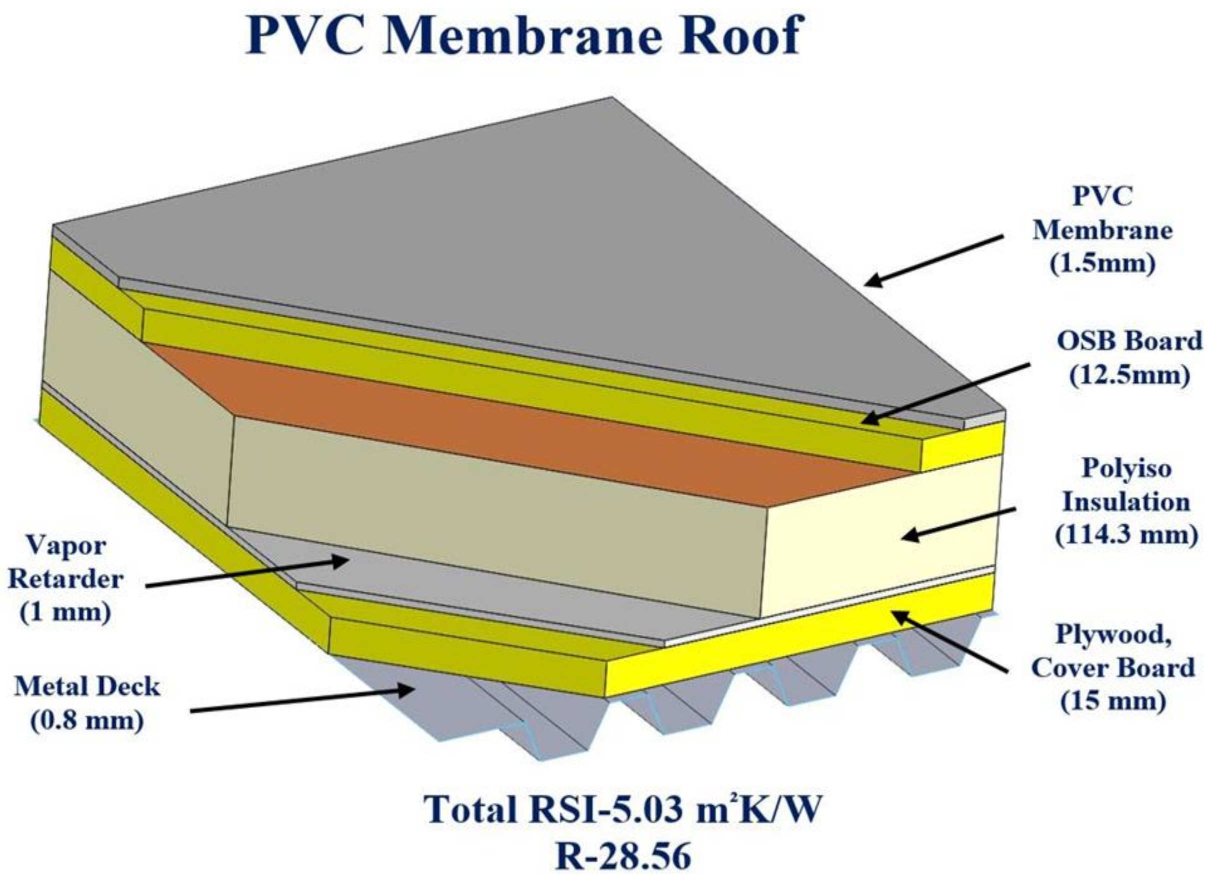

Figure 3 PVC membrane roof, Edited for demonstration; copyright CRCA Roofing Specifications Manual 2011 [22]

3.3 Hygrothermal Simulations

Hygrothermal simulations were performed using WUFI® Pro software package to assess the in-service boundary temperature conditions experienced by polyiso insulation used in EPDM membrane and PVC membrane roof assemblies when exposed to Canadian climatic conditions. The investigated roof assemblies are common low slope roof assemblies widely used in Canada. For each climate, the same roof configuration was selected, while the overall target was to keep the thermal resistance of whole assembly to 5.03 m^2K/W, according to recent building code requirements [23]**.**

To calculate in-service boundary conditions across roof assembly hygrothermal simulations consider local weather conditions of each city. Vancouver (BC), Edmonton (AB), Calgary (AB), Toronto (ON), and Saint John (NB) weather data was taken from WUFI® Pro software database.

However, weather data of Saskatoon (SK), Fort McMurray (AB), Whitehorse (YT), Yellowknife (NT), and Inuvik (NT) was taken from EnergyPlus software database [24].

Hygrothermal simulations performed under initial 80% relative humidity and 20°C initial component temperature. However, the building interior temperature was considered at 21°C as per ASHRAE 160 standard. The flat roof assemblies were considered 5° inclined to effectively drain water [4]. Hygrothermal simulations were performed for ten years' period starting from 01/01/2018 to 31/12/2027 to get the best possible results. Appendix B and C contain information related to hygrothermal simulation setup in WUFI® Pro software and WUFI® Graph output files.

3.4 Laboratory Measurements

Thermal conductivity measurements of polyiso insulation of standard size of 11.8×11.8 inch (300×300 mm) and three different nominal thickness of 1 inch (25mm), 2 inch (51mm), and 3 inch (76mm) were taken at -4, 4.5, 10, 24, 43°C mean temperatures and at a temperature difference of 28°C as per ASTM C1058 "Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation" [16]. Moreover, literature publications suggested laboratory aging techniques for foam insulations. Initially, as outlined in CAN/CGSB-51.5-92, prolonged elevated temperature condition was used to accelerate the aging of closed cell foam insulation with captive blowing agents (28 days at 100˚C for PUR/PIR, phenolic and SPF, and 70˚C for XPS) [3]. In this study, polyiso insulation was accelerated aged at elevated temperature in oven for 28 days at 100°C and similar thermal conductivity measurements were conducted for aged polyiso insulation samples.

Heat flow meter model NETZSCH-HFM436/Lambda was used, which determine thermal conductivity as ASTM C518 "Standard Test Method for Steady-State Thermal Transmission Properties by Mean of the Heat Flow Meter Apparatus" [15]. The sample size of thickness between 0.2 inch (5mm) to 3.9 inch (100mm) is placed in the testing chamber of heat flow meter, where temperature is maintained by two plates during the testing process. Appendix D demonstrates heat flow meter and polyiso insulation sample tested in laboratory. The thermal conductivity values were taken after achieving a constant temperature gradient throughout the sample. Q-Lab PC software controls the input and output data of heat flow meter during experiment. The heat flow meter was calibrated with a reference standard specimen before actual polyiso insulation testing to eliminate error during measurements. Table 3 reports the polyiso insulation board samples investigated during this experimental work.

Table 3 Polyiso insulation samples investigated in building science laboratory

Sample	Material (Condition)	Thickness Inch(mm)
$Polyiso_A$	Fiberglass Facer (new)	1" (25)
$Polyiso_B$	Fiberglass Facer (new)	2" (51)
$Polyiso_C$	Paper Facer (Warehouse Aged)	2" (51)
$Polyiso_D$	Paper Facer (Warehouse Aged)	3" (76)

Chapter 4 Results and Analysis

4.1 In-service boundary temperature

Hygrothermal simulation data was then analyzed by means of WUFI® Graph. This evaluation tool provides users the capability to plot simulation results at different thicknesses of polyiso insulation in a specific roof assembly. For better understanding, polyiso insulation used in roof assemblies was considered as composed of three equal layers of same thickness (named exterior, middle and interior layer) to determine in-service boundary temperature conditions across each layer. Appendix E represents in-service boundary temperature across polyiso insulation in Canadian climatic conditions.

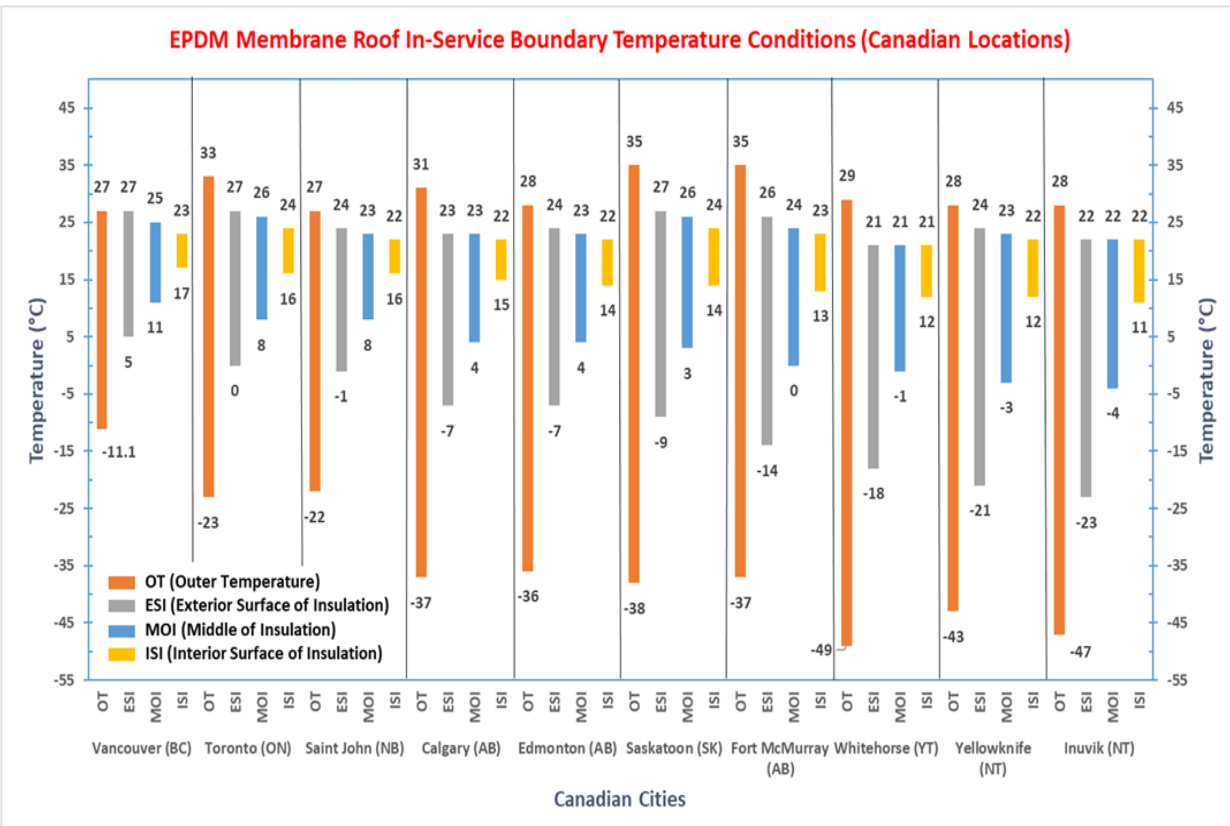

Figure 4 In-service boundary temperature conditions for EPDM membrane roof

It is evident from analysis that the temperature across polyiso insulation thickness varies linearly with temperature in selected ten Canadian locations. Polyiso insulation was subjected to cyclic loading of varying temperature conditions due to weather fluctuations based on specific location. During summer season, the outside temperature is more than the interior temperature of building envelope. Thus, due to temperature differential, heat flow occurs from outside to inside. Similarly, during winter season the heat flows in opposite direction. In both scenarios, the polyiso insulation was subjected to changes in boundary temperature conditions, thus influencing the thermal performance of insulation.

See Figure 4, it shows maximum and minimum in-service boundary temperature experienced by polyiso insulation in a particular year. The outdoor temperature variation ranges from -49°C to +35°C in selected Canadian locations. However, polyiso insulation experienced temperature variation from -23°C to +27°C. The exterior layer of insulation i.e. closer to outer environment experienced extreme cold temperatures during winters. However, the middle and interior layers of insulation experienced above 0°C temperature most of the time in a year.

Due to the fluctuating outer environmental conditions, the simulated in-service boundary temperature of polyiso insulation for each city was different. In Vancouver and Toronto, insulation experienced above 0°C temperature. However, in all other investigated cities, insulation was subjected to sub-zero temperatures during winters. However, during summer time, for all investigated cities, roof insulation in-service boundary temperatures ranges between +24°C to +27°C.

4.2 Thermal Conductivity and R-value measurements

The thermal conductivity measurements of four different size polyiso insulation samples were investigated as per ASTM C518, ASTM C1058 and ASTM C1045 standards. ASTM C1058 explains the importance of calculating thermal conductivity at more than one mean temperature [16]. Moreover, ASTM C1045 explains the thermal conductivity integral (TCI) method to calculate thermal conductivity value at particular mean temperature lies between calculated mean temperature thermal conductivity values [25]. See Appendix F for detailed explanation of TCI method .

Table 4 Laboratory measured R-value per inch data for selected polyiso samples

Sample	Mean Temperature (˚C) (ΔT =28˚C)	Experimental Data [R-value per inch]				
		Without Aging	Aged - 7 Days	Aged - 14 Days	Aged - 21 Days	Aged - 28 Days
A	-4	4.94	4.70	4.77	5.23	5.20
	4.5	5.24	5.05	5.07	5.24	5.07
	10	5.36	5.20	5.21	5.17	4.95
	24	5.18	5.22	5.17	4.87	4.66
	43	4.69	4.76	4.70	4.39	4.23
B	-4	5.39	4.82	4.78	4.58	4.62
	4.5	5.80	5.29	5.19	5.04	5.01
	10	5.90	5.49	5.40	5.28	5.23
	24	5.75	5.56	5.49	5.39	5.24
	43	5.08	5.10	4.92	4.89	4.73
C	-4	5.40	4.76	4.66	4.63	4.60
	4.5	5.85	5.28	5.19	5.01	5.05
	10	5.95	5.55	5.42	5.26	5.22
	24	5.82	5.69	5.54	5.39	5.19
	43	5.08	5.12	5.06	4.87	4.55
D	-4	5.45	4.88	4.59	4.43	4.29
	4.5	5.82	5.47	5.10	4.94	4.85
	10	5.92	5.56	5.40	5.26	5.16
	24	5.72	5.59	5.66	5.54	5.34
	43	4.89	5.07	5.06	4.94	4.84

Laboratory measured thermal conductivity values were used to determine R-value/inch for each investigated sample. Furthermore, R-value/inch data was extrapolated to -20°C from -4°C mean temperature. Figure 5-Figure 8, represents relationship between R-value/inch and mean temperature corresponding to each investigated sample. It is evident from results that thermal resistance of closed-cell polyiso foam insulation shows non-linear temperature dependency behaviour in all investigated samples.

See Figure 5, sample $Polyiso_{A}$ revealed non-linear temperature dependency between temperature range of -4°C to +43°C. R-value/inch varies almost linearly between temperature range of +12°C to +43°C being higher value at +12°C and lower value at +43°C. However, dip in R-value/inch was evident when mean temperature drops below +12°C. See Figure 6-Figure 8, $Polyiso_{B}$, $Polyiso_{C}$, and $Polyiso_{D}$ samples revealed almost similar R-value/inch temperature dependency as exhibit by $Polyiso_{A}$ sample. However, the effect of accelerated aging at elevated temperatures is different for each investigated sample. It is prominent in $Polyiso_{A}$ insulation sample. It is also evident from Figure 5 that the R-value/inch exhibited almost linear temperature dependency with temperature after 28 days of accelerated aging at 100°C. However, for $Polyiso_{B}$, $Polyiso_{C}$, and $Polyiso_{D}$, R-value/inch calculated at -4°C after 28 days of accelerated aging at 100°C shows slight signs of upward trend (increase instead of decrease in R-value/inch).

Thermal conductivity integral (TCI) method was used to extrapolate data from calculated thermal conductivity values at five mean temperatures. Since TCI method uses third degree polynomial equation, it gives slightly variable R-value/inch than actual laboratory measured R-value/inch at five selected mean temperatures. See Figure 5, R-value/inch ($Polyiso_{A\text{-}TCI}$) at -4°C is 2.5% higher than R-value/inch ($Polyiso_{LAB}$) and 0.3% lower at +43°C. Moreover, this variation reduces to 0.6% (higher) and 0.1% (lower) at -4°C and +43°C respectively.

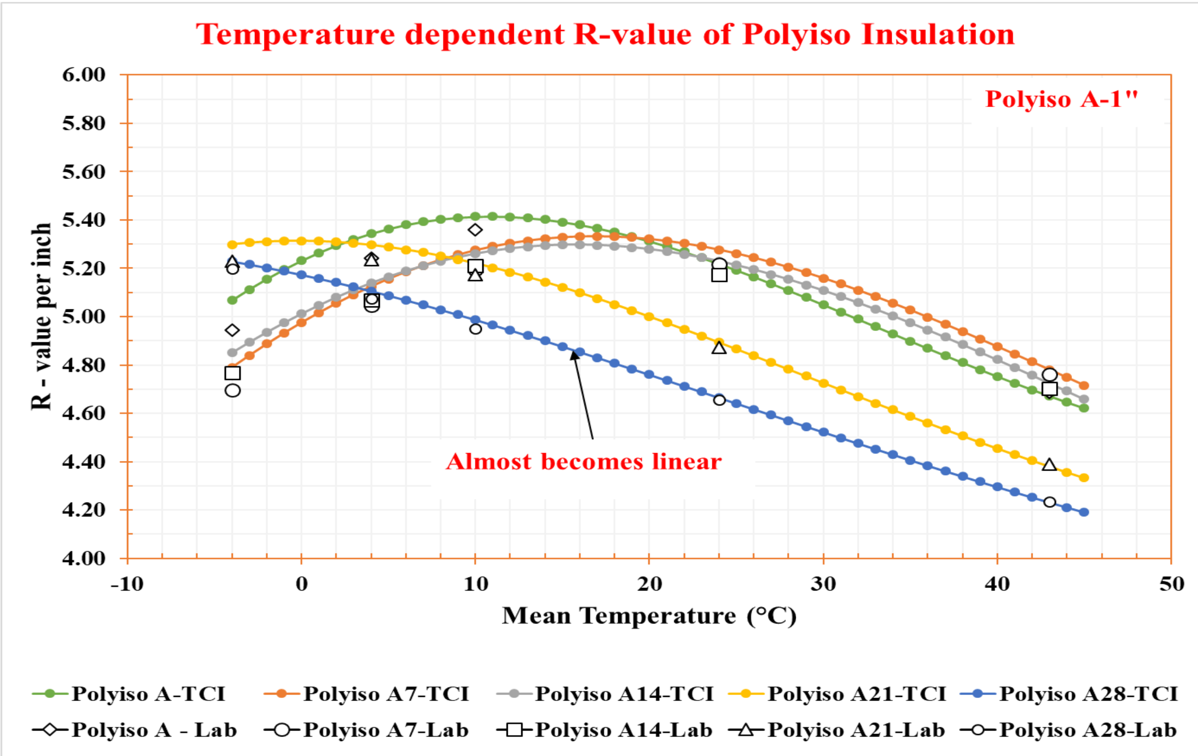

Figure 5 R-values of Polyiso$_A$ at different mean temperatures

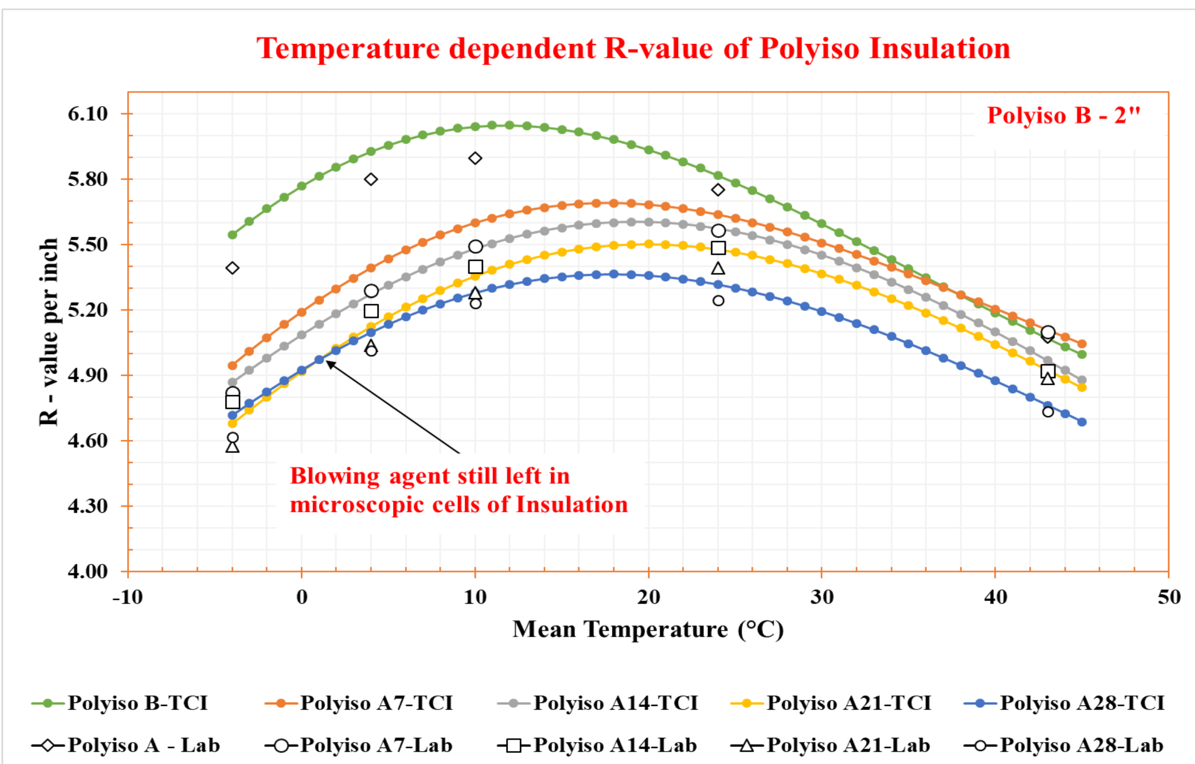

Figure 6 R-values of Polyiso$_B$ at different mean temperatures

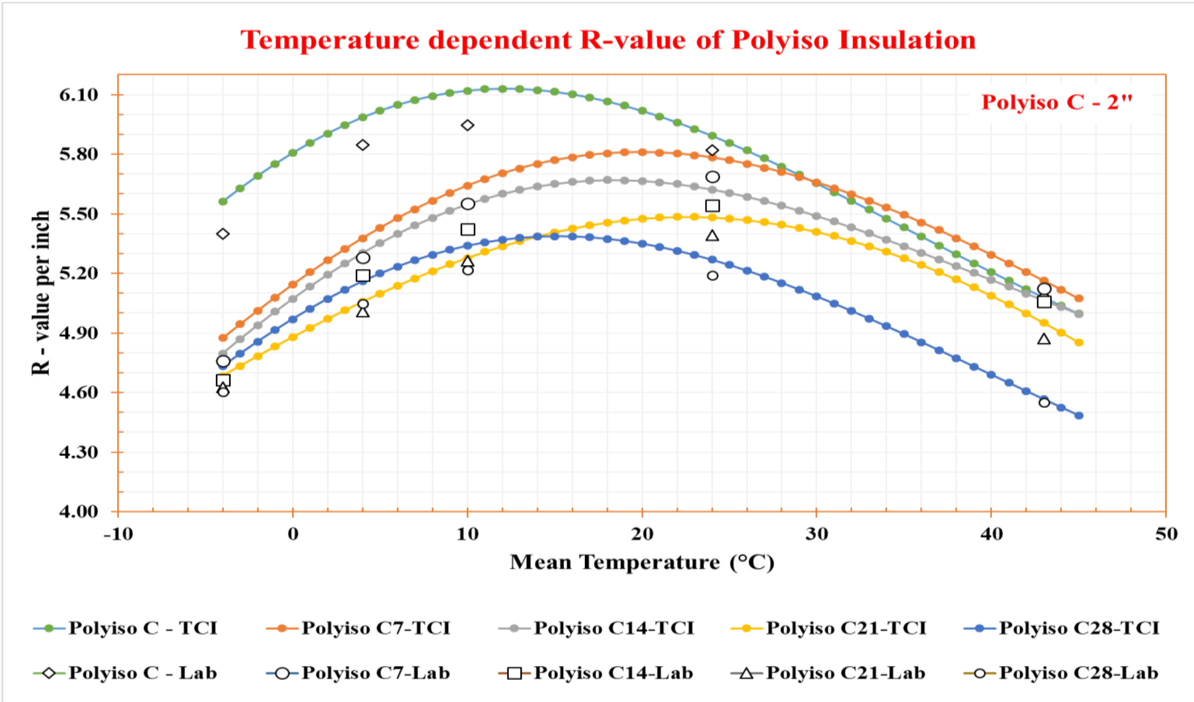

Figure 7 R-values of Polyiso$_C$ at different mean temperatures

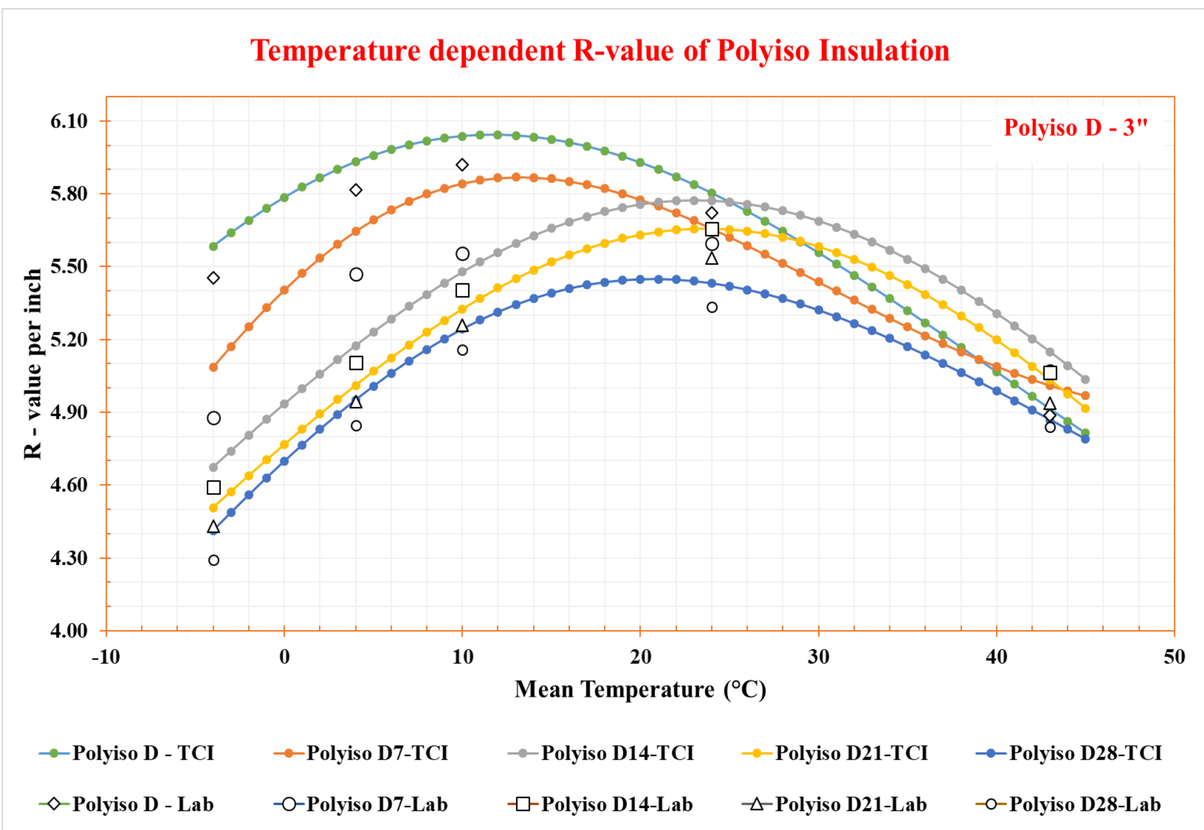

Figure 8 R-values of Polyiso$_D$ at different mean temperatures

4.3 Relationship between Thermal resistance and in-service boundary temperature

The analysis was based on considering the following technical details:

1. Hygrothermal simulation software (WUFI® Pro) consider linear temperature dependent R-value written with suffix WUFI in graphs.
2. Laboratory measured thermal conductivity data was used to calculate actual R-value/inch of polyiso foam insulation at different mean temperature for each sample investigated in this study.
3. R-value/inch data (from laboratory measurements & WUFI® Pro database) was normalized with R-value/inch at mean temperature of 22°C ($R_{T22°C}$), corresponding to each sample
4. In this study in-service boundary temperature of exterior insulation layer was taken into account for analyzing thermal performance of polyiso insulation.
5. For analysis, two seasons winter (October-March) and summer (May-September) were considered.

Figure 9 shows percentage variation of R-value from R-value at 22°C mean temperature ($R_{T22°C}$). The values above zero specify percentage increase in R-value from $R_{T22°C}$. However, values below zero indicate percentage decrease in R-value from $R_{T22°C}$. The laboratory measured data of samples $Polyiso_{A-D}$ revealed percentage decrease in R-value when insulation was subjected to sub-zero temperatures and temperatures higher than 22°C. It is evident from data that at -4°C, R-value of $Polyiso_{A-D}$ decreased from $R_{T22°C}$ between 4% to 7%. However, at 43°C, insulation R-value decreased by 14% to 17%. Moreover, the $Polyiso_{A-D}$ have higher R-value than $R_{T22°C}$ between mean temperature of +1°C to 22°C. Since, thermal resistance of $Polyiso_{WUFI}$ is linearly temperature dependent. Therefore, $Polyiso_{WUFI}$ have higher R-values than $R_{T22°C}$ at temperature lower than 22°C. However, at temperatures higher than 22°C, $Polyiso_{WUFI}$ reveal almost same R-value variation as demonstrated by laboratory measured R-value data of $Polyiso_{A-D}$.

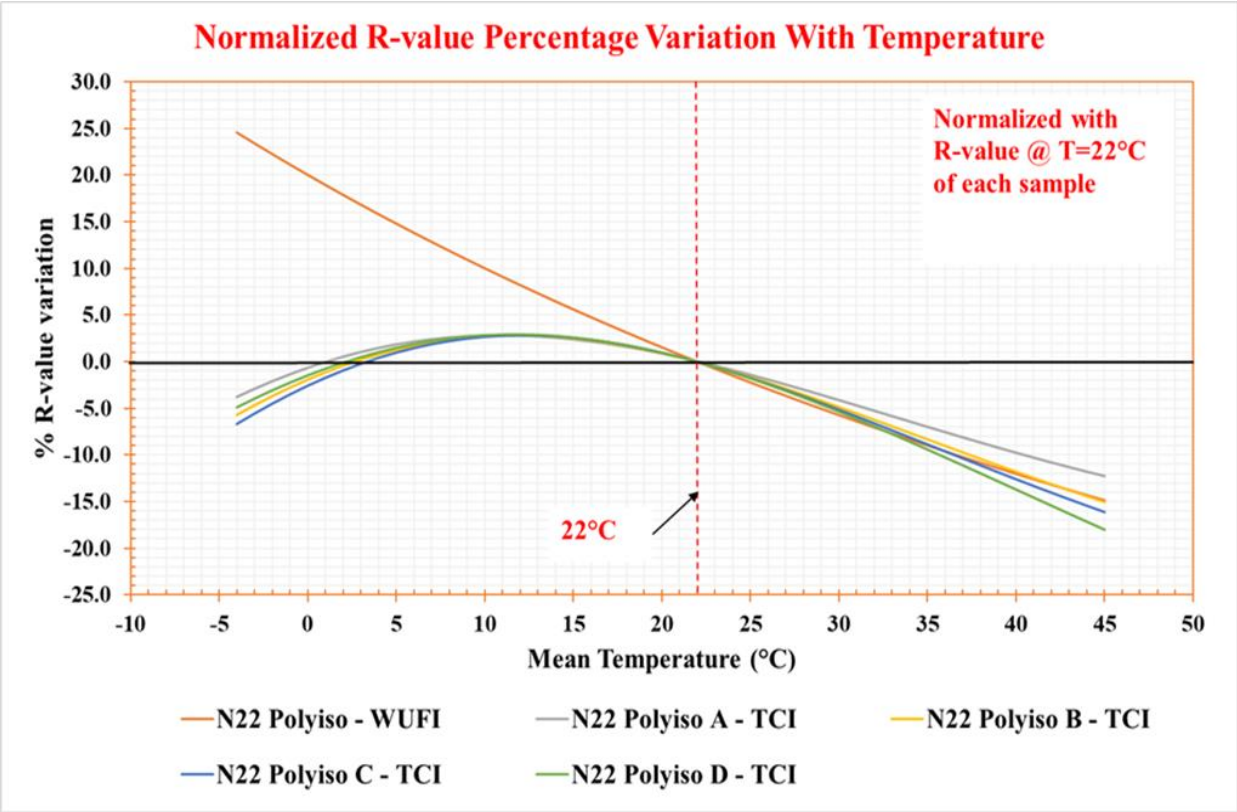

Figure 9 Normalized R-value variation with temperature (°C)

4.3.1 R-value variation in exterior layer of polyiso insulation

Figure 10-Figure 19 shows normalized R-value variation in relation to in-service boundary temperature of exterior layer of polyiso insulation in EPDM and PVC roof assemblies determined from hygrothermal simulations of ten Canadian cities. For Vancouver, Toronto and Saint John, it is evident from hygrothermal simulations that winter in-service temperature experienced by polyiso insulation exterior layer is above sub-zero temperature for most of the time in a year.

See Figure 10-Figure 12, laboratory measured data of samples $\text{Polyiso}_{A\text{-}D}$ indicated minimum R-value variation from $R_{T22°C}$ in each month. In Vancouver (BC) climate conditions, $\text{Polyiso}_{A\text{-}D}$ data actually showed 2.1-2.4% higher R-value than $R_{T22°C}$ during winter season. However, Toronto (ON), $\text{Polyiso}_{A\text{-}D}$ data indicated 0.7% to 1.5%, and Saint John (NB), $\text{Polyiso}_{A\text{-}D}$ data indicated 0.3% to 1% higher R-value than $R_{T22°C}$ during winter season.

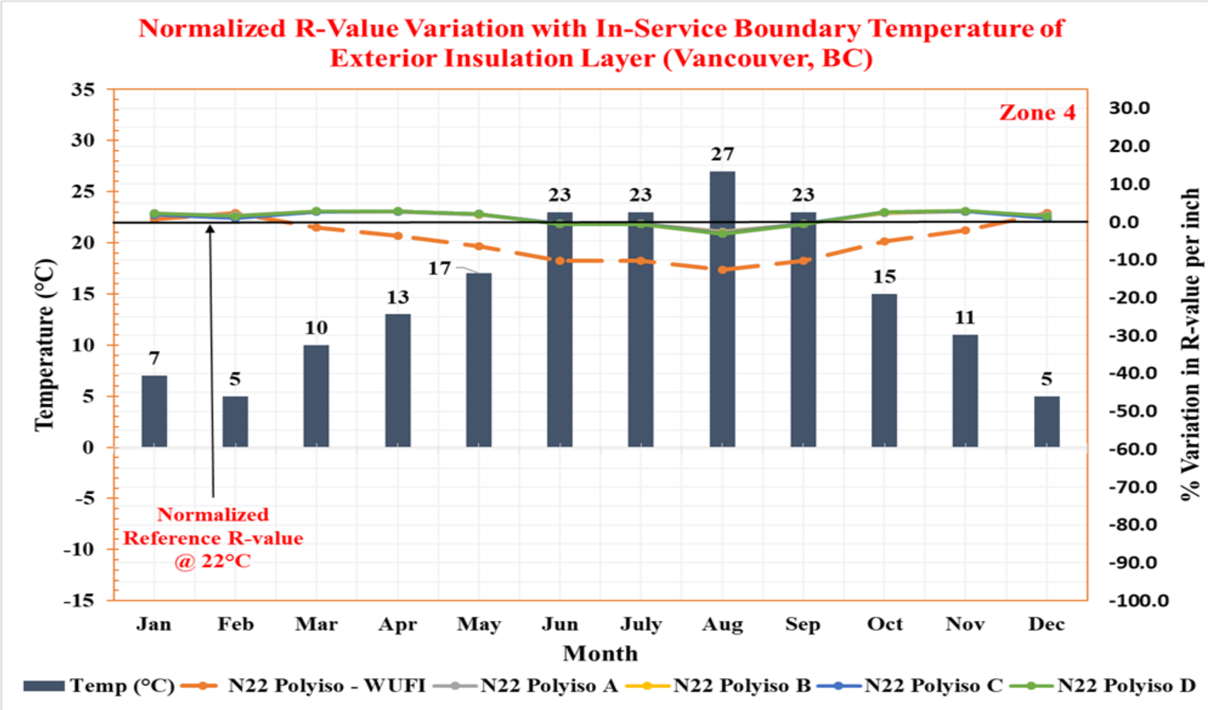

Figure 10 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Vancouver, BC)

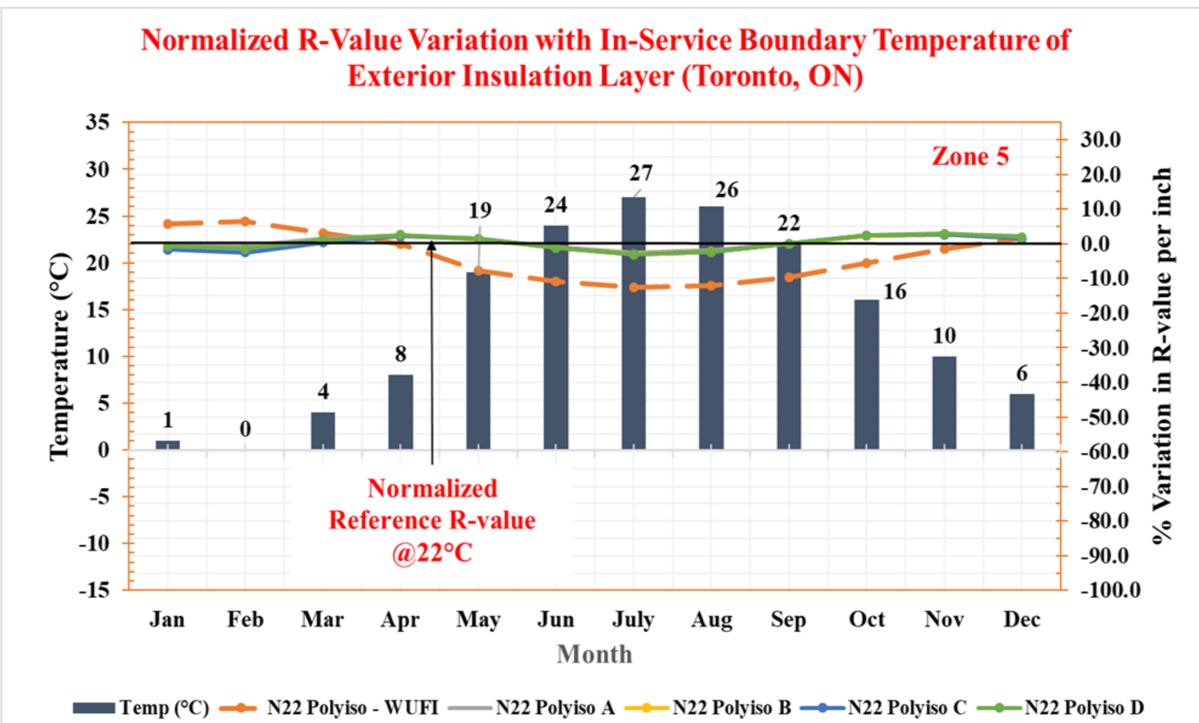

Figure 11 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Toronto, ON)

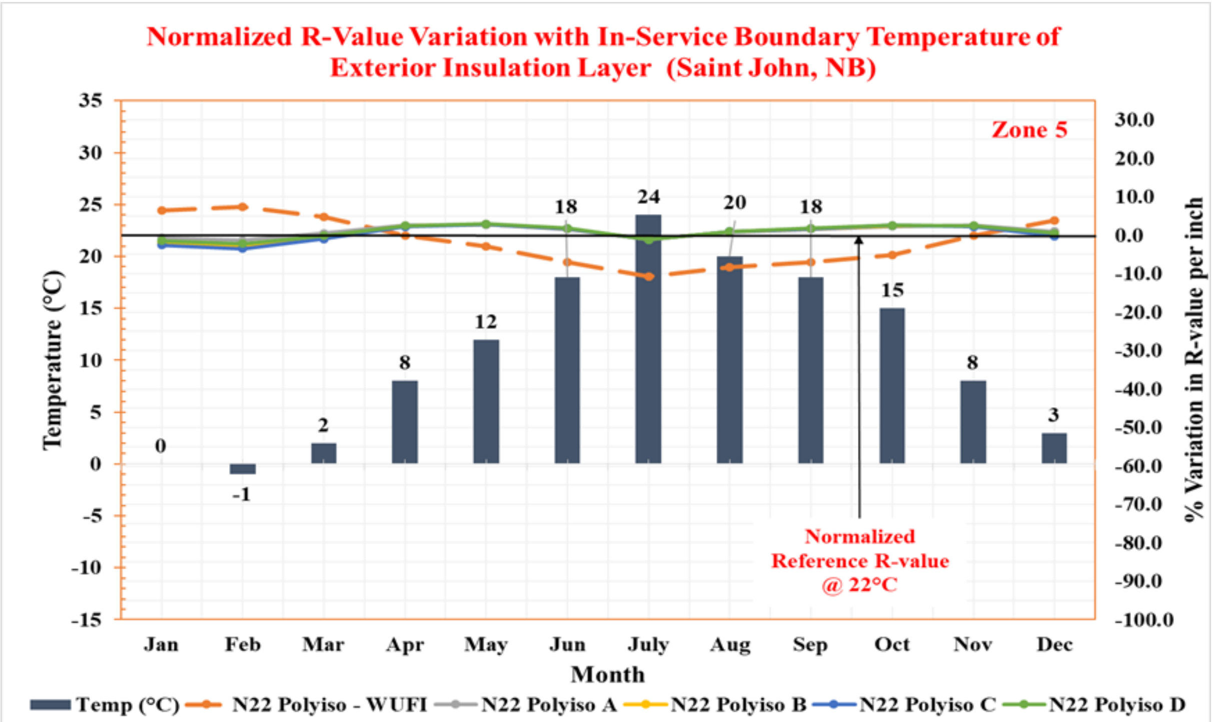

Figure 12 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Saint John, NB)

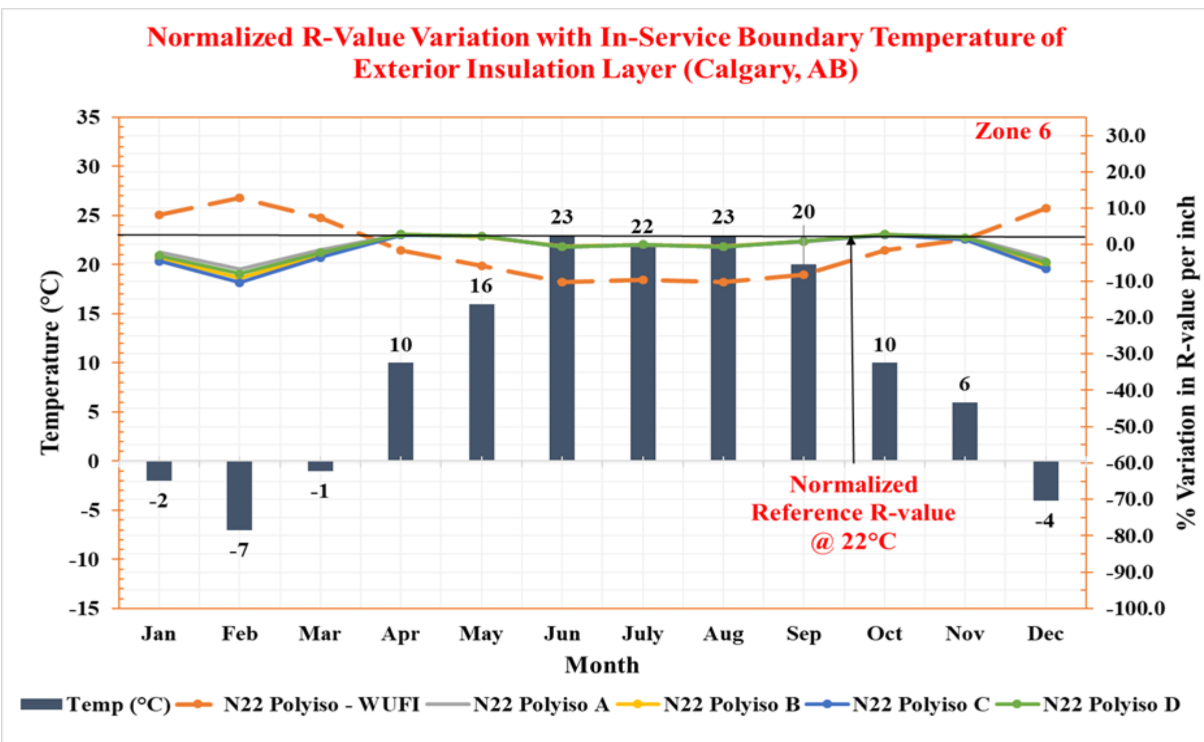

Figure 13 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Calgary, AB)

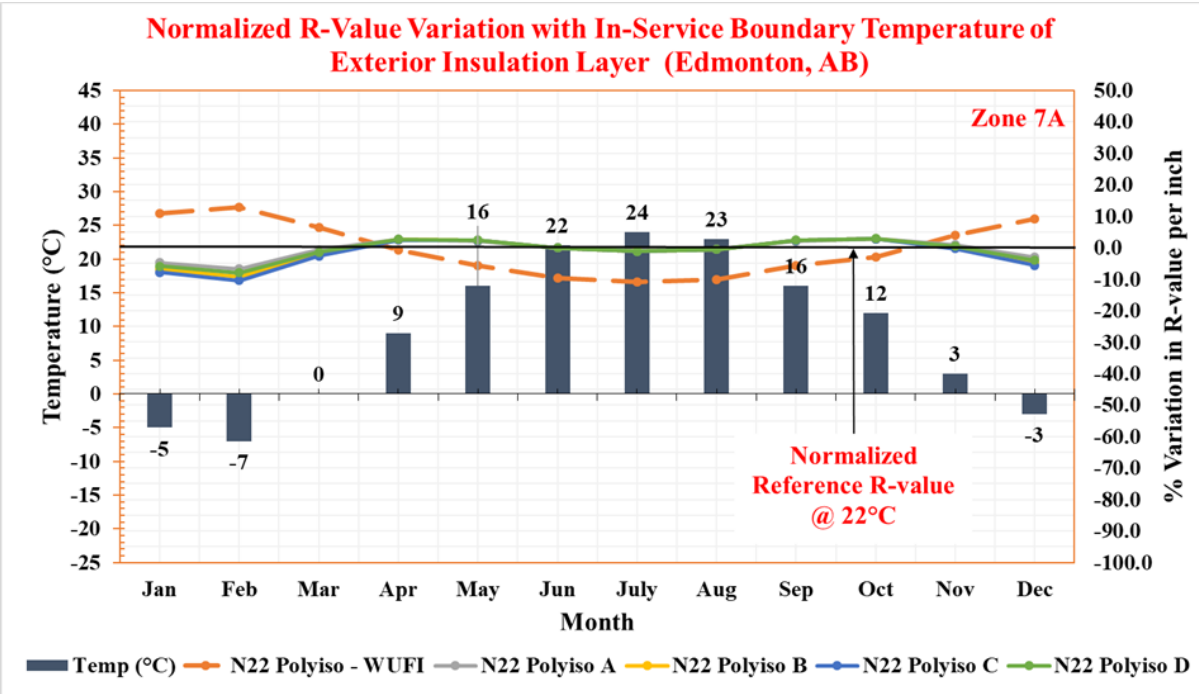

Figure 14 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Edmonton, AB)

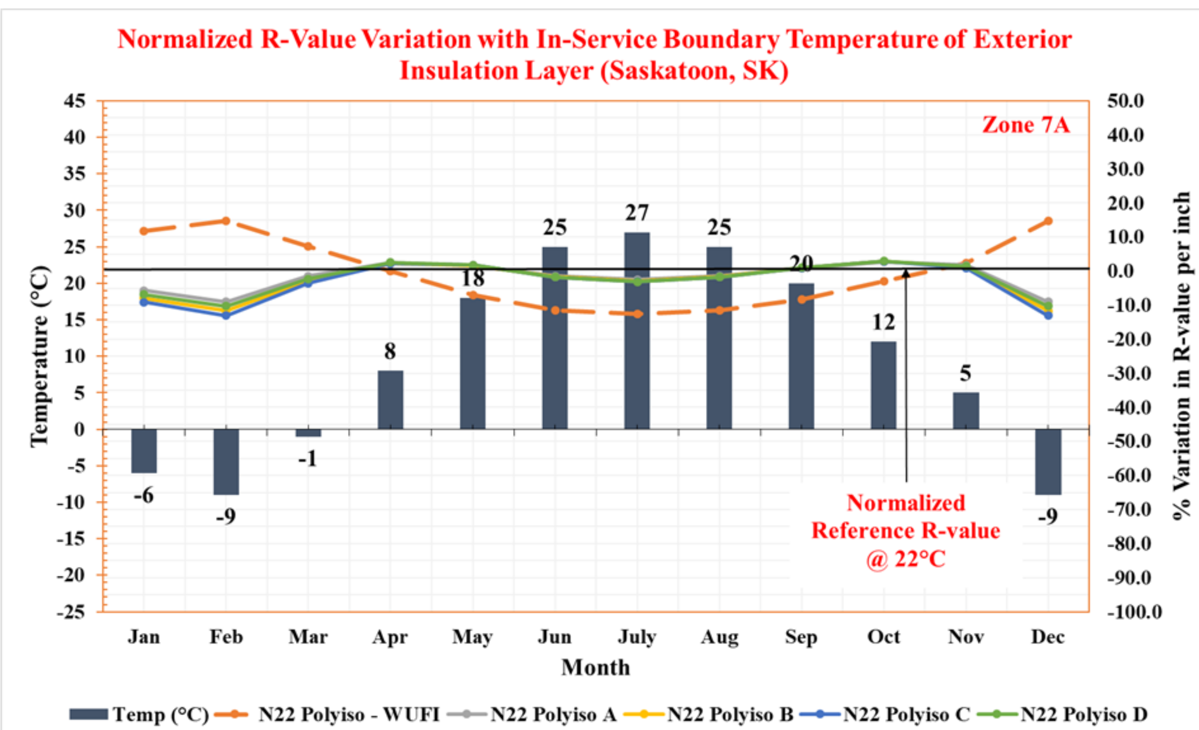

Figure 15 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Saskatoon, SK)

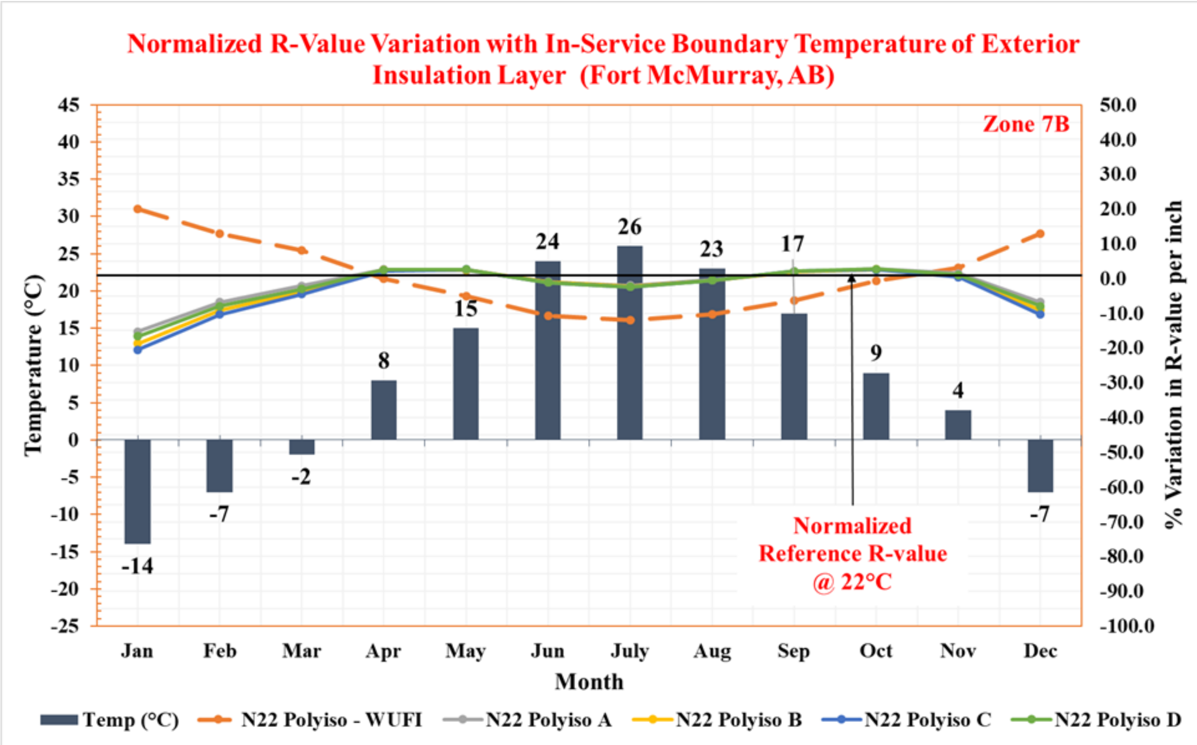

Figure 16 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Fort McMurray, AB)

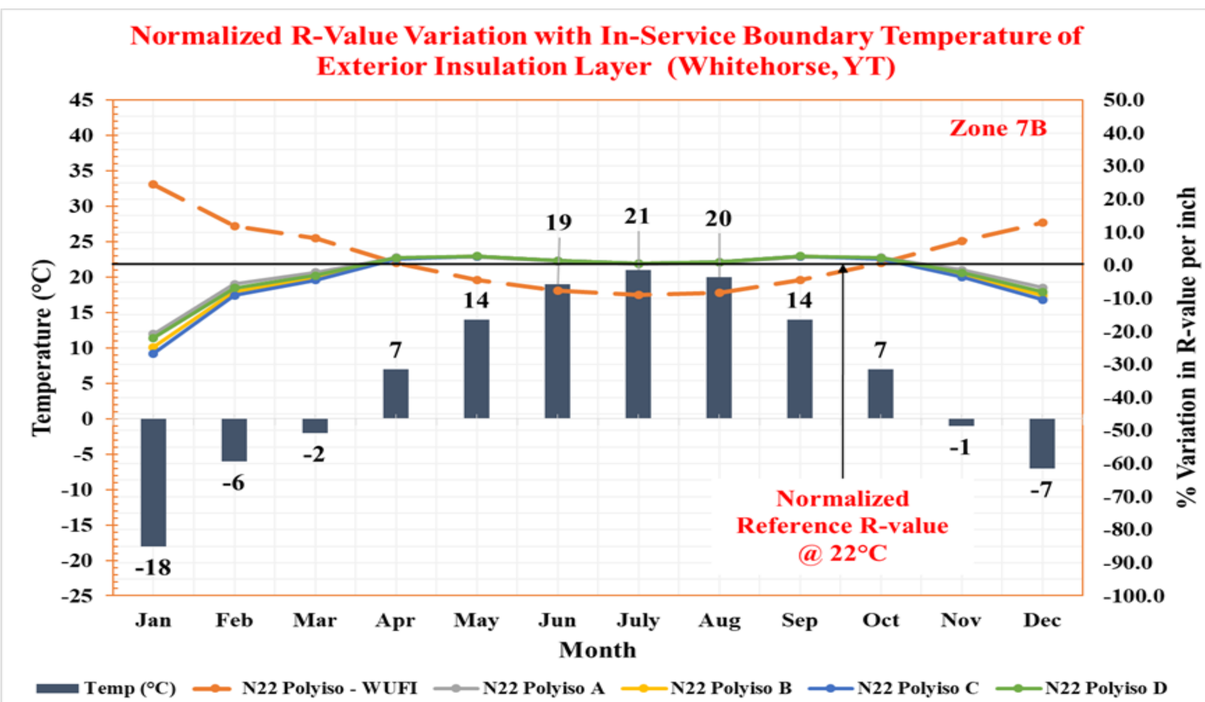

Figure 17 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Whitehorse, YT)

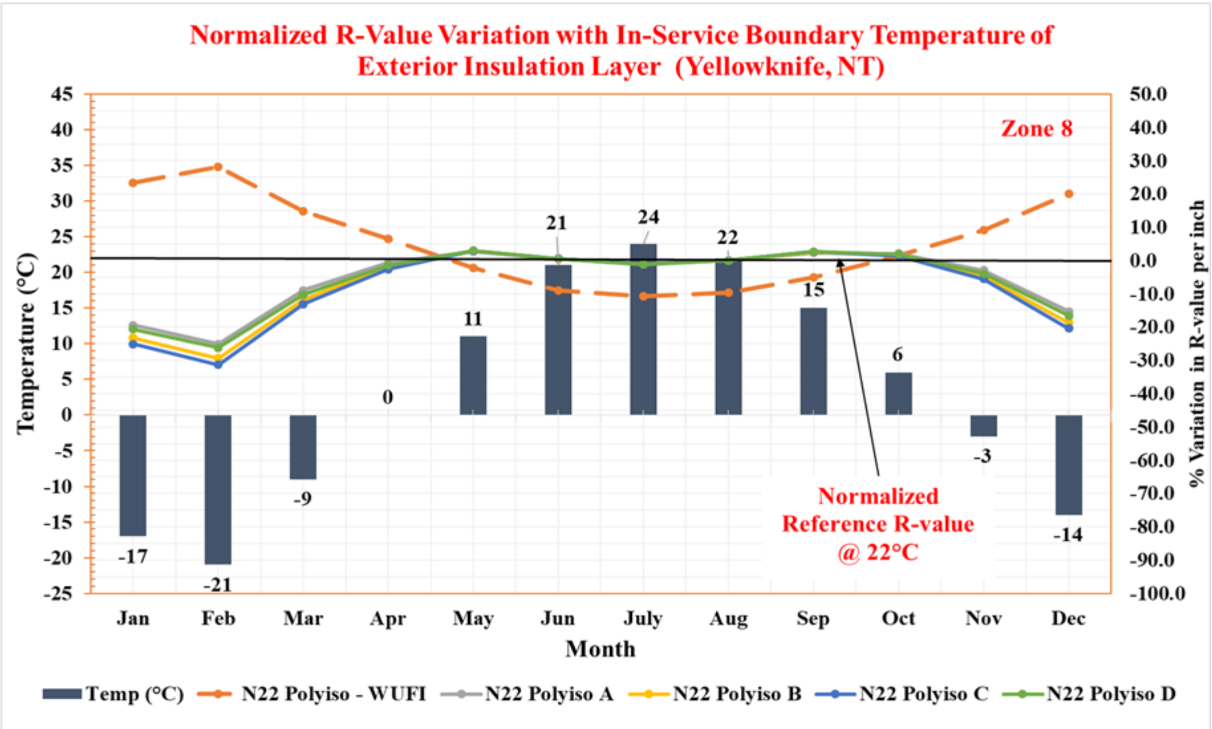

Figure 18 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Yellowknife, NT)

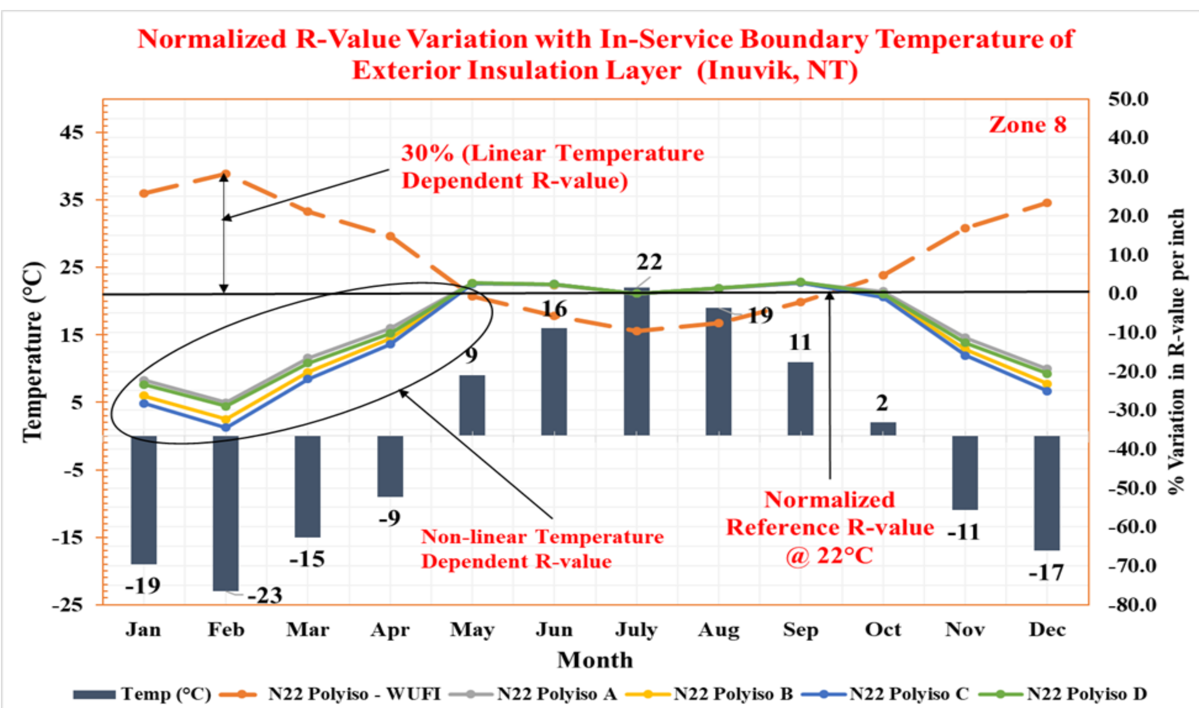

Figure 19 Normalized R-value variation with in-service boundary temperature of exterior insulation layer (Inuvik, NT)

In extreme cold climates like Whitehorse (YT), Yellowknife (NT), and Inuvik (NT), polyiso insulation exterior layer experienced -18, -21, and -23°C boundary temperature during winter season. See Figure 17-Figure 19, it is noticeable that R-value of polyiso insulation decrease drastically in winter season when temperature drops below sub-zero temperature. In winter season, considering Whitehorse (YT), Yellowknife (NT), and Inuvik (NT), $Polyiso_{A-D}$ data indicated 4.6% to 20% lower R-value than $R_{T22°C}$. From Figure 4, Inuvik (Zone 8) having extreme cold winters, outdoor temperature drops to -47°C. However, the exterior insulation layer experienced temperature close to -23°C. See Figure 19, normalized R-value data of $Polyiso_{A-D}$ anticipated maximum variation of -34% during month of February. In zone 8, during winter season, R-value of $Polyiso_{A-D}$ insulation on average decrease drastically by 17.4% from $R_{T22°C}$

In Calgary (AB), Edmonton (AB), Saskatoon (SK), and Fort McMurray (AB) $Polyiso_{A-D}$ data indicated 0.9% to 5.8% lower R-value than $R_{T22°C}$ during winter season. However, during summer season, R-value data of $Polyiso_{A-D}$ revealed variation between -1.1% to +1.9% for selected ten Canadian locations. Furthermore, $Polyiso_{WUFI}$ R-value data showed 5.2% to 10.2% lower R-values from $R_{T22°C}$ during summer season. In winter season $Polyiso_{WUFI}$ revealed R-value variation between -1% to 19.6% from $R_{T22°C}$.

4.3.2 R-value variation in middle layer of polyiso insulation

Figure 20-Figure 29 shows normalized R-value variation in relation to in-service boundary temperature of middle layer of polyiso insulation in selected roof assemblies determined from hygrothermal simulations of ten Canadian cities.

In winter season, polyiso insulation middle layer experienced temperature variation between -4°C to 18°C. See Figure 20, in Vancouver (BC), in-service boundary temperature experienced by polyiso insulation middle layer is between 11˚C to 25˚C annually. However, in winter season this variation is 11˚C-17˚C and during summer it is 19˚C -25˚C. $Polyiso_{A-D}$ data actually showed 2.4% to 2.7% higher R-value and $Polyiso_{WUFI}$ showed 6.6% higher R-values than $R_{T22°C}$ during winter season. However, for Toronto (ON), winter season in-service temperature variation is between 8˚C to 18˚C and $Polyiso_{A-D}$ and $Polyiso_{WUFI}$ indicated 2.5% to 2.7% and 8.1% R-value variation from $R_{T22°C}$ respectively. In climate zone 6, Saint John (NB), winter in-service boundary temperature experienced by polyiso insulation middle layer is between 8˚C to 17˚C resulting 2.5% to 2.7% higher R-value of $Polyiso_{A-D}$ than $R_{T22°C}$ during winter season.

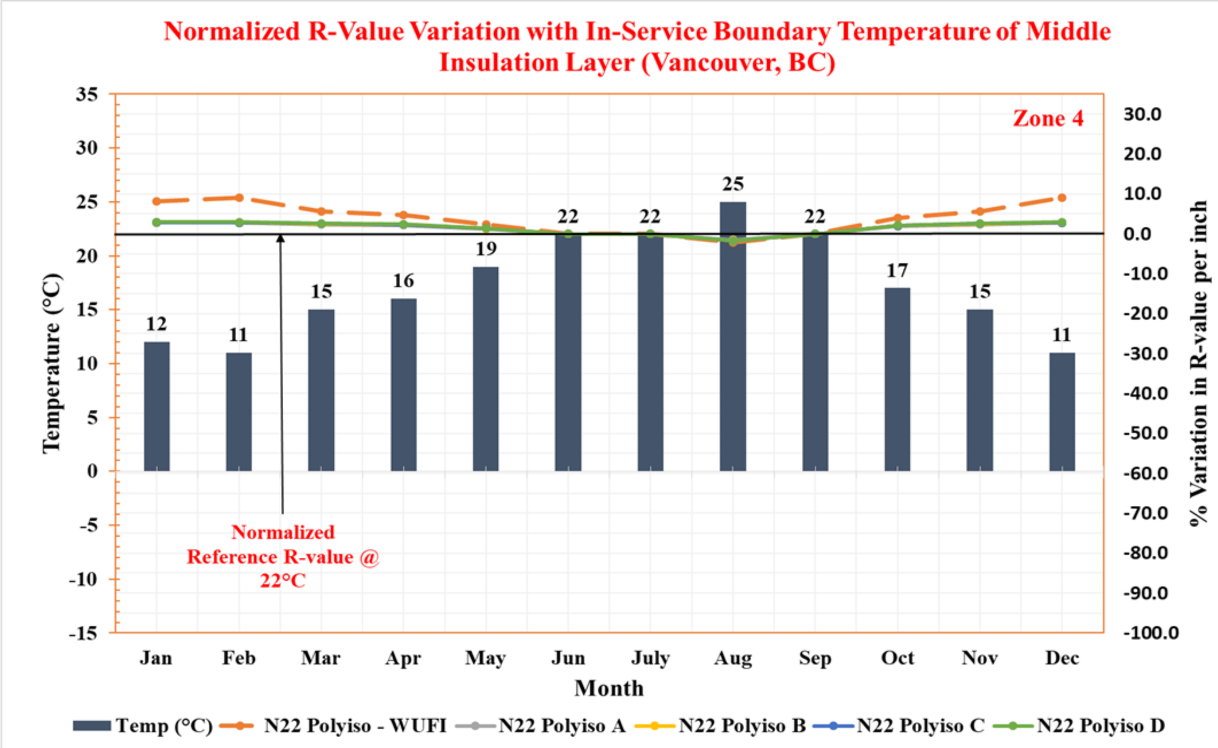

Figure 20 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Vancouver, BC)

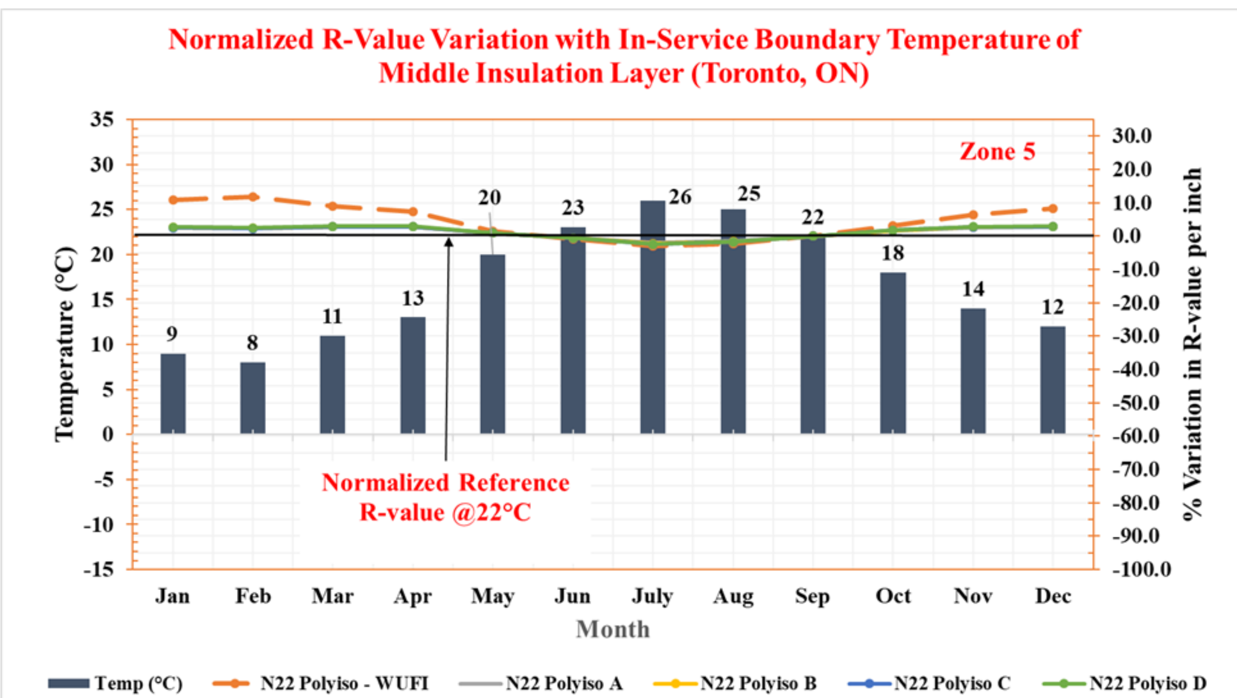

Figure 21 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Toronto, ON)

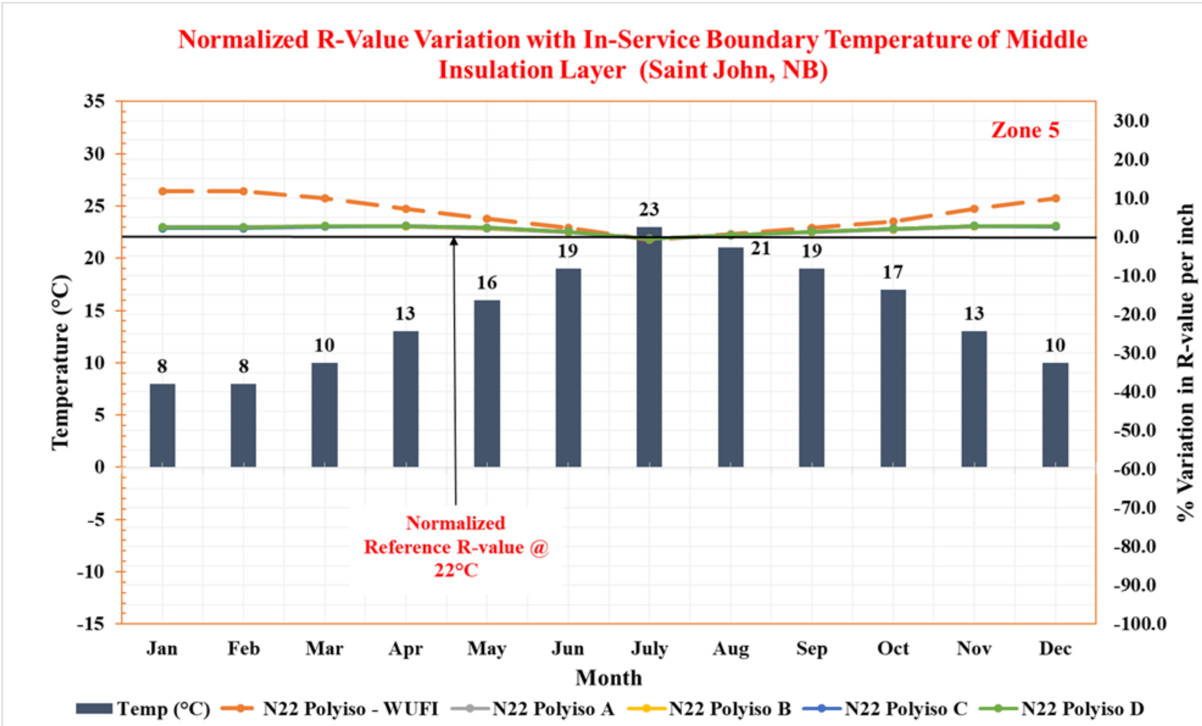

Figure 22 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Saint John, NB)

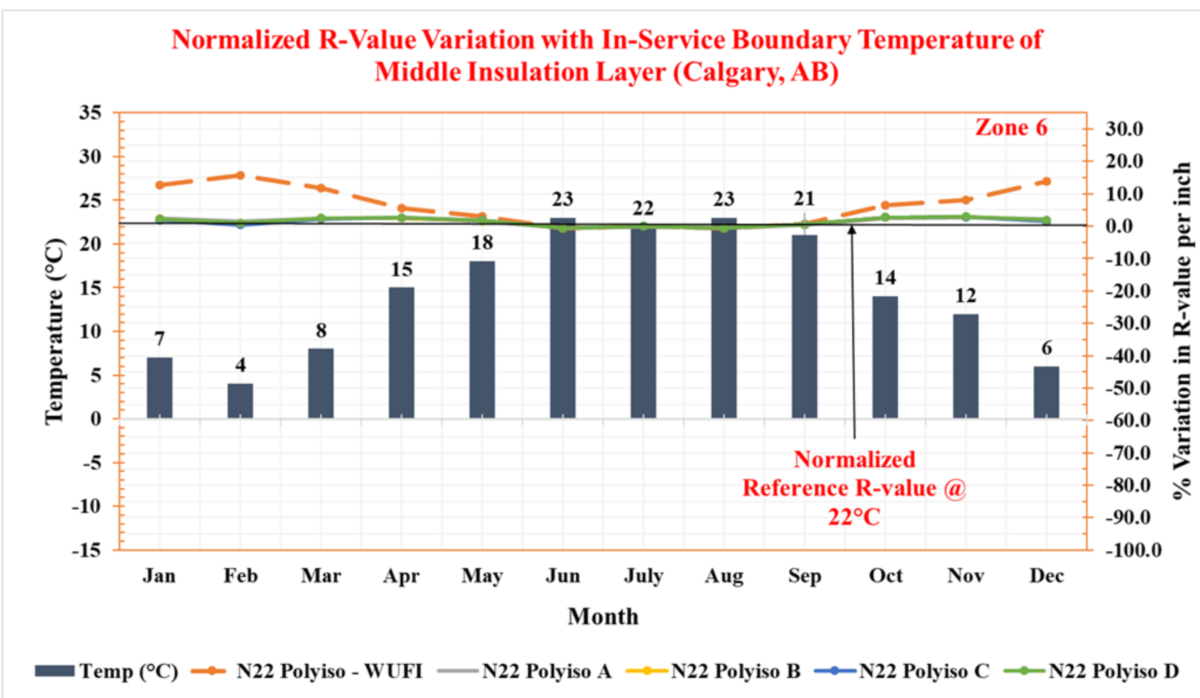

Figure 23 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Calgary, AB)

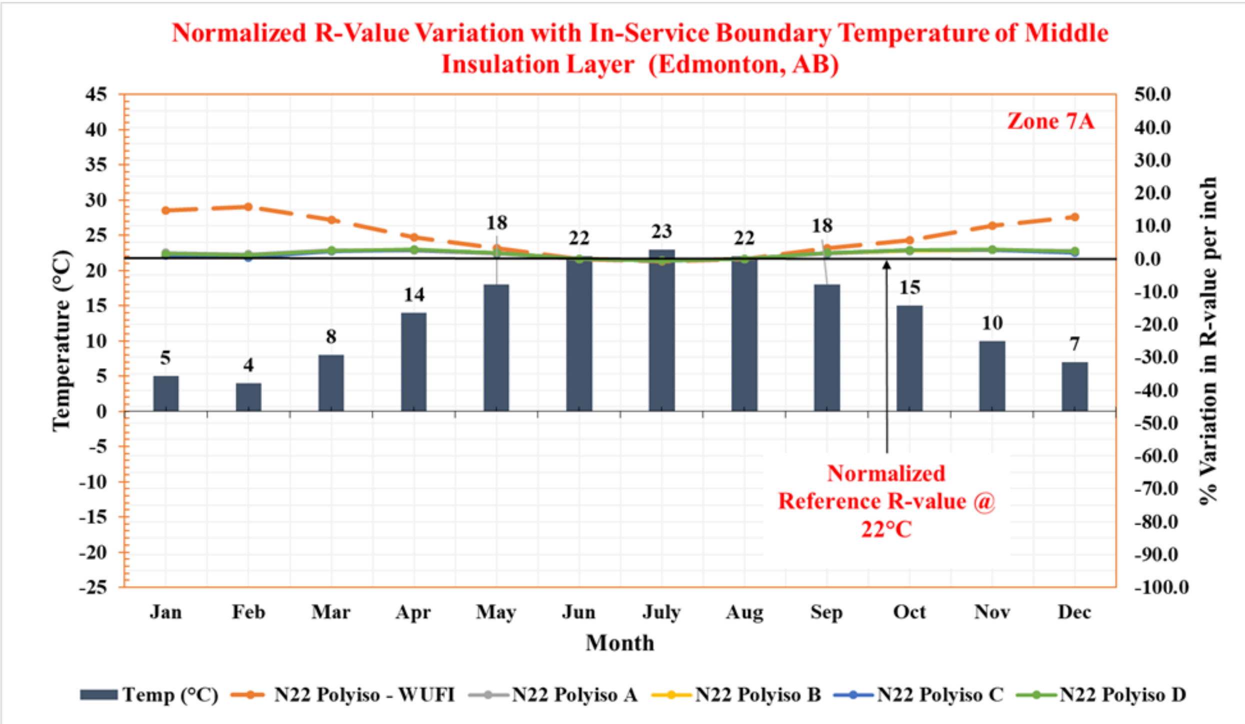

Figure 24 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Edmonton, AB)

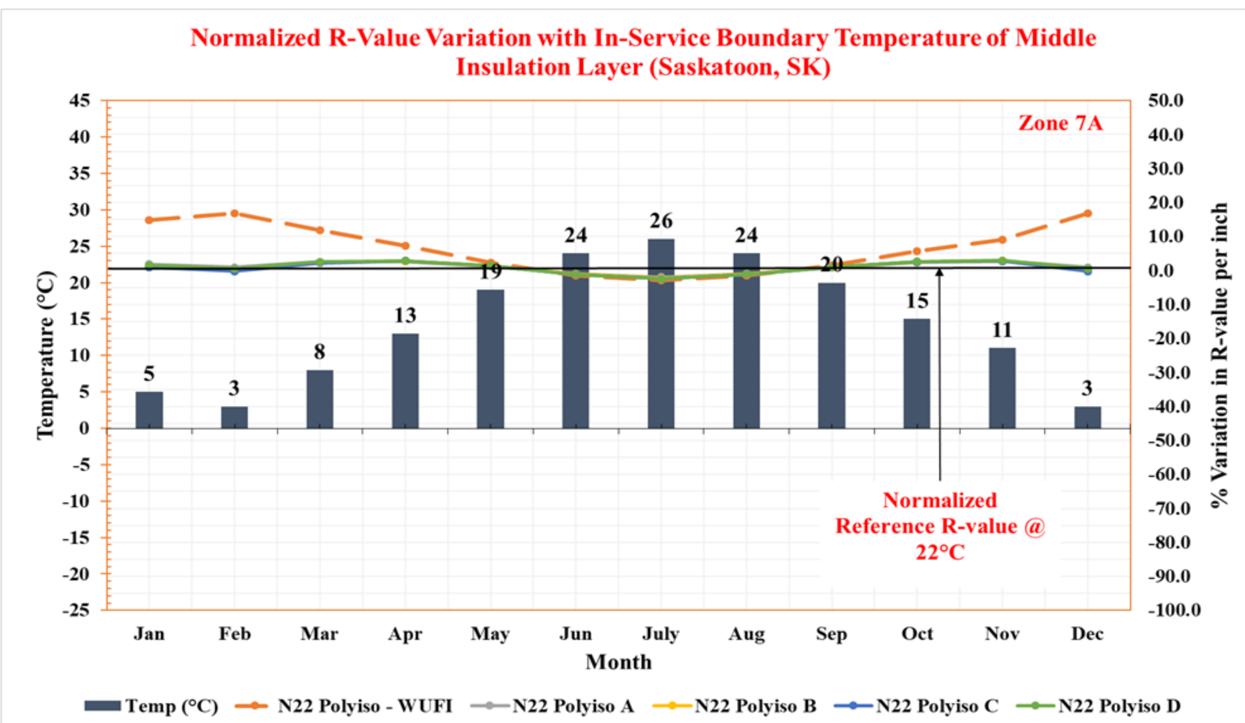

Figure 25 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Saskatoon, SK)

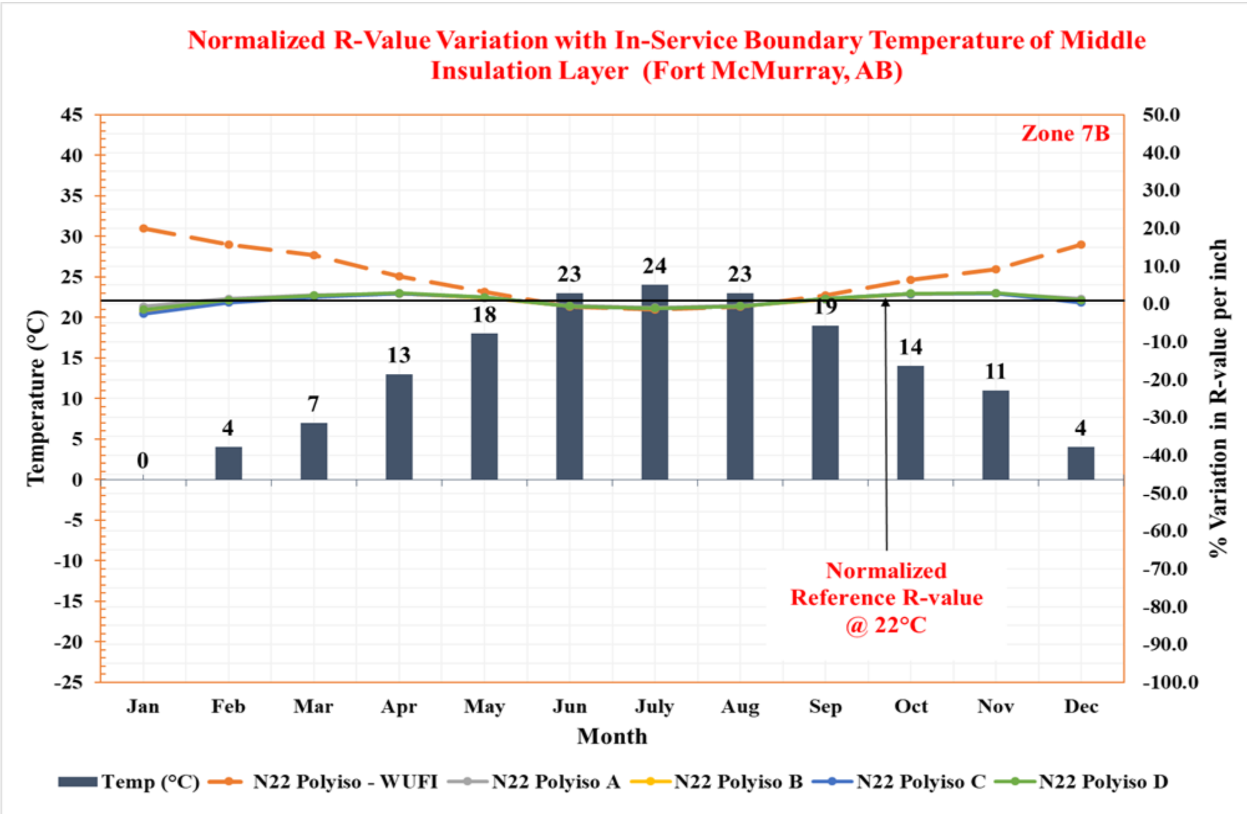

Figure 26 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Fort McMurray, AB)

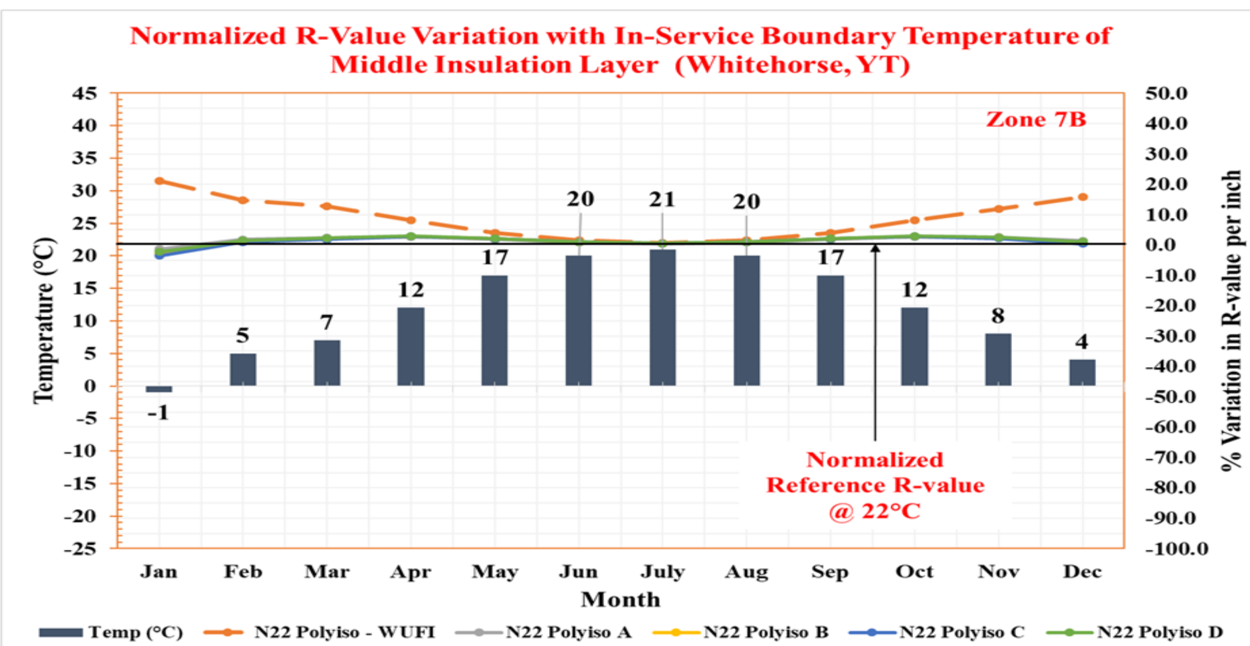

Figure 27 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Whitehorse, YT)

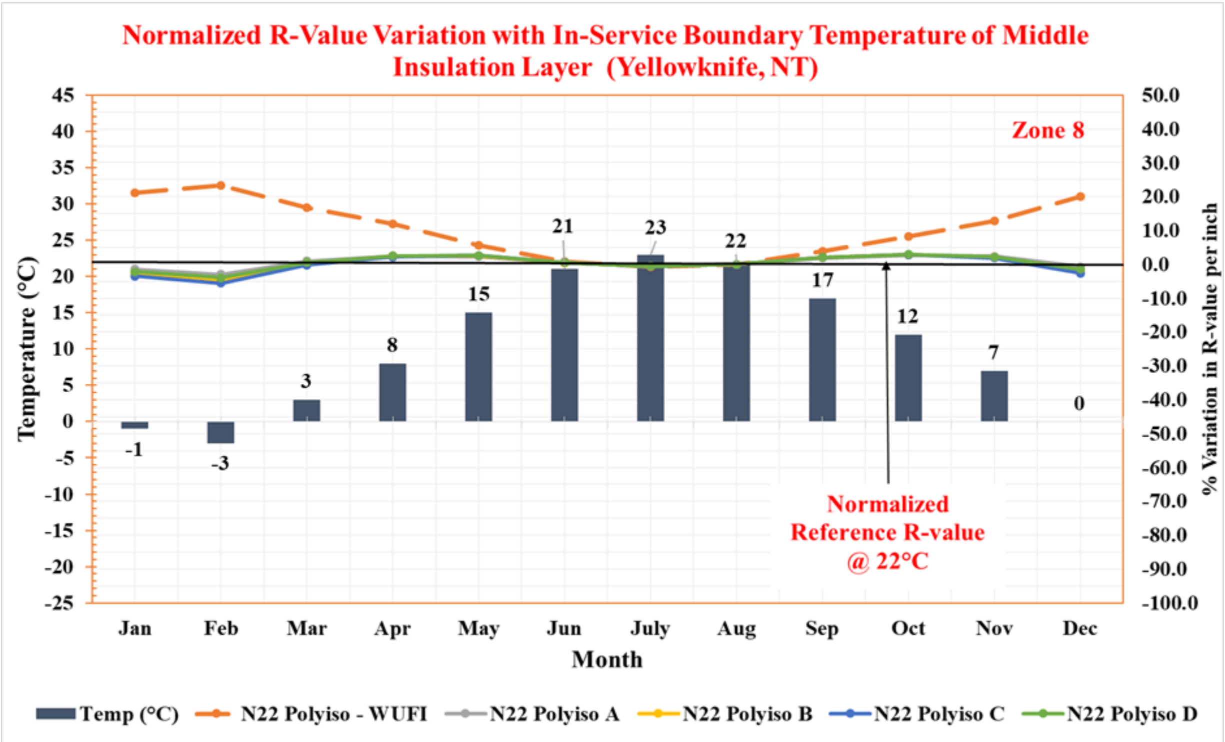

Figure 28 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Yellowknife, NT)

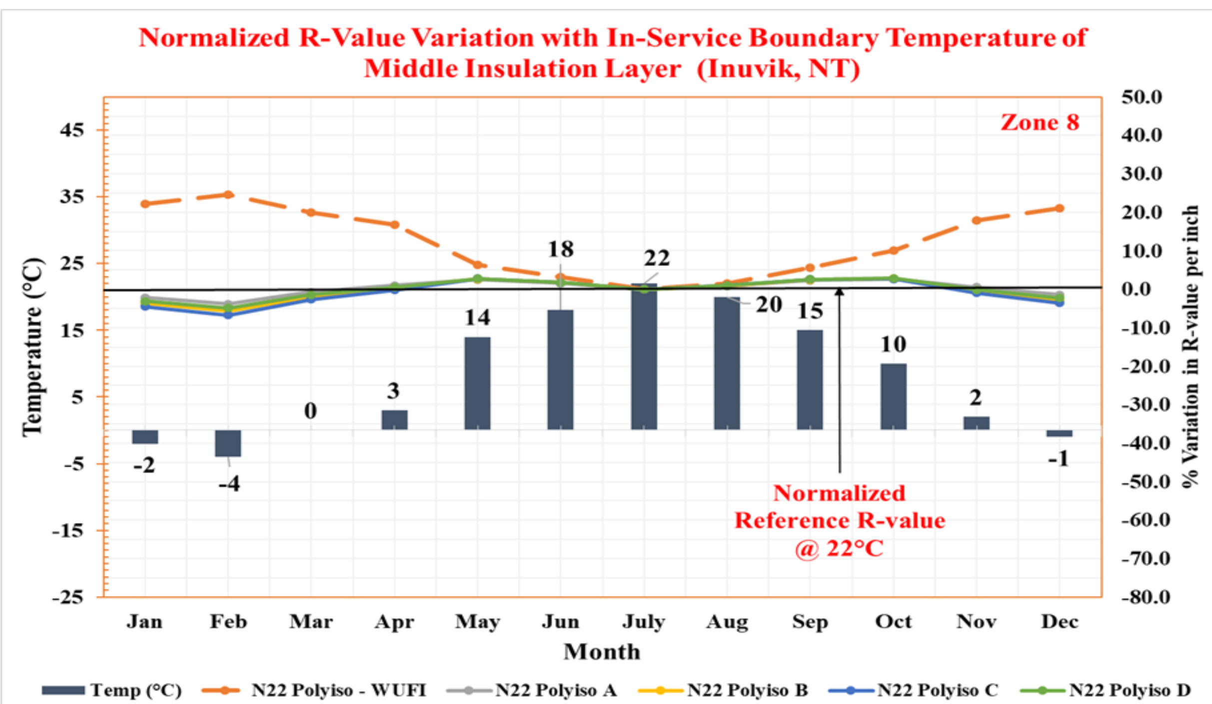

Figure 29 Normalized R-value variation with in-service boundary temperature of middle insulation layer (Inuvik, NT)

See Figure 25-Figure 27, $Polyiso_{A-D}$ data indicated 1.1% to 2.0% lower R-value than $R_{T22°C}$ during winter season considering climates of Saskatoon (SK), Fort McMurray (AB), Whitehorse (YT). However, during summer season, R-value data of $Polyiso_{A-D}$ revealed variation between -0.5% to +1.3% for mentioned three cities. In extreme cold climates like Yellowknife (NT), and Inuvik (NT), polyiso insulation middle layer experienced -3, and -4°C boundary temperature respectively during winter season. See Figure 28-Figure 29, in winter season, considering Yellowknife (NT), and Inuvik (NT), $Polyiso_{A-D}$ data indicated 0.5% to 2.3% lower R-value than $R_{T22°C}$.

During summer season polyiso insulation middle layer experienced temperature variation between 14°C to 26°C. Thus, R-value data of $Polyiso_{A-D}$ revealed variation between -0.8% to +1.6% for selected ten Canadian locations. Furthermore, $Polyiso_{WUFI}$ R-value data showed -1.9% to 3.3% variable R-values from $R_{T22°C}$ during summer season. However, in winter season, $Polyiso_{WUFI}$ revealed R-value variation between 6.6% to 18.9% from $R_{T22°C}$.

4.3.3 R-value variation in interior layer of polyiso insulation

Figure 30-Figure 39 shows normalized R-value variation in relation to in-service boundary temperature of interior layer of polyiso insulation in selected roof assemblies determined from hygrothermal simulations of ten Canadian cities.

In winter season, polyiso insulation interior layer experienced temperature variation between 11°C to 17°C. See Figure 30, in Vancouver (BC), in-service boundary temperature experienced by polyiso insulation interior layer is between 17˚C to 23˚C annually. However, in winter season this variation is 17˚C to 20˚C and during summer it is 20˚C -23˚C. $Polyiso_{A-D}$ data actually showed 1.4% to 1.6% higher R-value and $Polyiso_{WUFI}$ showed 2.8% higher R-values than $R_{T22°C}$ during winter season. However, for Toronto (ON), winter season in-service temperature variation is between 16˚C to 20˚C and $Polyiso_{A-D}$ and $Polyiso_{WUFI}$ indicated 1.7% to 1.9% and 3.6% R-value variation from $R_{T22°C}$ respectively. In climate zone 6, Saint John (NB), winter in-service boundary temperature experienced by polyiso insulation interior layer is between 16˚C to 19˚C resulting 1.8% to 2.0% higher R-value of $Polyiso_{A-D}$ than $R_{T22°C}$ during winter season.

Considering climate of Calgary (AB), in-service boundary temperature experienced by polyiso insulation interior layer is between 15˚C to 22˚C. Thus, $Polyiso_{A-D}$ data actually showed 1.9% to 1.6% higher R-value than $R_{T22°C}$ during winter season. However, in summer season this variation is only 0.3% to 0.4%. See Figure 34-Figure 35, Edmonton (AB) and Saskatoon (SK), in-service boundary temperature experienced by polyiso insulation interior layer is between 14°C to 24°C. Polyiso$_{A-D}$ data indicated 2.0% to 2.3% higher R-value than $R_{T22°C}$ during winter season. However, during summer season, R-value data of Polyiso$_{A-D}$ revealed variation between -0.2% to +0.5% for mentioned three cities.

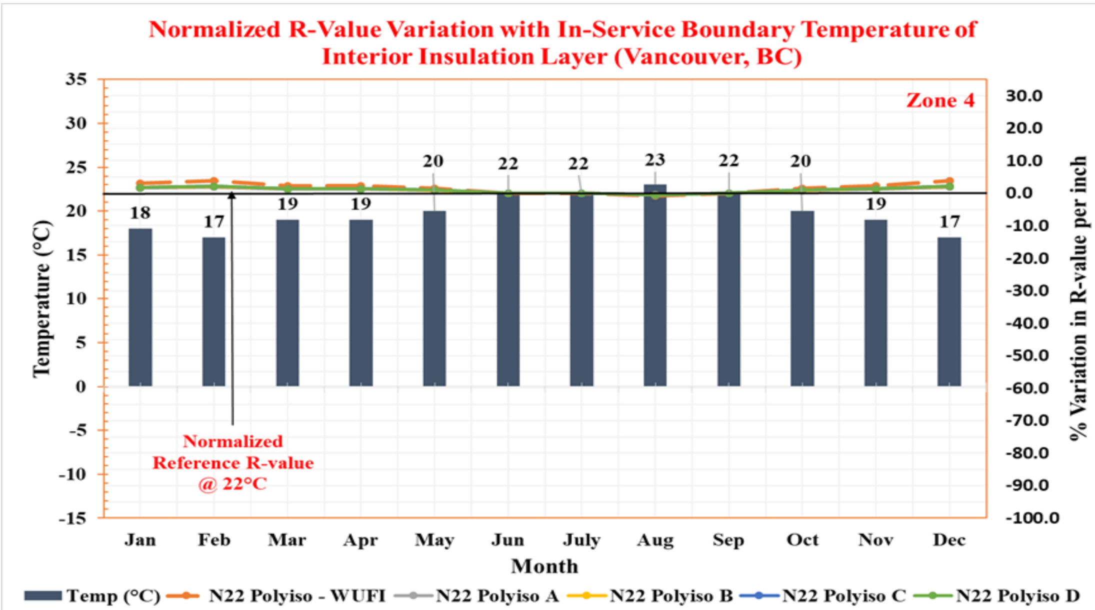

Figure 30 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Vancouver, BC)

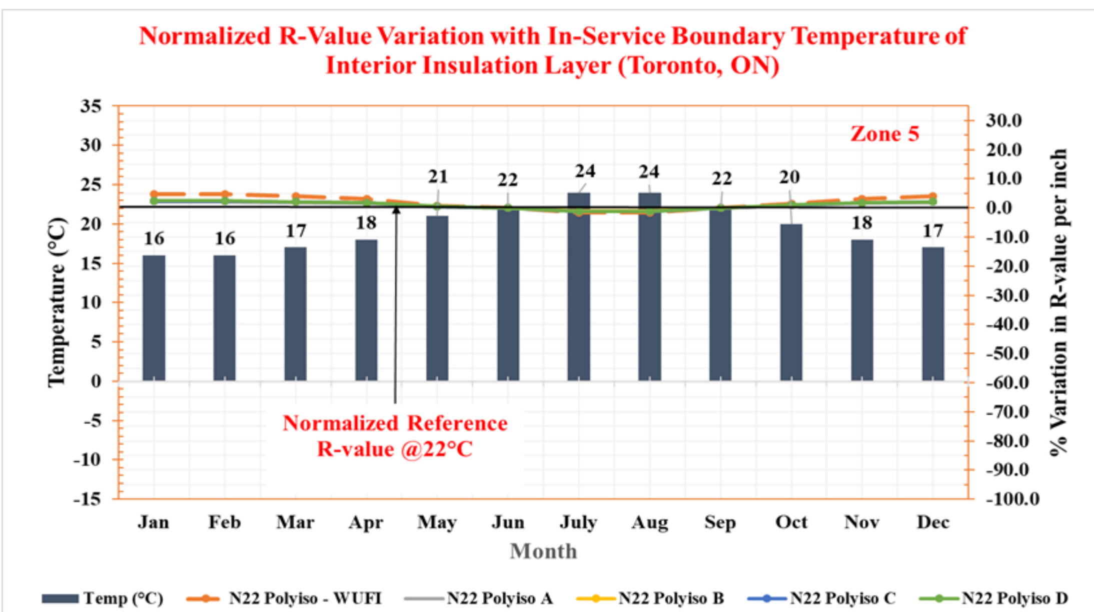

Figure 31 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Toronto, ON)

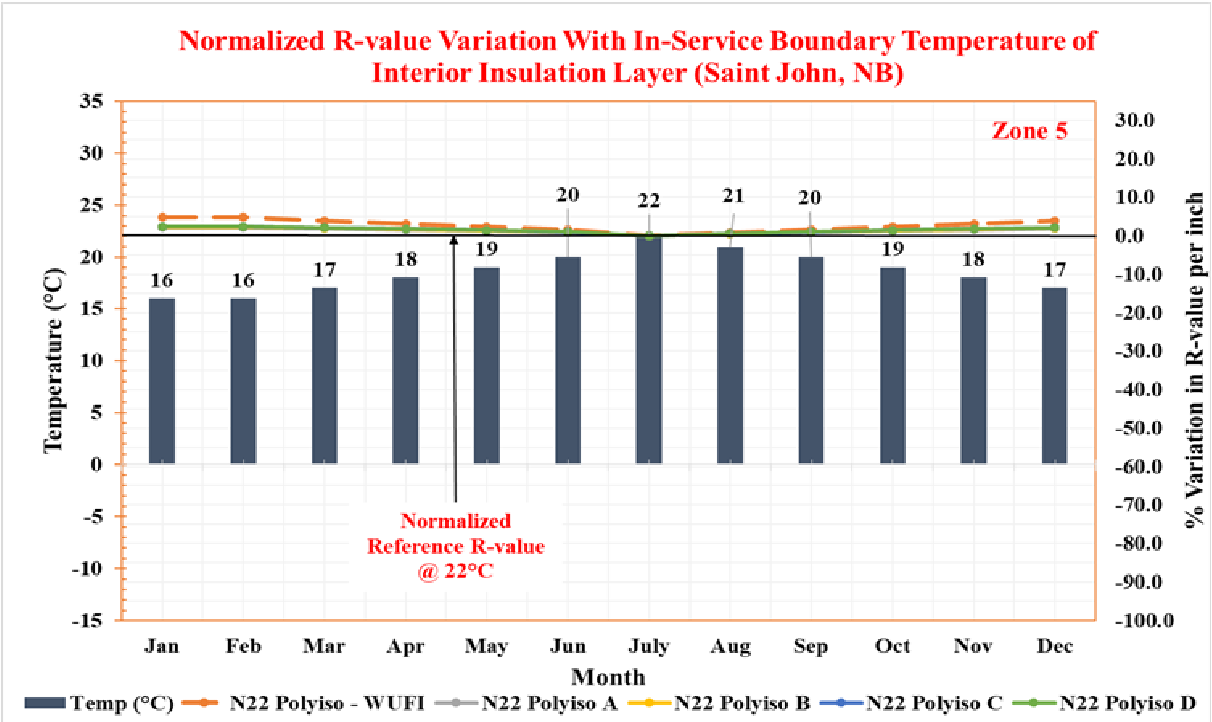

Figure 32 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Saint John, NB)

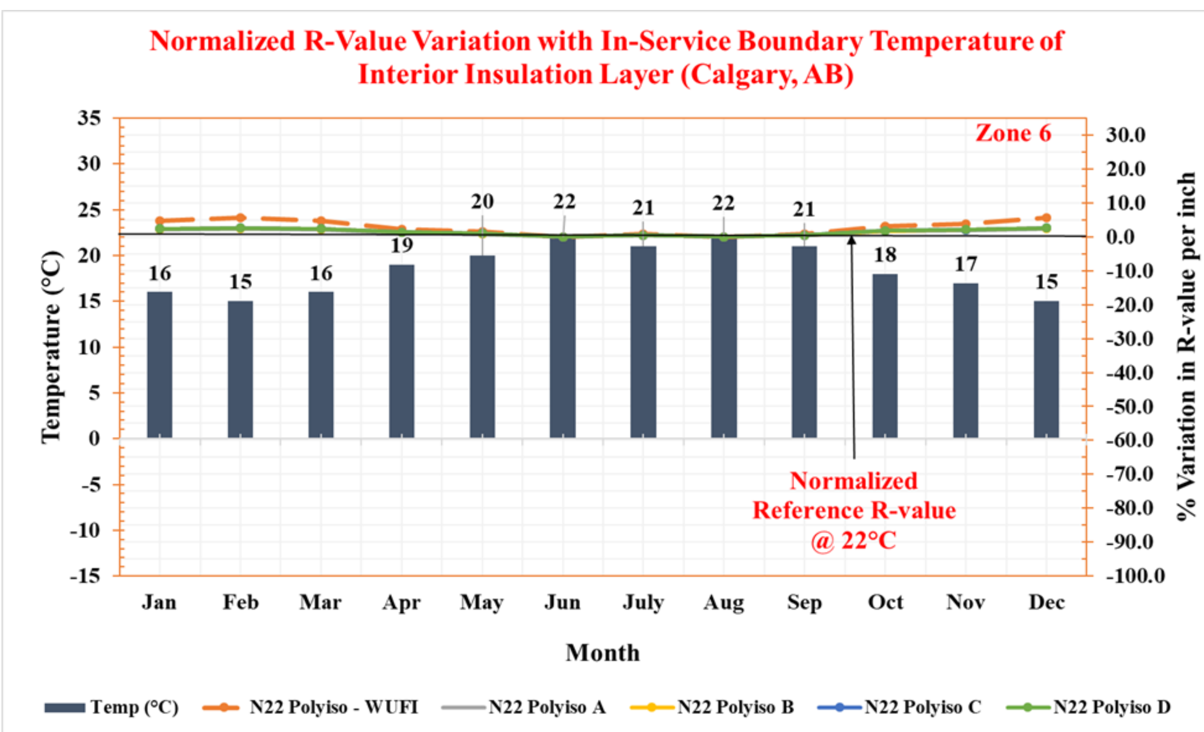

Figure 33 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Calgary, AB)

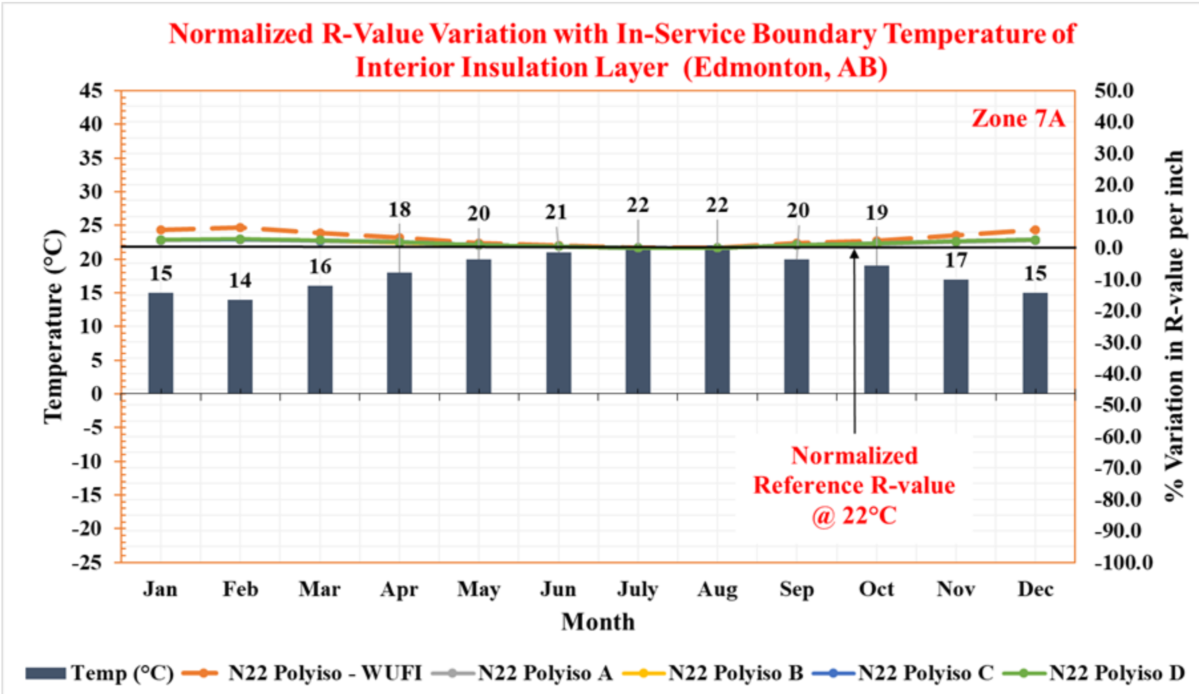

Figure 34 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Edmonton, AB)

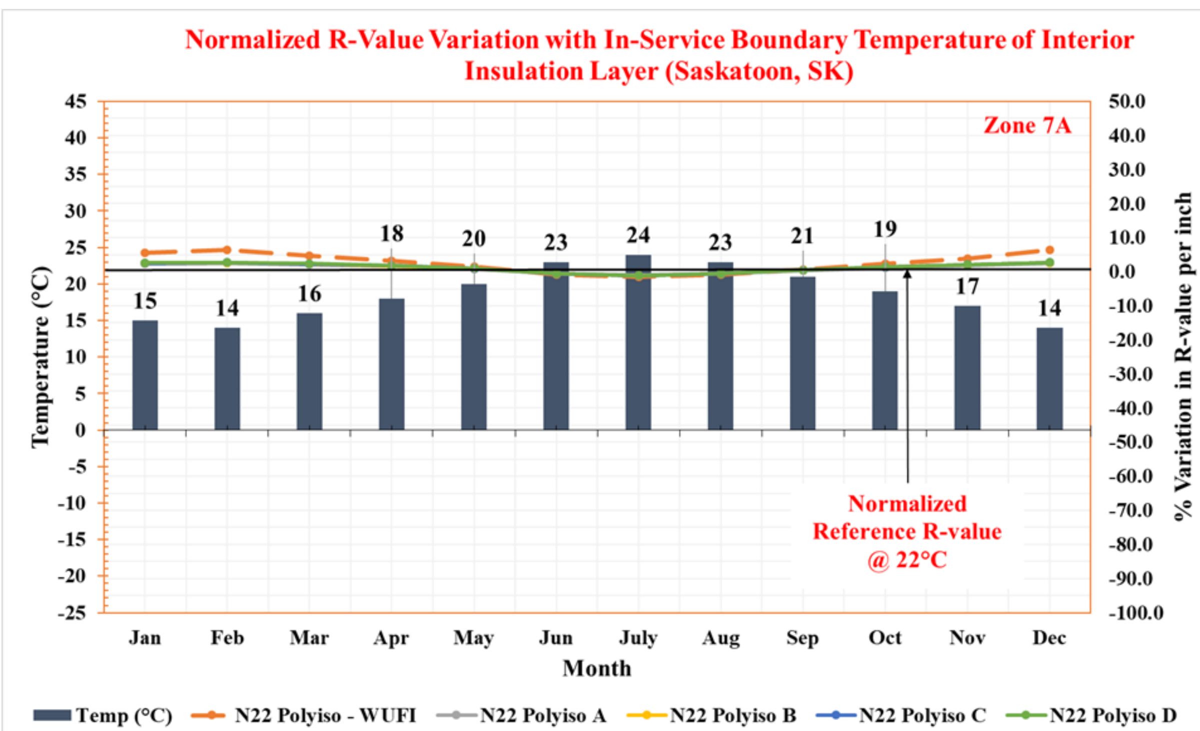

Figure 35 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Saskatoon, SK)

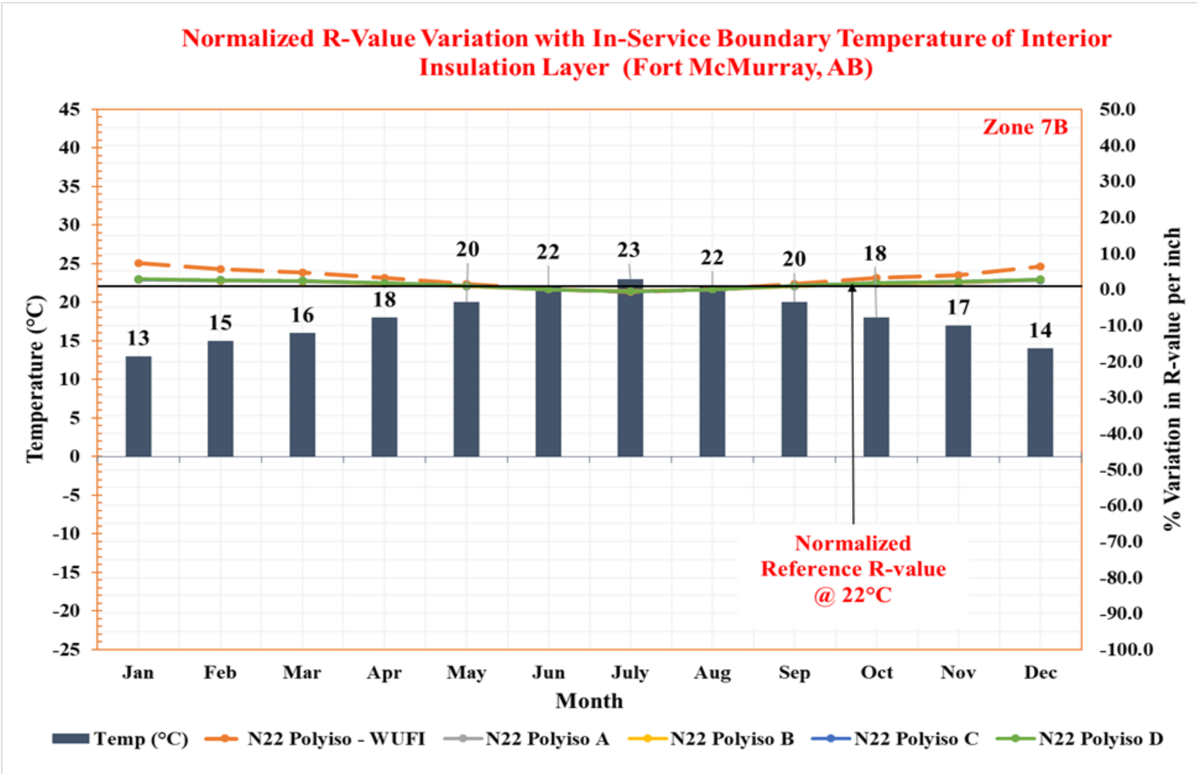

Figure 36 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Fort McMurray, AB)

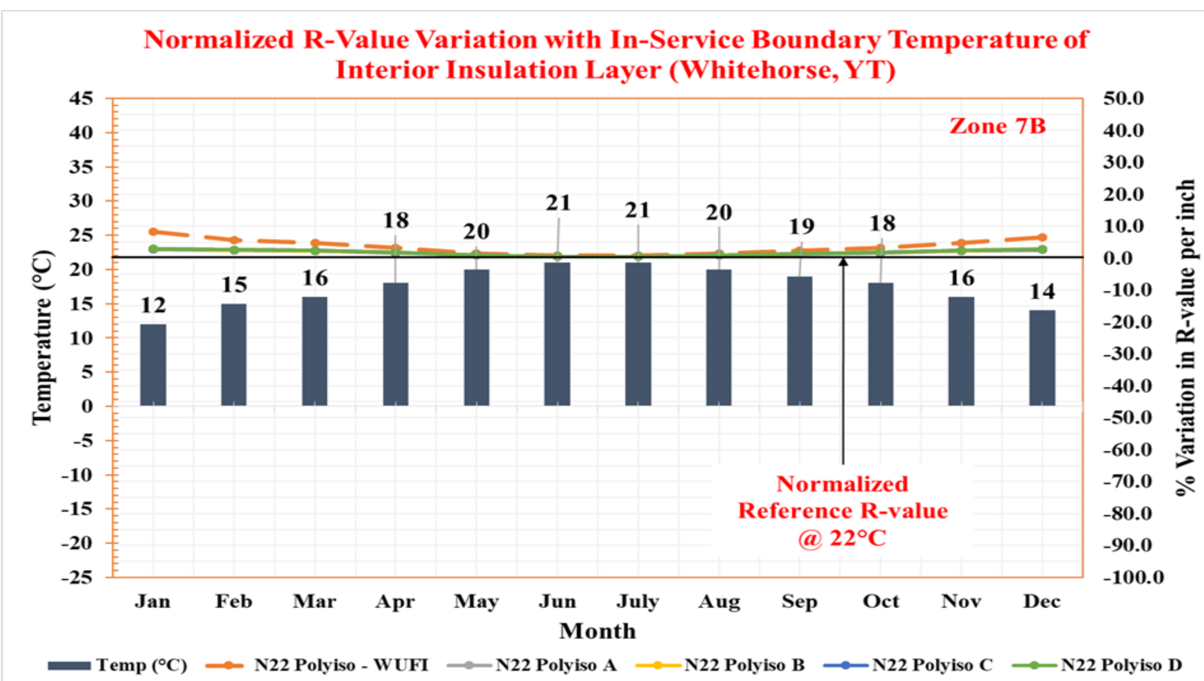

Figure 37 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Whitehorse, YT)

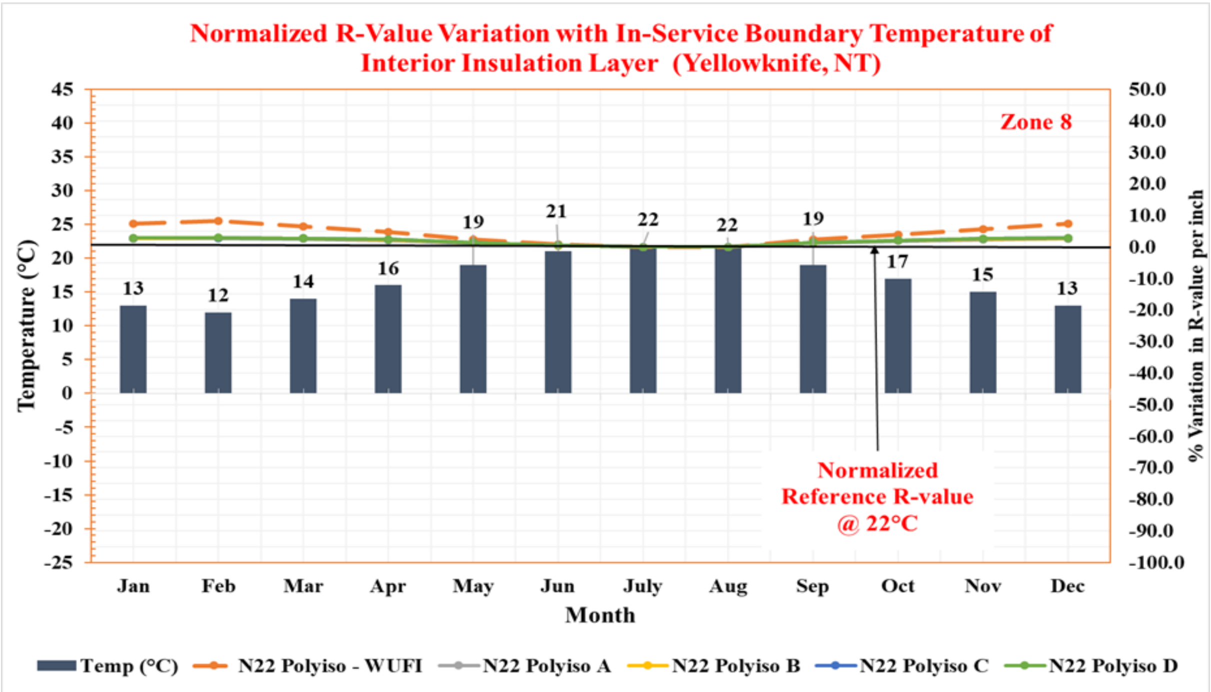

Figure 38 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Yellowknife, NT)

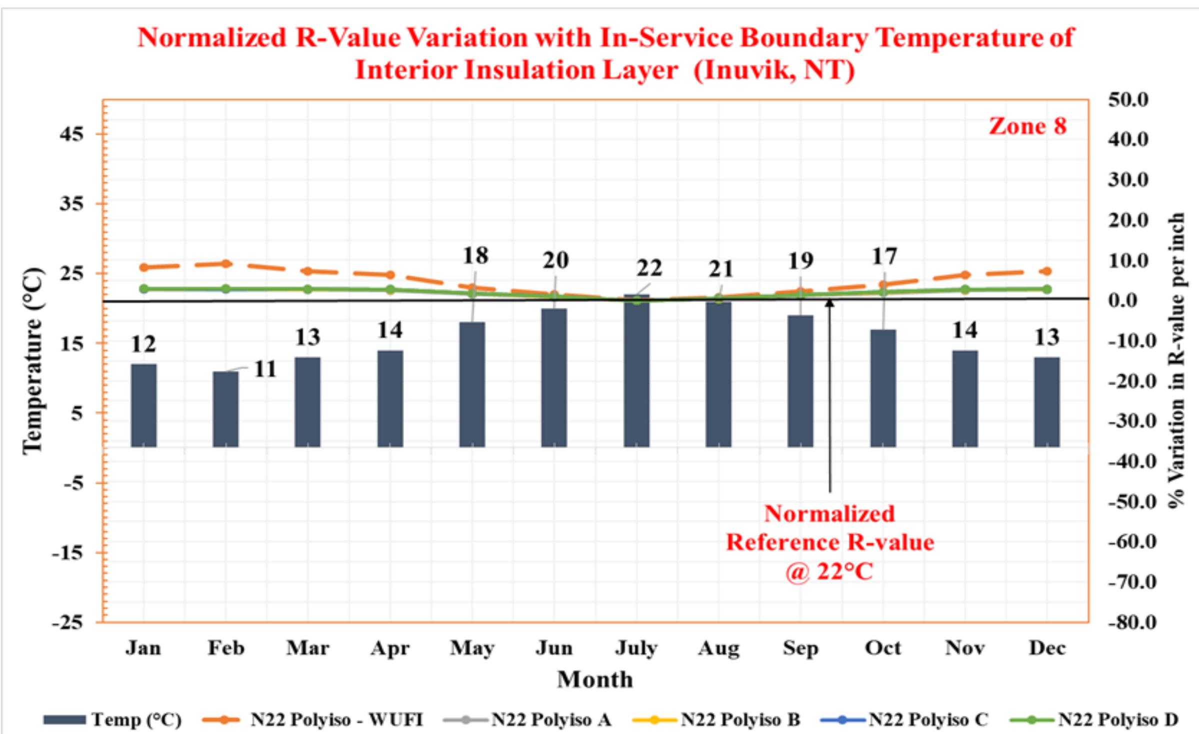

Figure 39 Normalized R-value variation with in-service boundary temperature of interior insulation layer (Inuvik, NT)

For Fort McMurray (AB), and Whitehorse (YT) in-service boundary temperature experienced by polyiso insulation interior layer is between 12°C to 23°C. In Fort McMurray (AB), Whitehorse (YT) $Polyiso_{A\text{-}D}$ data indicated 2.1% to 2.4% higher R-value than $R_{T22°C}$ during winter season. However, in summer season $Polyiso_{A\text{-}D}$ data predicted variation between 0.2% to 0.9% from $R_{T22°C}$.

In extreme cold climates like Yellowknife (NT), and Inuvik (NT), polyiso insulation interior layer experienced boundary temperature between 11°C to 17°C during winter season. See Figure 38-Figure 39, in winter season, considering Yellowknife (NT), and Inuvik (NT), $Polyiso_{A\text{-}D}$ data indicated 2.4% to 2.8% lower R-value than $R_{T22°C}$.

During summer season polyiso insulation interior layer experienced temperature variation between 18°C to 24°C. Thus, R-value data of $Polyiso_{A\text{-}D}$ revealed variation between -0.4% to +0.9% for selected ten Canadian locations. Furthermore, $Polyiso_{WUFI}$ R-value data showed -0.4% to 1.5% variable R-values from $R_{T22°C}$ during summer season. However, in winter season, $Polyiso_{WUFI}$ revealed R-value variation between 2.8% to 7.0% from $R_{T22°C}$.

4.3.4 Seasonal thermal performance of polyiso insulation

Table 5-Table 7 shows R-value percentage difference between $Polyiso_{A\text{-}D}$ and $R_{T22°C}$, and $Polyiso_{WUFI}$ and $R_{T22°C}$ in different Canadian climate zones. A positive value means that the R-value estimated using laboratory measured data or from WUFI® Pro database is higher than $R_{T22°C}$ and vice versa. The detailed analysis of thermal performance of each layer is provided in following sections.

4.3.4.1 Exterior insulation layer

Figure 40-Figure 42 shows seasonal and annual thermal performance of polyiso insulation under Canadian climatic conditions. The comparison between $Polyiso_{A\text{-}D}$ and $R_{T22°C}$ shows that polyiso insulation perform worse in winter season. See Figure 40, during winter season, R-value of $Polyiso_{A\text{-}D}$ revealed significant decrease of -12.6% to -16.9% from $R_{T22°C}$ when subjected to severe temperature conditions of Zone 8.

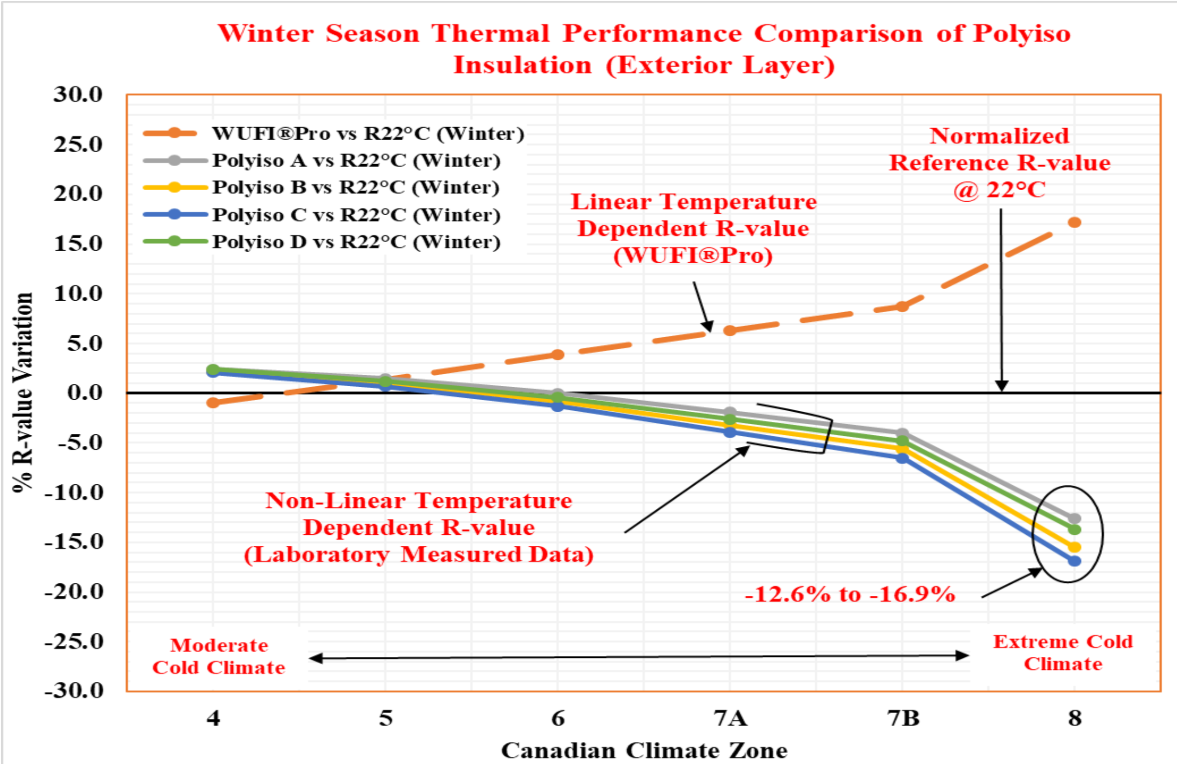

Figure 40 Winter season thermal performance of polyiso insulation exterior layer in Canadian climates

Figure 41, shows annual thermal performance of polyiso insulation exterior layer. It is evident that Polyiso$_{A-D}$ indicated a decrease of -6.8% to -9.3% in R-value under extreme cold temperatures of zone 8. However, in moderate cold climate of Zone 4 and Zone 5, Polyiso$_{A-D}$ perform well during winter season. In zone 4, Polyiso$_{A-D}$ showed annual variation between 1.0% to 1.2% and in zone 5 Polyiso$_{A-D}$ showed annual variation between 0% to 0.5% from $R_{T22°C}$. Furthermore, Polyiso$_{WUFI}$ revealed R-value variation of -4.7% in climate zone 4 and -3.6% in climate zone 5.

In climate zone 6, Polyiso$_{WUFI}$ indicated lower R-values than $R_{T22°C}$ by -1.1%. However, for Polyiso$_{A-D}$ showed annual variation between -0.4% to 0.3%. In climate zone 7B and 8, Polyiso$_{WUFI}$ indicated higher and Polyiso$_{A-D}$ indicated lower R-values than $R_{T22°C}$. In climate zone 7A, Polyiso$_{WUFI}$ and Polyiso$_{A-D}$ showed minimum variation from $R_{T22°C}$. In zone 7B, annual variation of Polyiso$_{WUFI}$ from $R_{T22°C}$ is 1.8%. However, for Polyiso$_{A-D}$ annual variation is between -2.0% to -3.4%. In zone 8, annual variation of Polyiso$_{WUFI}$ from $R_{T22°C}$ is 7.4%. However, for Polyiso$_{A-D}$ annual variation is between -6.8% to -9.3%.

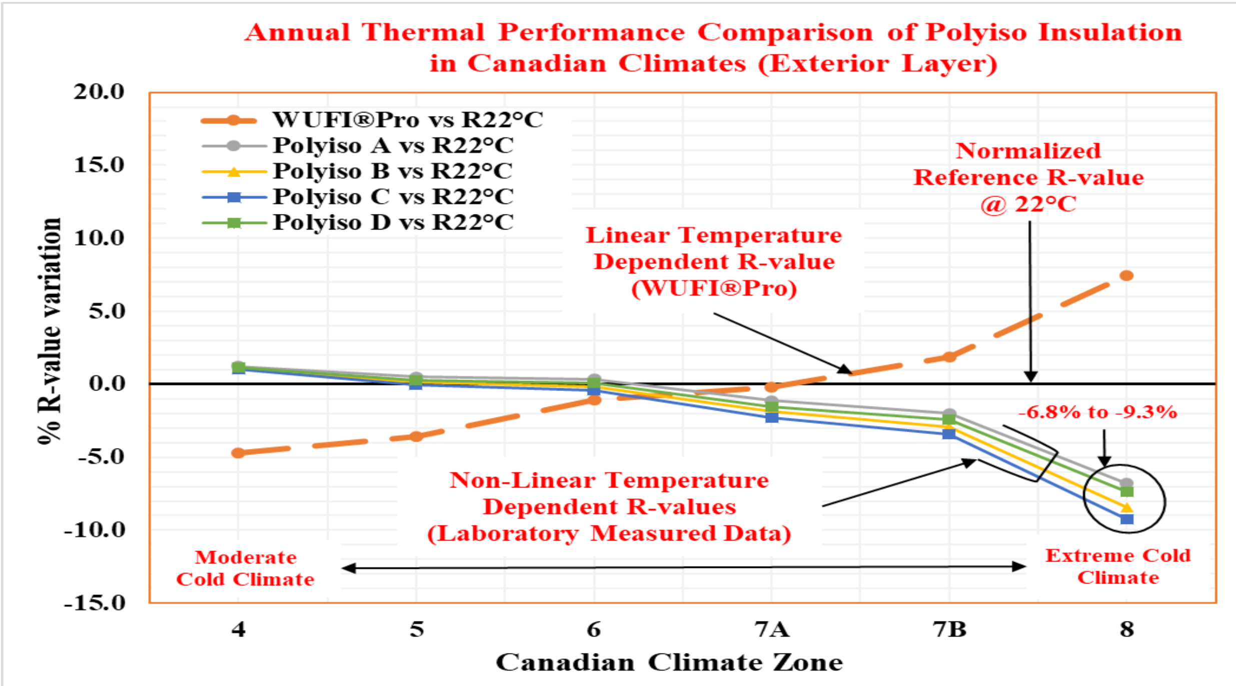

Figure 41 Annual thermal performance of polyiso insulation exterior layer in Canadian climates

See Figure 42, during summer season, in all climate zone the laboratory measured polyiso R-value show variation between -1.1% to 1.4% which is much less than winter season. However, R-value of $Polyiso_{WUFI}$ revealed variation of -6.3% to -10.5% from $R_{T22°C}$ in Canadian climate zones.

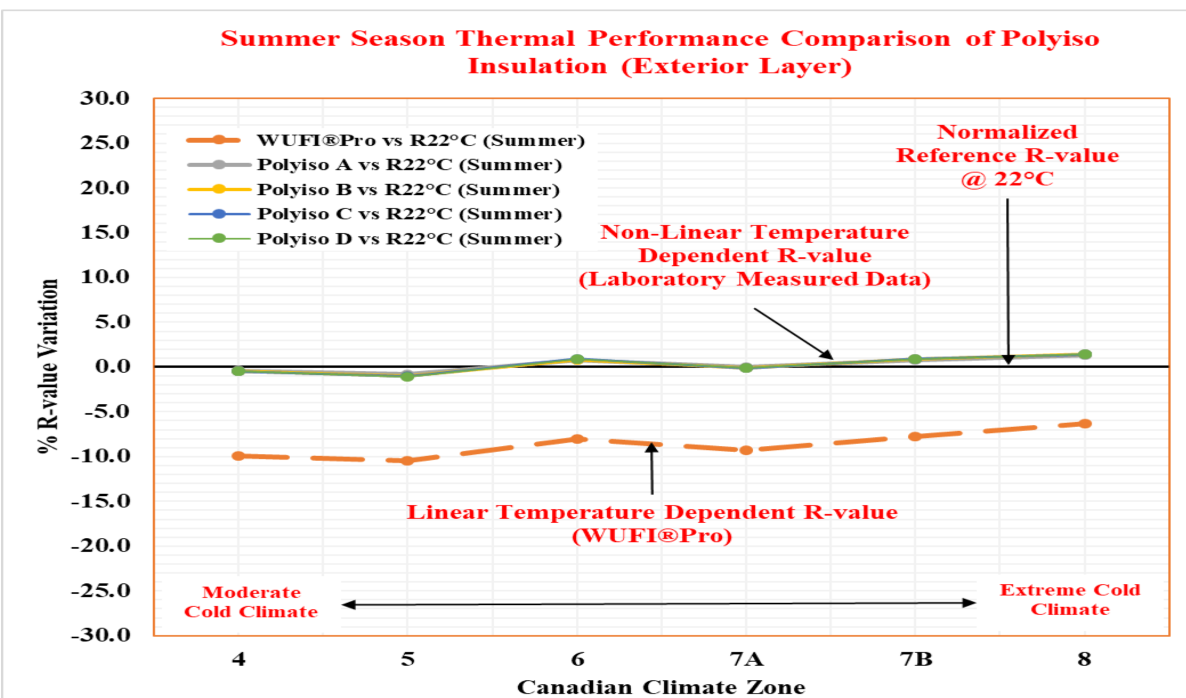

Figure 42 Summer season thermal performance of polyiso insulation exterior layer in Canadian climates

Table 5Thermal performance of polyiso foam insulation exterior layer under Canadian climates

Zone	Polyiso$_{WUFI}$ vs R$_{T22°C}$			Polyiso$_{A}$ vs R$_{T22°C}$			Polyiso$_{B}$ vs R$_{T22°C}$			Polyiso$_{C}$ vs R$_{T22°C}$			Polyiso$_{D}$ vs R$_{T22°C}$		
	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)
4	-4.7	-1.0	-9.9	1.2	2.4	-0.4	1.1	2.2	-0.5	1.0	2.1	-0.5	1.2	2.4	-0.5
5	-3.6	1.4	-10.5	0.5	1.5	-0.8	0.2	1.0	-1	0.0	0.7	-1	0.3	1.2	-1.1
6	-1.1	3.9	-8.0	0.3	0.0	0.8	-0.1	-0.8	0.8	-0.4	-1.3	0.9	0.1	-0.4	0.9
7A	-0.2	6.3	-9.3	-1.1	-1.9	0.0	-1.9	-3.2	-0.1	-2.3	-3.9	-0.1	-1.5	-2.6	-0.1
7B	1.8	8.7	-7.8	-2.0	-4.0	0.8	-2.9	-5.6	0.9	-3.4	-6.5	0.9	-2.4	-4.8	0.9
8	7.4	17.2	-6.3	-6.8	-12.6	1.3	-8.4	-15.5	1.4	-9.3	-16.9	1.4	-7.4	-13.7	1.4

4.3.4.2 Middle insulation layer

Figure 43-Figure 45 represents seasonal thermal performance of polyiso insulation middle layer under Canadian climatic conditions.

The comparison between $Polyiso_{A\text{-}D}$ and $R_{T22°C}$ shows that polyiso insulation middle layer perform good in winter season for all Canadian climate zone except zone 8. See Figure 43, during winter season, R-value of $Polyiso_{A\text{-}D}$ revealed increase of 1.1% to 2.7% from $R_{T22°C}$ when subjected to temperature conditions of Zone 5, 6, 7A, and 7B. However, due to extreme cold climate of zone 8, R-value of $Polyiso_{A\text{-}D}$ revealed decrease of 0.5% to 2.3% from $R_{T22°C}$ Furthermore, the comparison between $Polyiso_{WUFI}$ and $R_{T22°C}$ indicated that polyiso insulation middle layer always perform better in winter season. In winter, R-value of $Polyiso_{WUFI}$ revealed increase of 6.6% to 18.9% from $R_{T22°C}$ in Canadian climate zones.

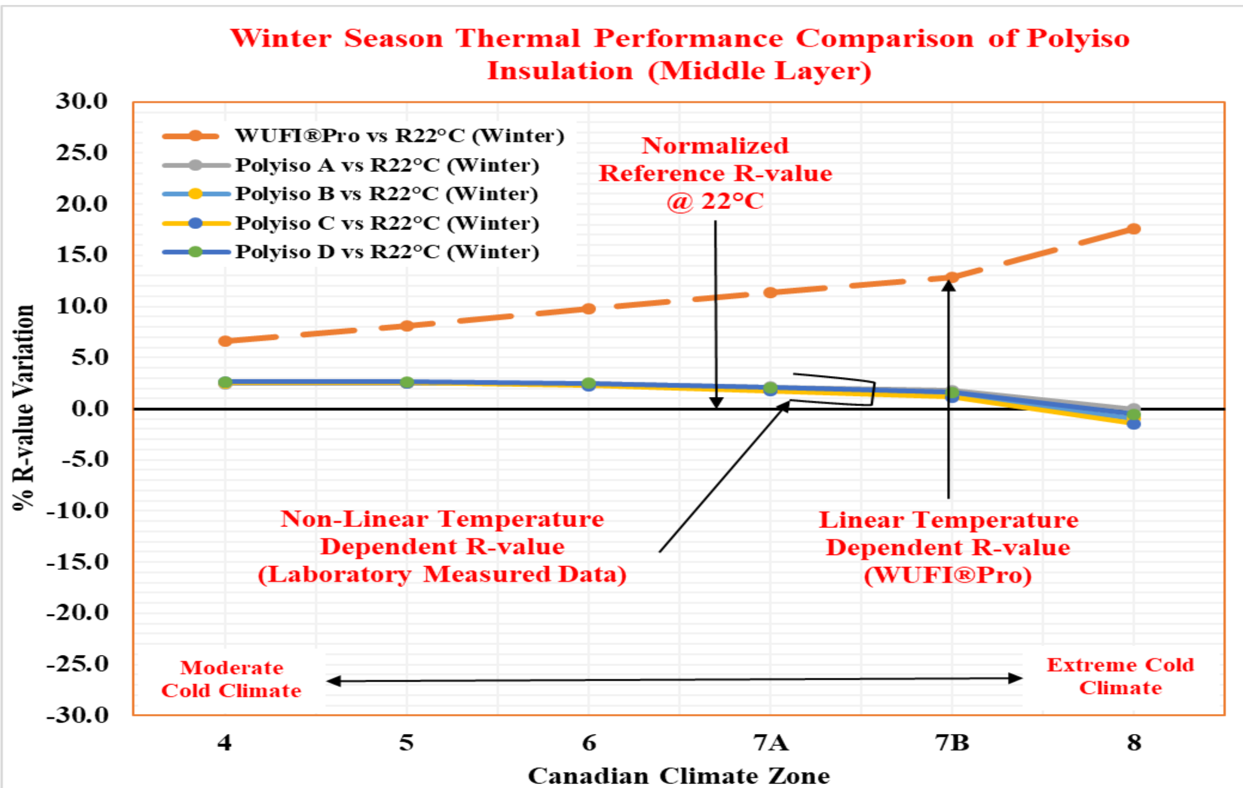

Figure 43 Winter season thermal performance of polyiso insulation middle layer in Canadian climates

Figure 44, shows annual thermal performance of polyiso insulation middle layer. $Polyiso_{A\text{-}D}$ indicated variation of -0.6% to 2.0% and $Polyiso_{WUFI}$ revealed increase of 3.9% to 12.4% from $R_{T22°C}$ in Canadian climate zones.

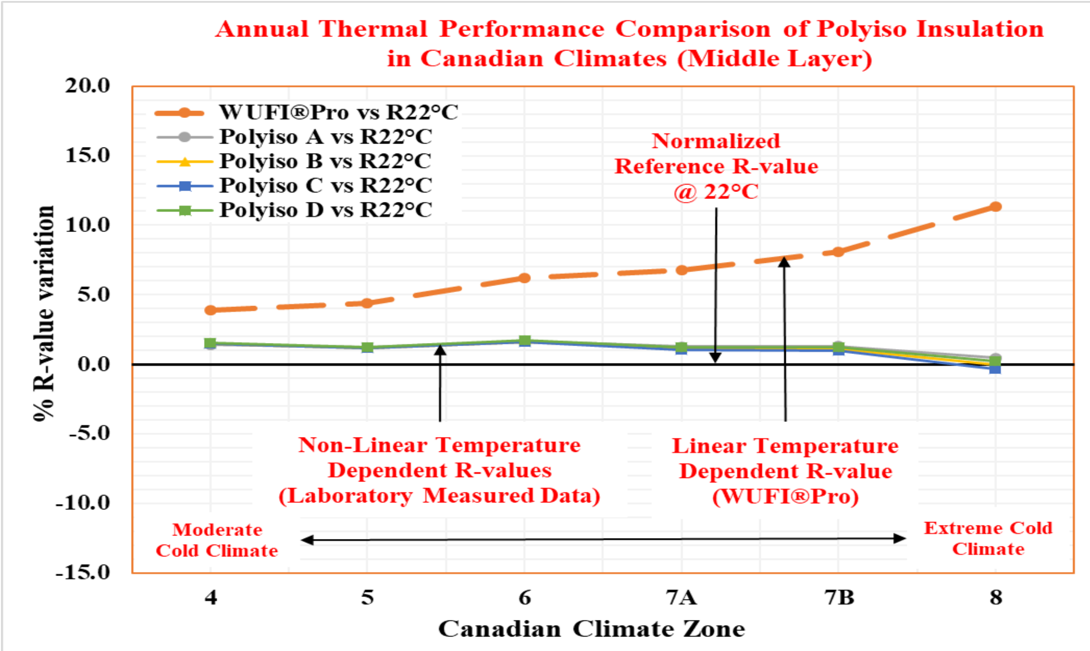

Figure 44 Annual thermal performance of polyiso insulation middle layer in Canadian climates

See Figure 45, during summer season, in all climate zone the laboratory measured polyiso R-value show variation between -0.8% to 1.6 % which is much less than winter season. However, R-value of Polyiso$_{WUFI}$ revealed variation of -1.9% to 3.3% from $R_{T22°C}$ in Canadian climate zones.

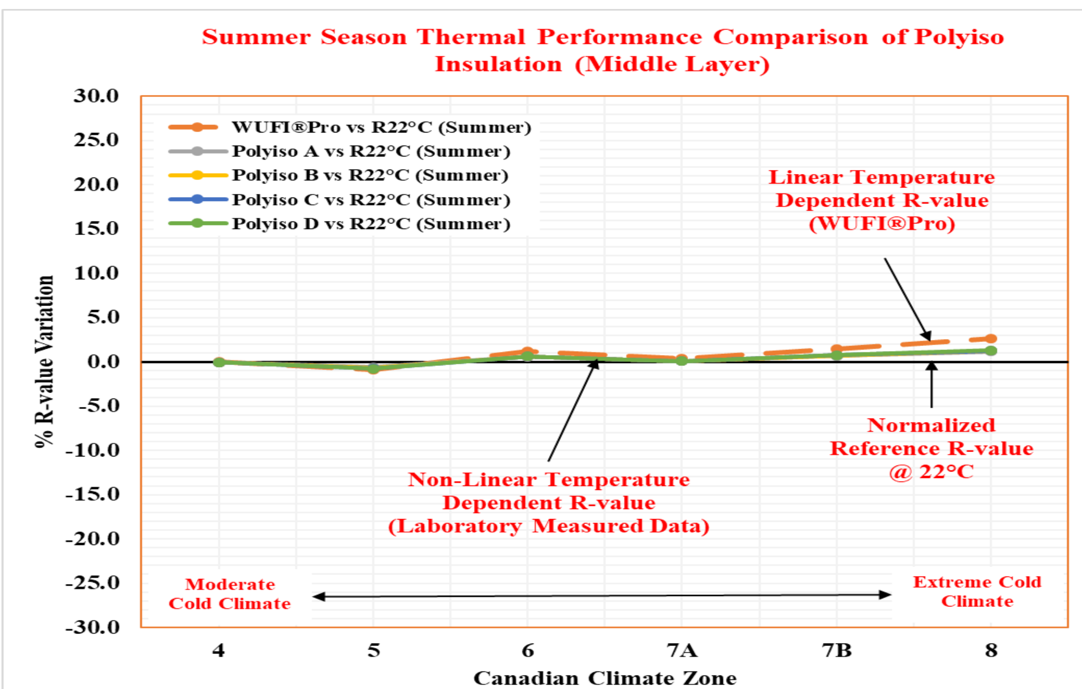

Figure 45 Summer season thermal performance of polyiso insulation middle layer in Canadian climates

Table 6 Thermal performance of polyiso foam insulation middle layer under Canadian climates

Zone	Polyiso$_{WUFI}$ vs R$_{T22°C}$			Polyiso$_{A}$ vs R$_{T22°C}$			Polyiso$_{B}$ vs R$_{T22°C}$			Polyiso$_{C}$ vs R$_{T22°C}$			Polyiso$_{D}$ vs R$_{T22°C}$		
	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)
4	3.9	6.6	0.0	1.4	2.4	0.0	1.5	2.6	-0.1	1.5	2.6	-0.1	1.5	2.7	-0.1
5	4.4	8.1	-0.9	1.2	2.5	-0.6	1.2	2.5	-0.7	1.2	2.5	-0.7	1.2	2.7	-0.8
6	6.2	9.8	1.2	1.6	2.4	0.6	1.6	2.3	0.6	1.6	2.3	0.6	1.7	2.5	0.6
7A	6.8	11.4	0.3	1.3	2.1	0.1	1.1	1.9	0.1	1.1	1.7	0.1	1.2	2.1	0.1
7B	8.1	12.9	1.4	1.3	1.8	0.7	1.1	1.4	0.7	1.0	1.2	0.8	1.3	1.6	0.8
8	11.4	17.6	2.6	0.5	0.0	1.1	0.0	-1.0	1.2	-0.3	-1.5	1.3	0.2	-0.6	1.3

4.3.4.3 Interior insulation layer

Interior insulation layer is subjected to temperature variation of 11˚C-24˚C for selected ten Canadian locations. Since it is evident from laboratory R-value data that for all samples investigated dip in R-value start when temperature drop below 10˚C or higher than 24˚C. Thus R-value variation in polyiso insulation interior layer is higher than $R_{T22°C}$.

Figure 46 revealed winter season thermal performance of polyiso insulation interior layer under Canadian climatic conditions. $Polyiso_{WUFI}$ and $Polyiso_{A-D}$ have higher R-values than $R_{T22°C}$ in all Canadian climate zones. R-value of $Polyiso_{A-D}$ revealed increase of 1.4% to 2.3% from $R_{T22°C}$ when subjected to temperature conditions of Zone 4, 5, 6, and 7A. However, due to extreme cold climate of zone 7A and 8, R-value of $Polyiso_{A-D}$ revealed 2.1% to 2.7% higher R-values from $R_{T22°C}$. Furthermore, the comparison between $Polyiso_{WUFI}$ and $R_{T22°C}$ indicated that R-value of $Polyiso_{WUFI}$ are higher than $R_{T22°C}$ by 2.8% to 6.6% from in Canadian climate zones.

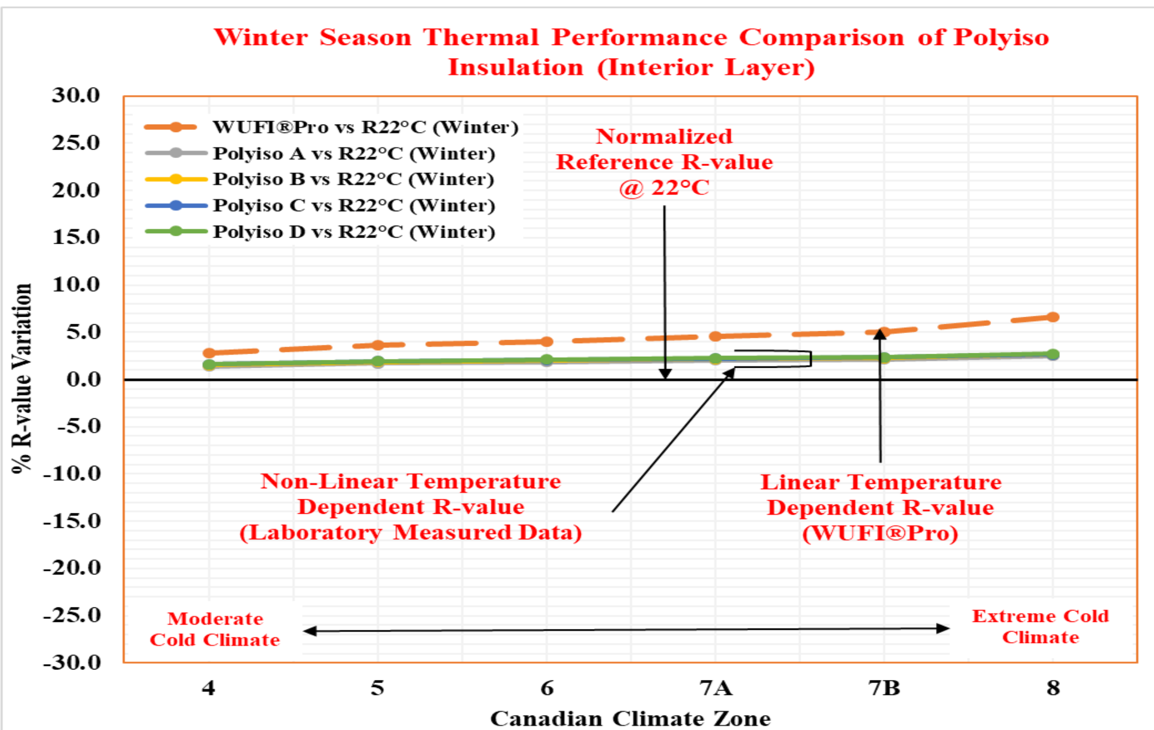

Figure 46 Winter season thermal performance of polyiso insulation interior layer in Canadian climates

Figure 47, shows annual thermal performance of polyiso insulation middle layer. $Polyiso_{A-D}$ indicated variation of 0.8% to 1.9% and $Polyiso_{WUFI}$ revealed increase of 1.7% to 4.4% from $R_{T22°C}$ in Canadian climate zones.

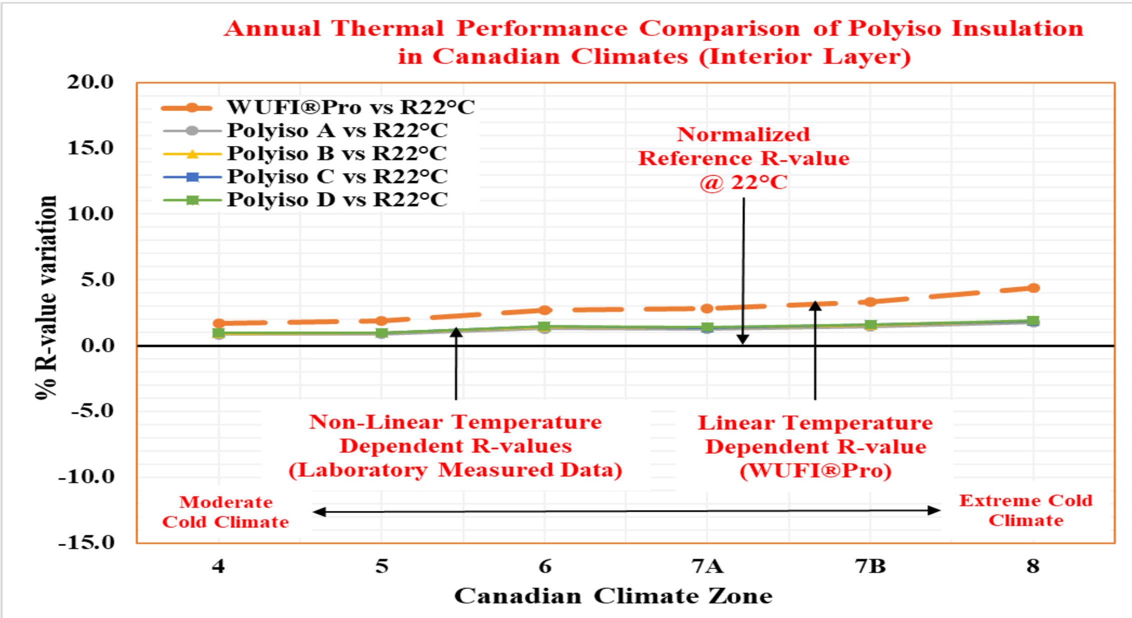

Figure 47 Annual thermal performance of polyiso insulation interior layer in Canadian climates

See Figure 48, during summer season, in all climate zone the laboratory measured polyiso R-value show variation between -0.4% to 0.8 % which is much less than winter season. However, R-value of Polyiso$_{WUFI}$ revealed variation of -0.4% to 1.3% from $R_{T22°C}$ in Canadian climate zones.

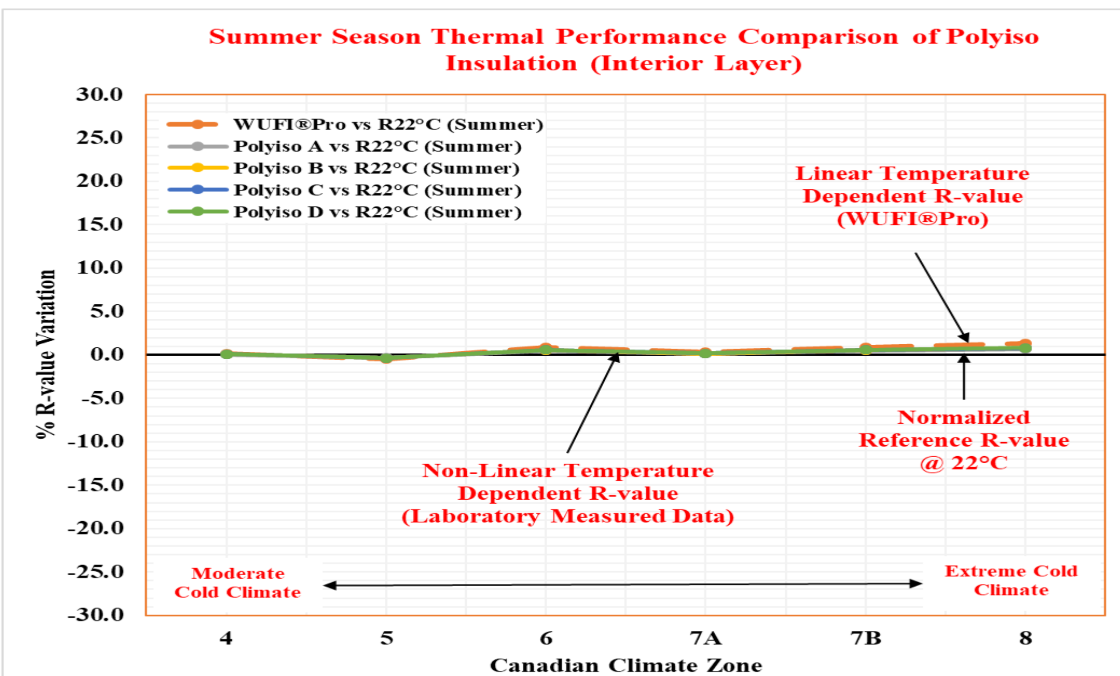

Figure 48 Summer season thermal performance of polyiso insulation interior layer in Canadian climates

Table 7 Thermal performance of polyiso foam insulation interior layer under Canadian climates

Zone	Polyiso$_{WUFI}$ vs R$_{T22°C}$			Polyiso$_{A}$ vs R$_{T22°C}$			Polyiso$_{B}$ vs R$_{T22°C}$			Polyiso$_{C}$ vs R$_{T22°C}$			Polyiso$_{D}$ vs R$_{T22°C}$		
	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)	Annual (%)	Winter (%)	Summer (%)
4	1.7	2.8	0.2	0.8	1.4	0.1	0.9	1.5	0.1	1.0	1.6	0.1	1.0	1.6	0.1
5	1.9	3.6	-0.4	0.9	1.7	-0.3	0.9	1.9	-0.3	1.0	1.9	-0.3	1.0	1.9	-0.4
6	2.7	4.0	0.9	1.3	1.8	0.5	1.4	2.0	0.6	1.5	2.1	0.6	1.5	2.1	0.6
7A	2.8	4.6	0.3	1.2	2.0	0.2	1.3	2.2	0.2	1.4	2.2	0.2	1.4	2.3	0.2
7B	3.3	5.0	0.9	1.4	2.1	0.5	1.6	2.3	0.6	1.6	2.3	0.6	1.6	2.4	0.6
8	4.4	6.6	1.3	1.7	2.5	0.7	1.8	2.6	0.8	1.9	2.7	0.8	1.9	2.7	0.8

The comparison between $Polyiso_{WUFI}$ and $R_{T22°C}$ indicated that polyiso insulation with linear temperature dependent R-value always perform better in winter season. However, this is not the actual behaviour of polyiso R-value in real climatic conditions. However, the laboratory measured R-value of polyiso samples established non-linear behaviour with mean temperature which depict the actual performance of polyiso. Thus, considering linear temperature dependent R-value and constant R-value for energy calculations would give inaccurate results. Furthermore, it means that the actual R-value of polyiso insulation would be overestimated for energy calculations by considering constant R-value and linear temperature dependent R-value.

Chapter 5 Conclusion & Recommendations

1. The impact of in-service boundary temperature conditions on the thermal resistance of polyiso foam insulation board is investigated using hygrothermal simulation tool WUFI® Pro and experimental thermal characteristics test data. Hygrothermal simulation tool considers linear temperature dependent thermal conductivity profiles. The thermal conductivity of polyiso foam in WUFI® Pro at -20°C is 0.018 W/mK which increase by 0.0002 W/mK^2 with every one-degree rise in temperature making it 0.038 W/mK at +80°C.
2. The hygrothermal simulation results indicated that the temperature across polyiso insulation thickness in EPDM and PVC membrane roof assemblies varies linearly in all Canadian locations considered in this study. The outdoor temperature variation ranges from -49°C to 35°C. However, the polyiso insulation exterior layer (1/3rd of total thickness 114.3mm) experienced the maximum temperature variation from as low as -23°C to a high of 27°C. The polyiso insulation middle layer experienced temperature variation between -4°C to 26°C and the same interior layer varied between 11°C to 23°C. Critical observations presented in this paper are based on the thermal response of the exterior layer.
3. The hygrothermal simulation results revealed that building material (e.g. insulation, cover board, type of roof deck etc.) properties also impact in-service boundary temperatures. In this study same insulation thickness, vapour retarder, cover board, and roof deck were considered in the modelled assembly. The hygrothermal simulations predicted similar boundary temperatures across polyiso insulation in EPDM and PVC membrane roofs.
4. Laboratory test data show that in all polyiso samples, thermal resistance is a non-linear function of temperature and the extent of non-linearity reduces with aging. It is observed that polyiso insulation thermal resistance reduces significantly at sub-zero and temperatures higher than 22°C. The data indicate that the laboratory measured thermal resistance of polyiso insulation samples at a mean temperature of -4°C is 3.8% to 6.7% lower than at 22°C mean temperature. The results reported here also indicate that the functional relationship of thermal resistance with temperature changes as a result of accelerated aging at elevated temperature. However, in one instance this functional relationship became almost linear after 28 days aging at 100°C.
5. The thermal performance of polyiso insulation decreases with extreme cold in-service boundary temperature. The laboratory measured results analyzed with in-service boundary temperatures revealed that thermal resistance of polyiso insulation exterior layer decreases

significantly (-14.7%) during winter season for climate Zone 8. Similar trends are noticed for Zone 6 (-1.8%), 7A (-2.9%) and 7B (-5.3%). During summer season, insulation exterior layer is exposed to temperature close to 24°C, and the thermal performance of polyiso remains close (-0.1 to 1.3%) to the reference R-value at 22°C.

6. Considering constant thermal resistance value for energy calculations would give satisfactory results in moderate climate locations like Vancouver (BC), Saint John (NB), and Toronto (ON). However, in extreme cold climate locations like Yellowknife (NT) and Inuvik (NT), polyiso insulation thermal resistance decreases drastically with in-service temperature. Thus, for energy calculations non-linear temperature dependent thermal resistance should be considered in extreme cold climates.
7. Overall, the results from this study confirm that the thermal insulation material manufacturers and hygrothermal simulation software developers should consider thermal resistance values of polyiso insulation at different operating temperatures, as this would allow building designers to accurately assess the energy requirements of buildings.
8. The effect of temperature dependent thermal resistance and aging of insulation on energy performance of building should be investigated in future studies and thereafter appropriate recommendations should be made for the building codes, standards and technical guides.

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Appendix A: Component characteristics of modelled roof configuration in WUFI® Pro

1. EPDM Membrane Roof

Table 8 Component characteristics of modelled EPDM membrane roof [26]

Component	Thickness m (mm)	Density (kg/m^3)	Thermal conductivity (W/m.K)	Specific heat capacity (J/kgK)
EPDM, 60 mil Black	0.00152 (1.52)	1500	0.2	1500
Oriented Strand Board (OSB)	0.0125 (12.5)	725	0.115	1880
Polyisocyanurate Insulation	0.1143 (114.3)	26.5	0.024	1470
Vapour Retarder (1 perm)	0.001 (1)	130	2.3	2300
Plywood	0.015 (15)	600	0.101	1880
Metal deck, perforated	0.0008 (0.8)	7800	46	450

2. PVC Membrane Roof

Table 9 Component characteristics of modelled PVC membrane roof [26]

Component	Thickness m (mm)	Density (kg/m^3)	Thermal conductivity (W/m.K)	Specific heat capacity (J/kgK)
PVC membrane	0.00152 (1.52)	1500	0.2	1500
Oriented Strand Board (OSB)	0.0125 (12.5)	725	0.115	1880
Polyisocyanurate Insulation	0.1143 (114.3)	26.5	0.024	1470
Vapour Retarder (1 perm)	0.001 (1)	130	2.3	2300
Plywood	0.015 (15)	600	0.101	1880
Metal deck, perforated	0.0008 (0.8)	7800	46	450

Appendix B Hygrothermal simulation software (WUFI® Pro) setup

Canadian City: Inuvik, NT (Zone 8)

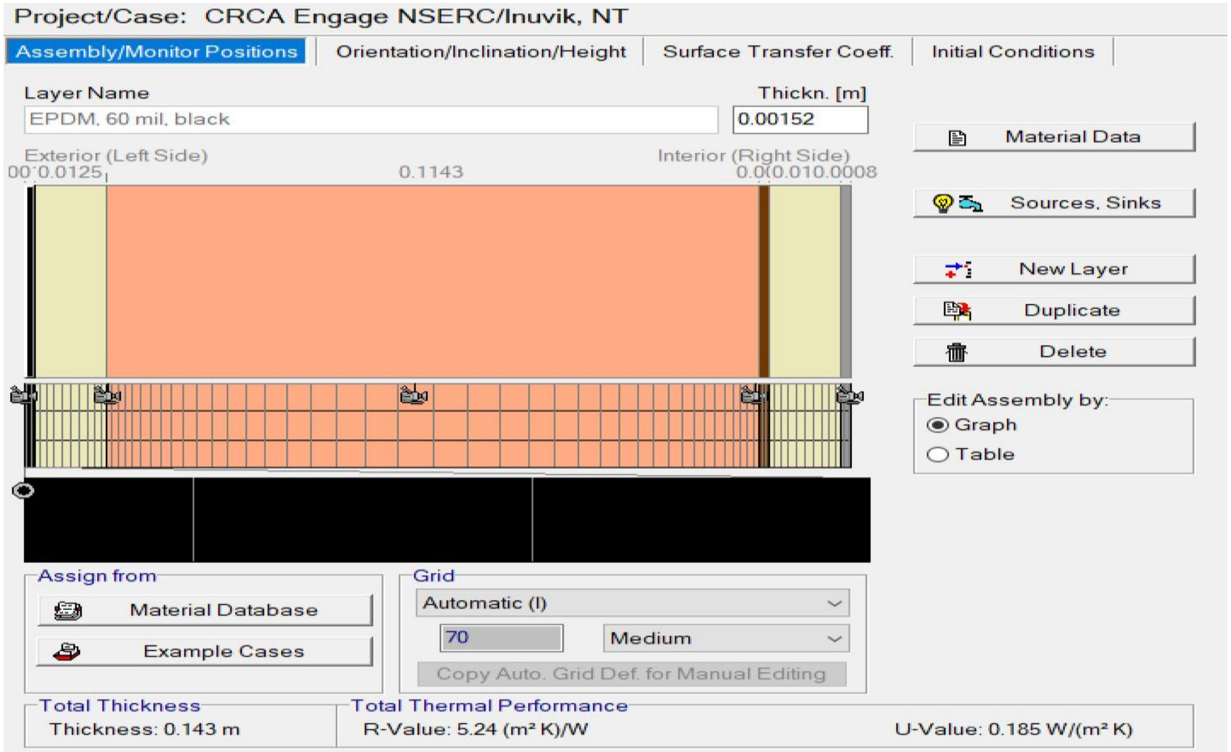

Figure 49 Modelled EPDM roof assembly in WUFI® Pro

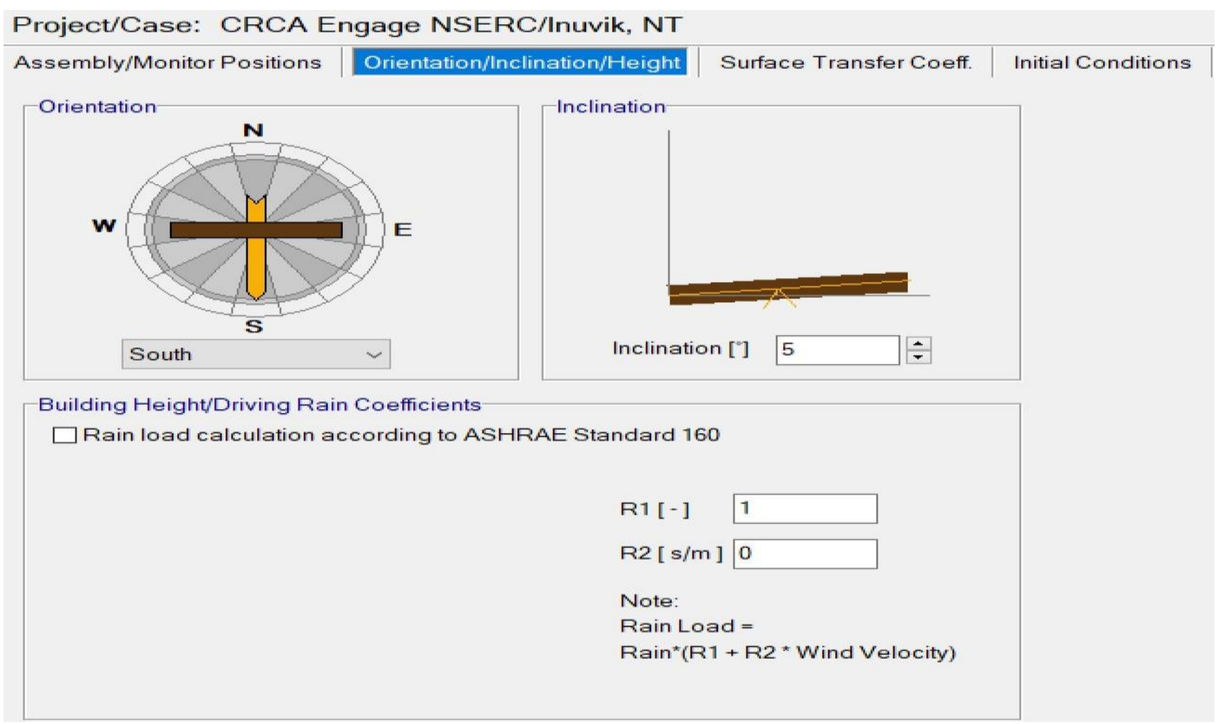

Figure 50 Roof assembly initial orientation/inclination and height setup in WUFI® Pro

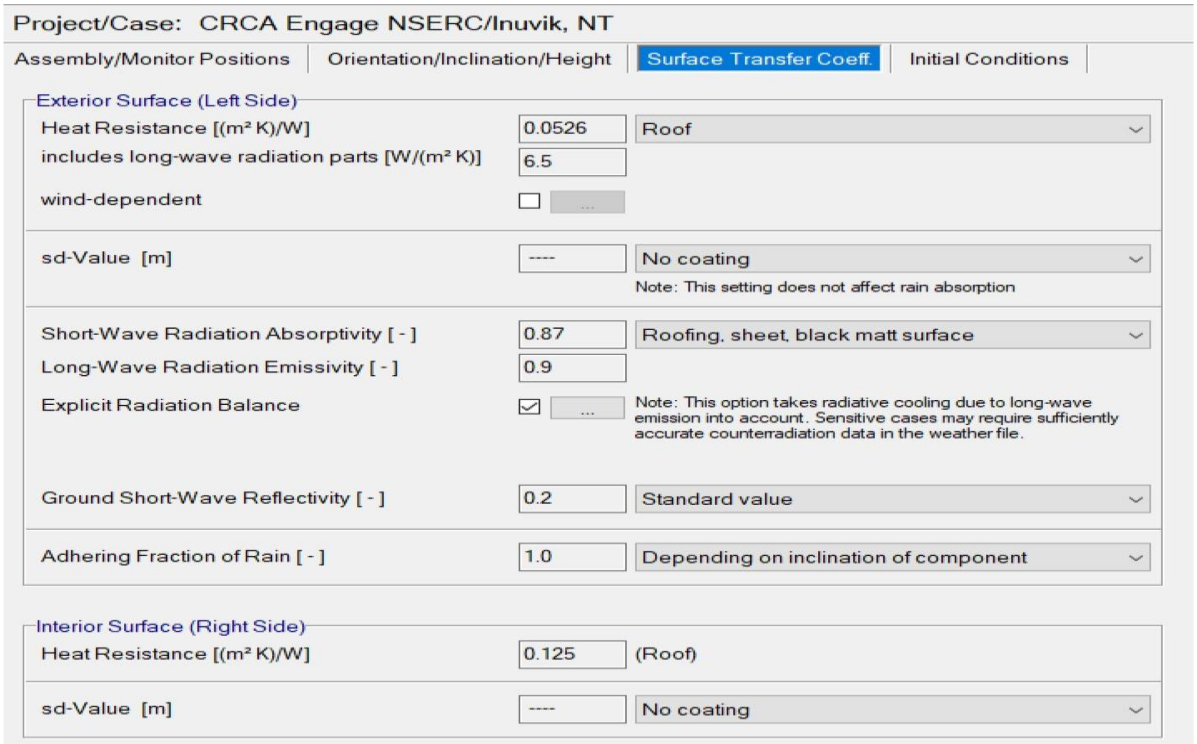

Figure 51 Initial surface transfer coefficient in WUFI® Pro

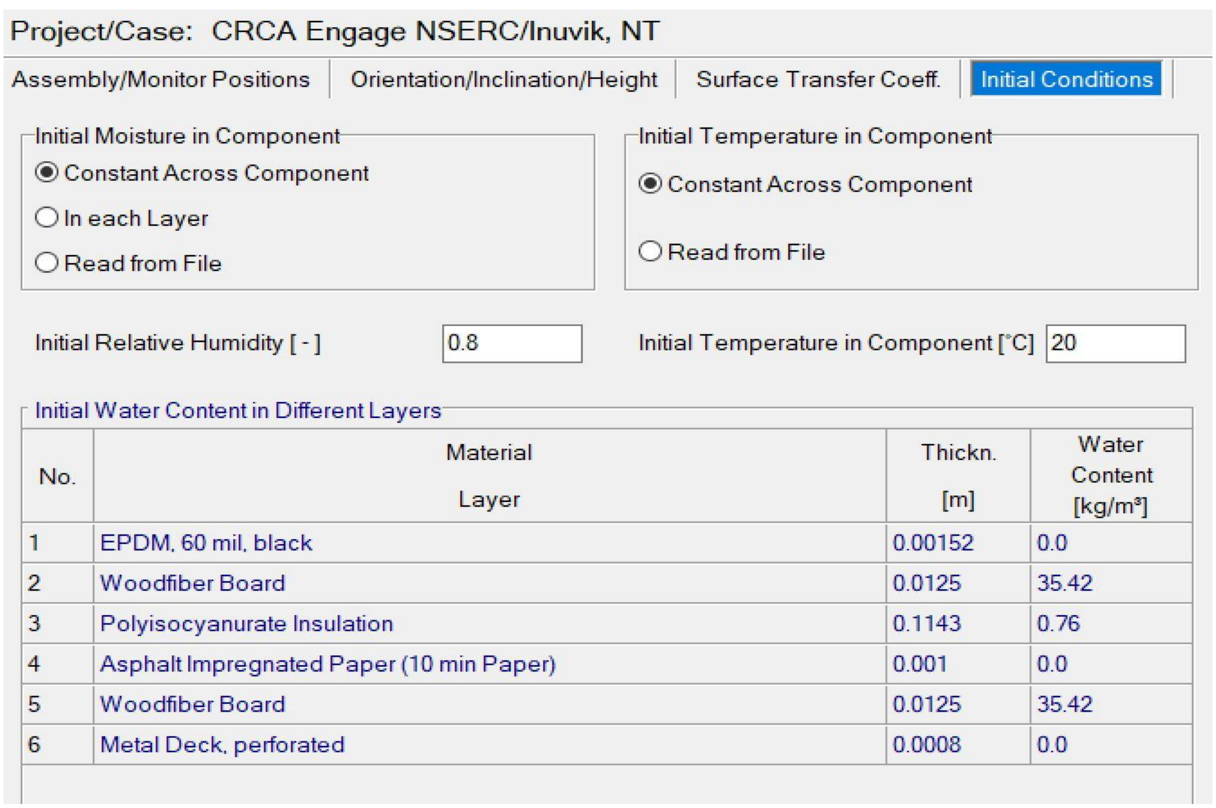

Figure 52 Initial moisture and temperature conditions in WUFI® Pro

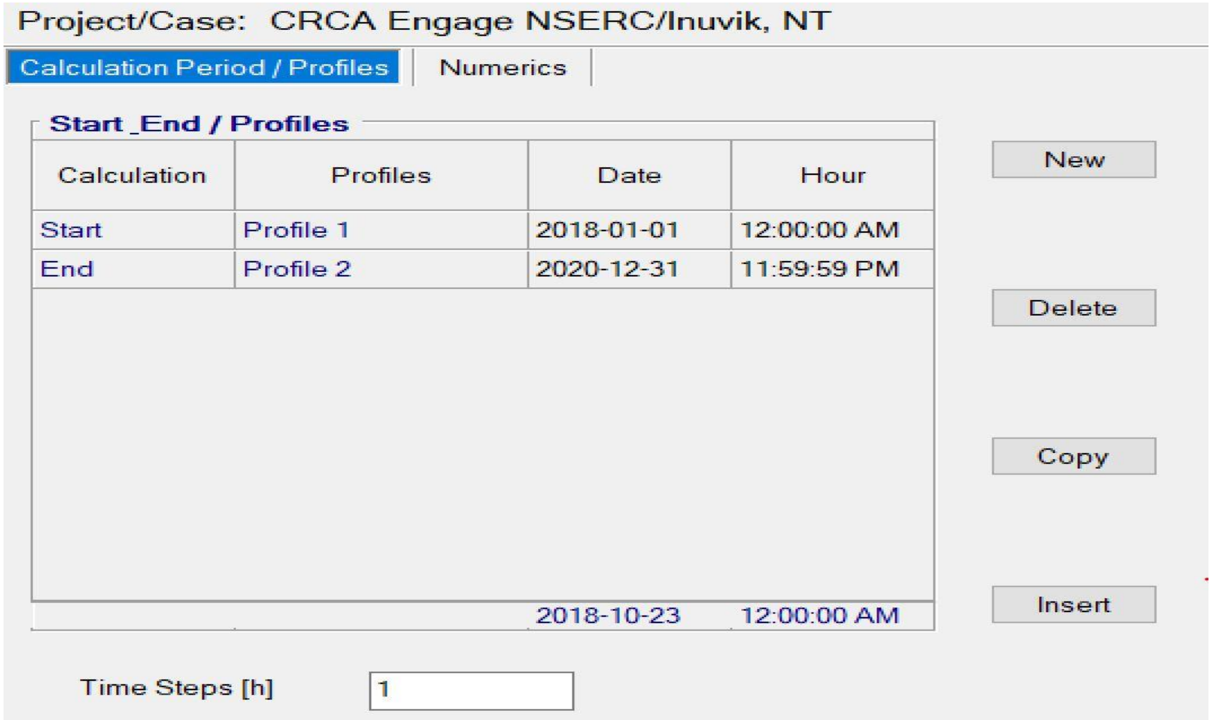

Figure 53 Calculation period selected for hygrothermal simulations in WUFI® Pro

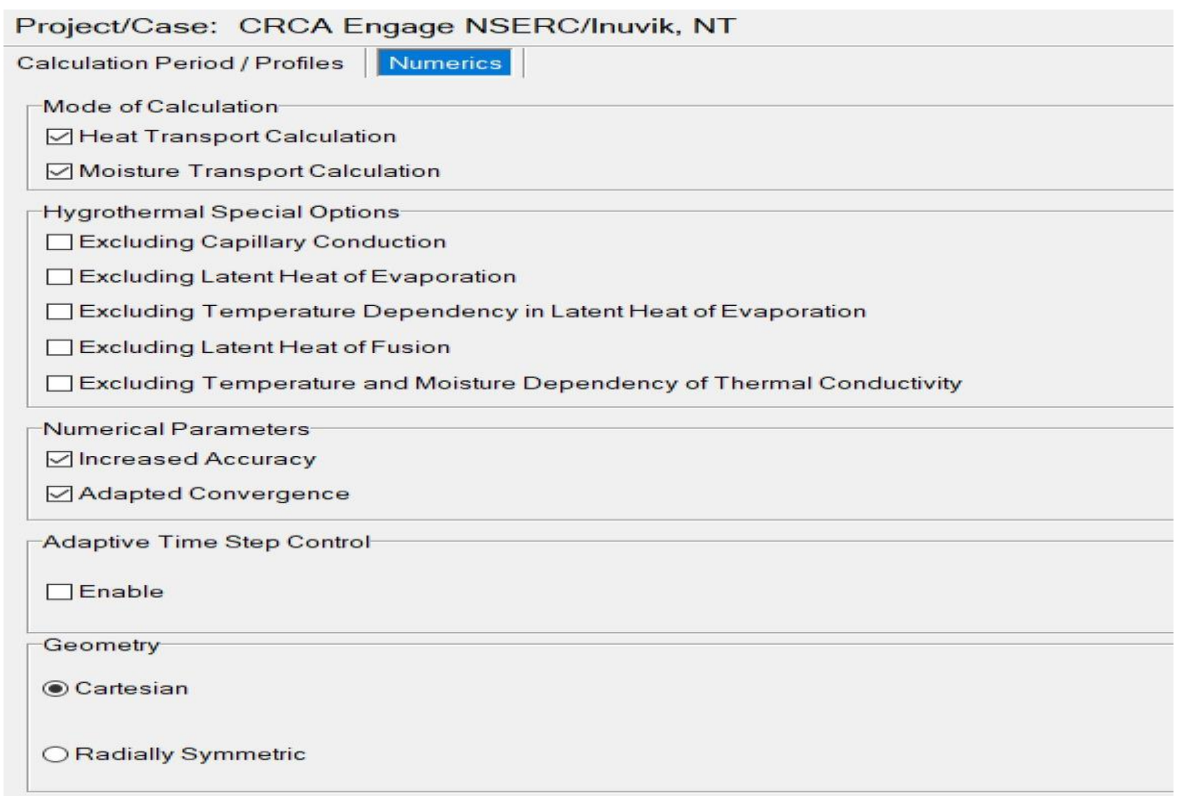

Figure 54 Numeric set up in WUFI® Pro

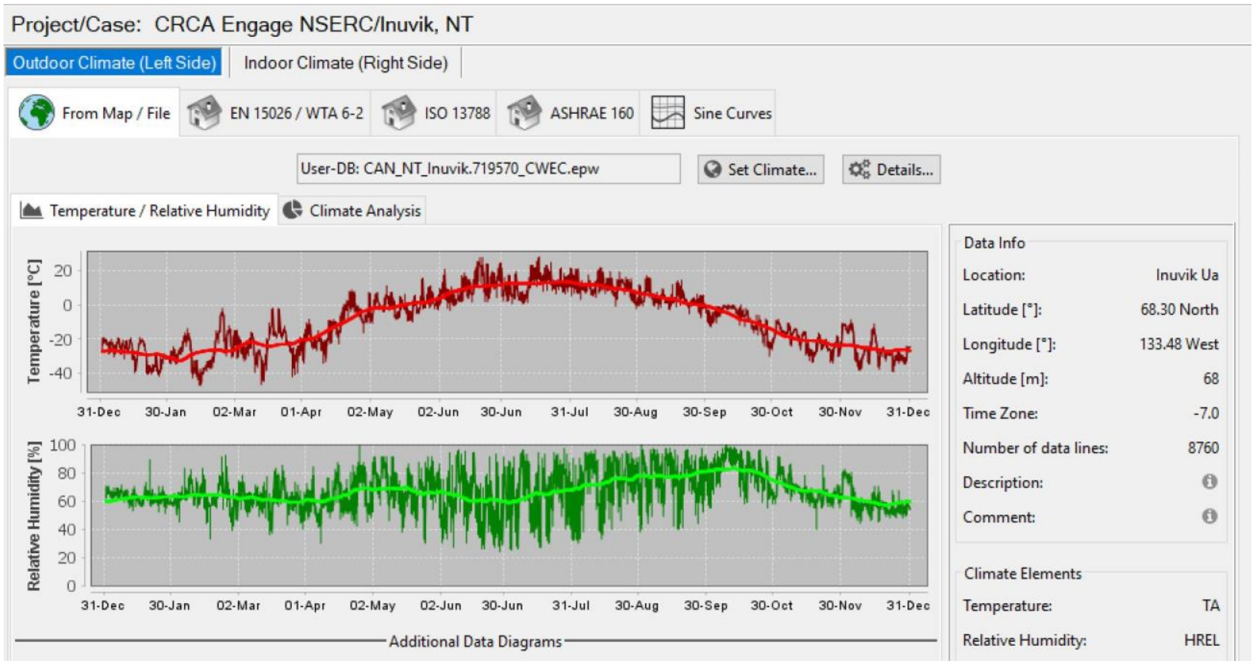

Figure 55 Selected outdoor climate conditions in WUFI® Pro (Inuvik, NT)

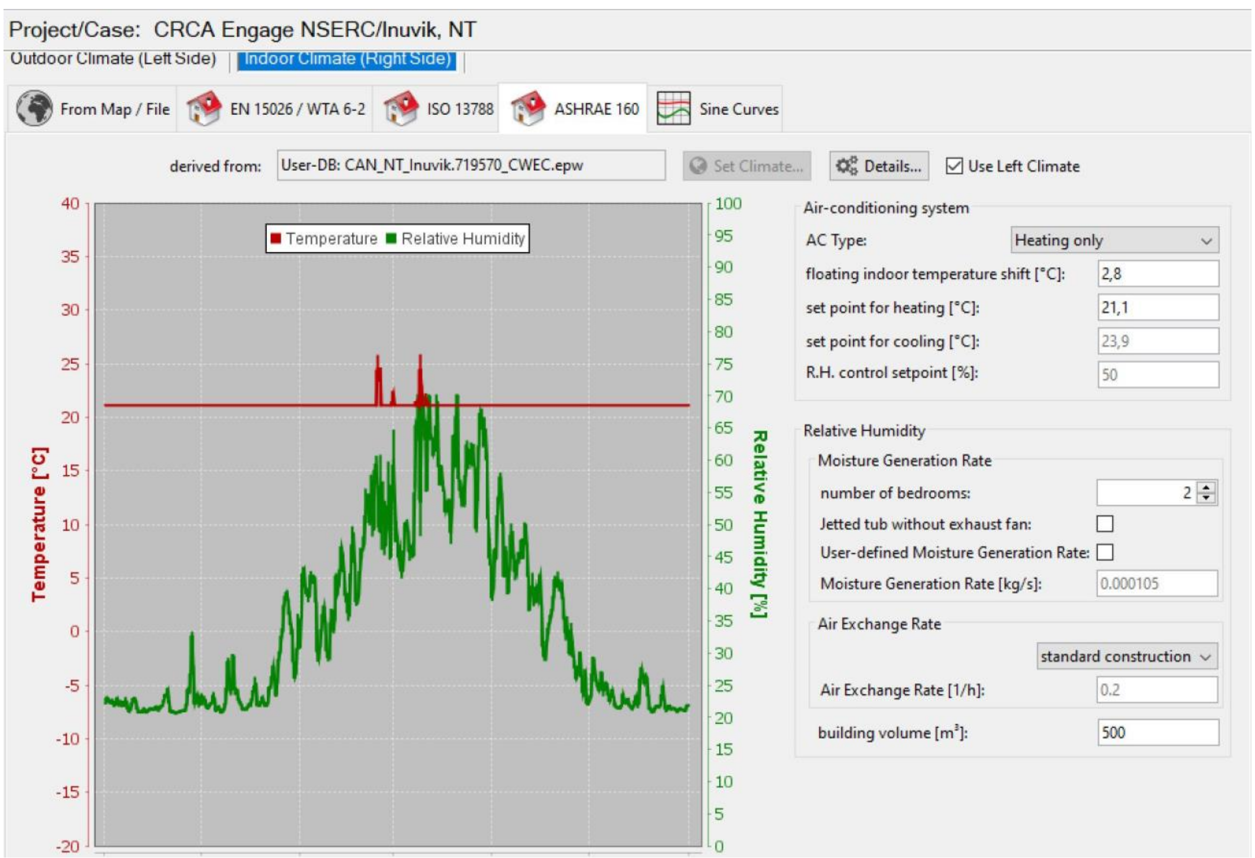

Figure 56 Selected indoor climate conditions in WUFI® Pro (Inuvik, NT)

Appendix C: Hygrothermal simulation output files for ten selected Canadian cities

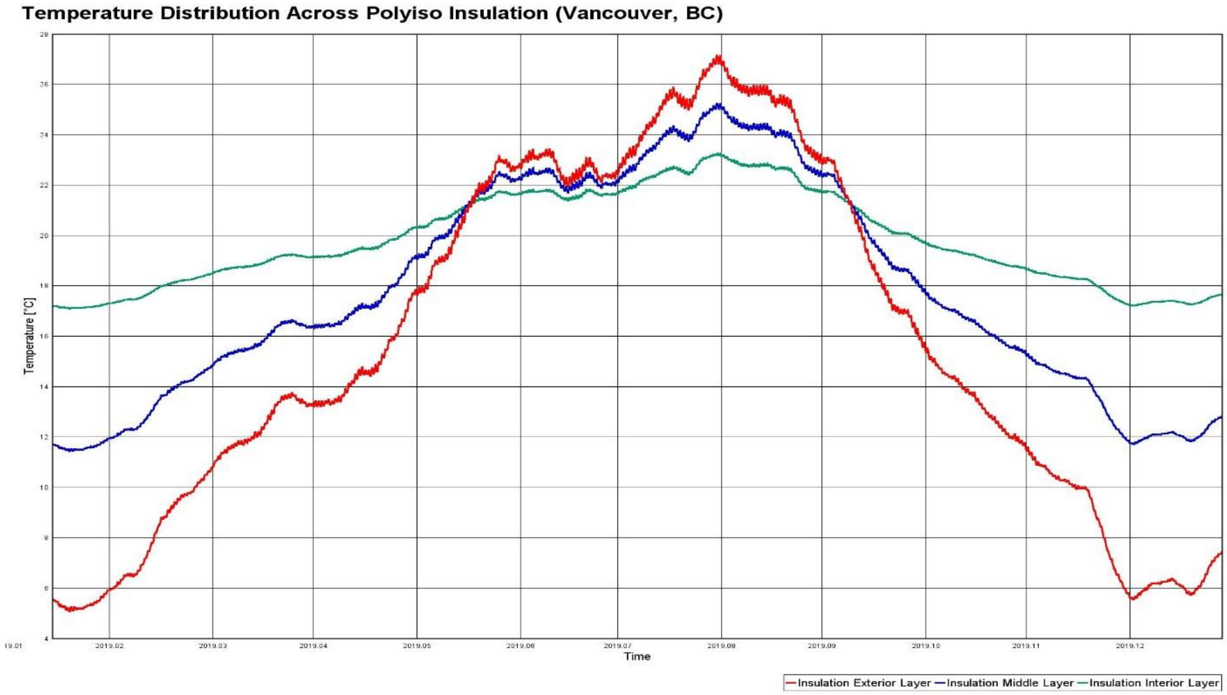

Figure 57 In-service boundary temperature distribution across polyiso insulation for Vancouver, BC

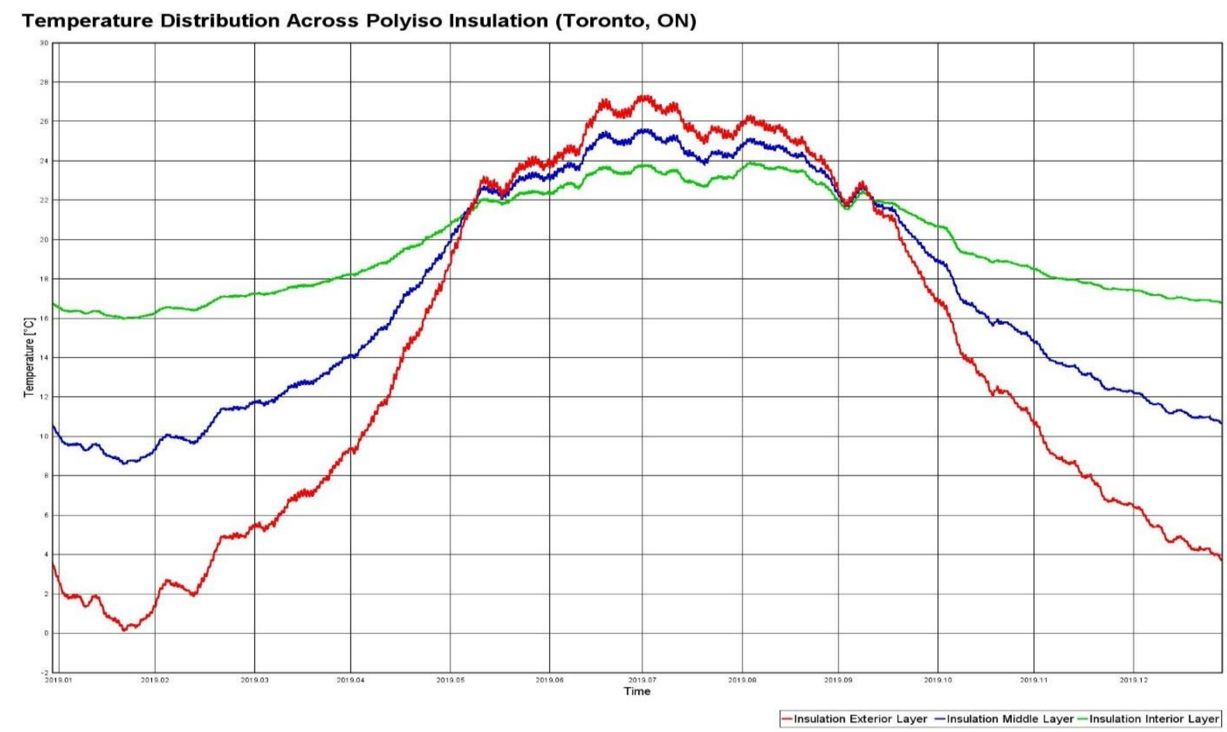

Figure 58 In-service boundary temperature distribution across polyiso insulation for Toronto, ON

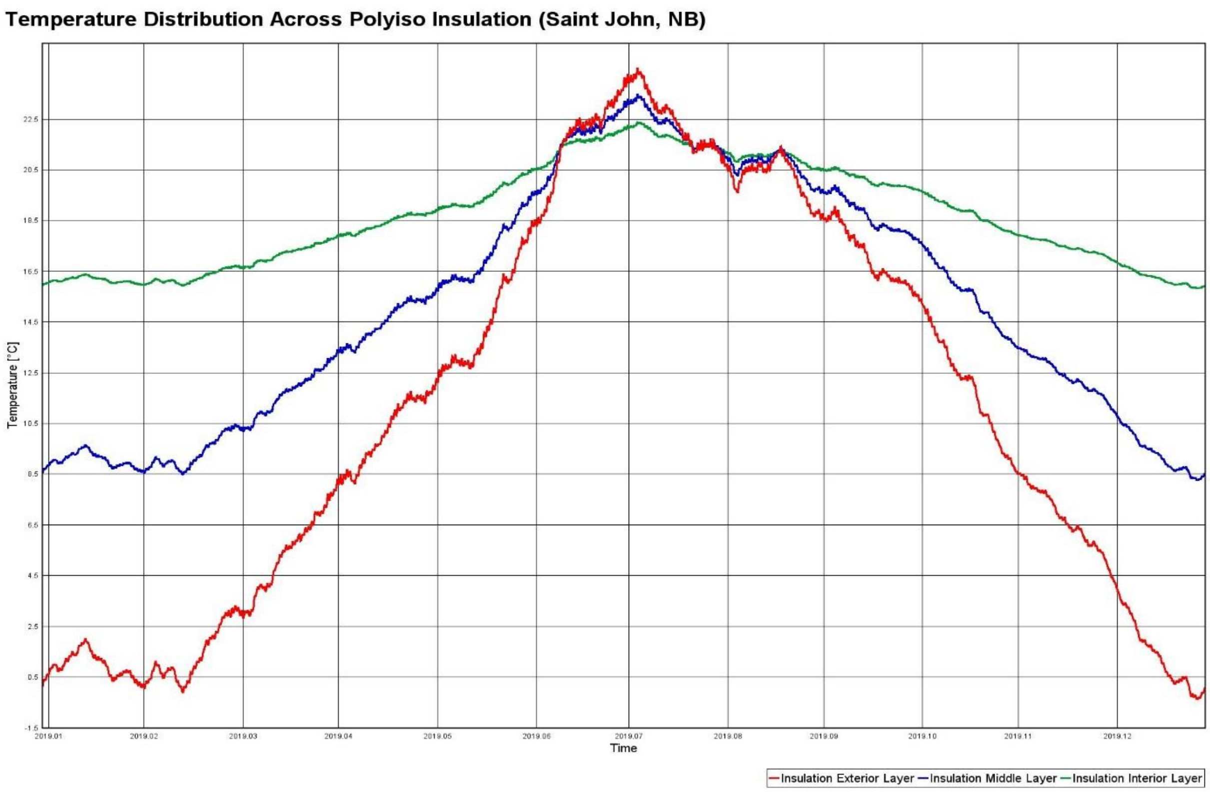

Figure 59 In-service boundary temperature distribution across polyiso insulation for Saint John, NB

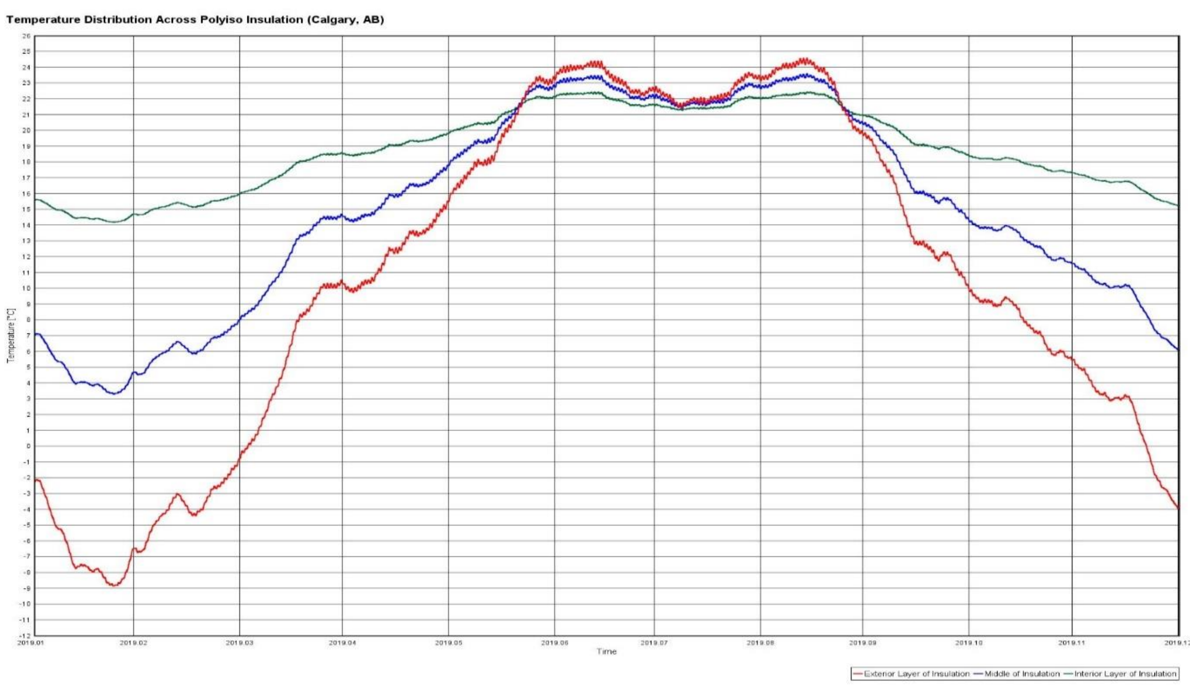

Figure 60 In-service boundary temperature distribution across polyiso insulation for Calgary, AB

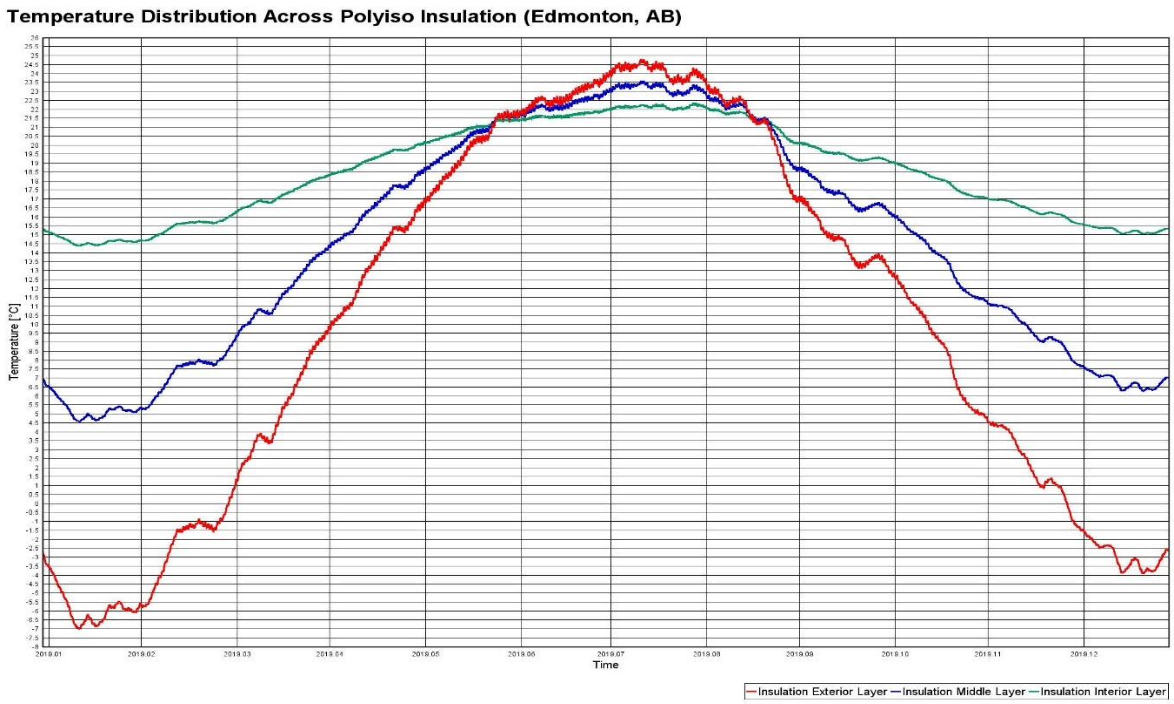

Figure 61 In-service boundary temperature distribution across polyiso insulation for Edmonton, AB

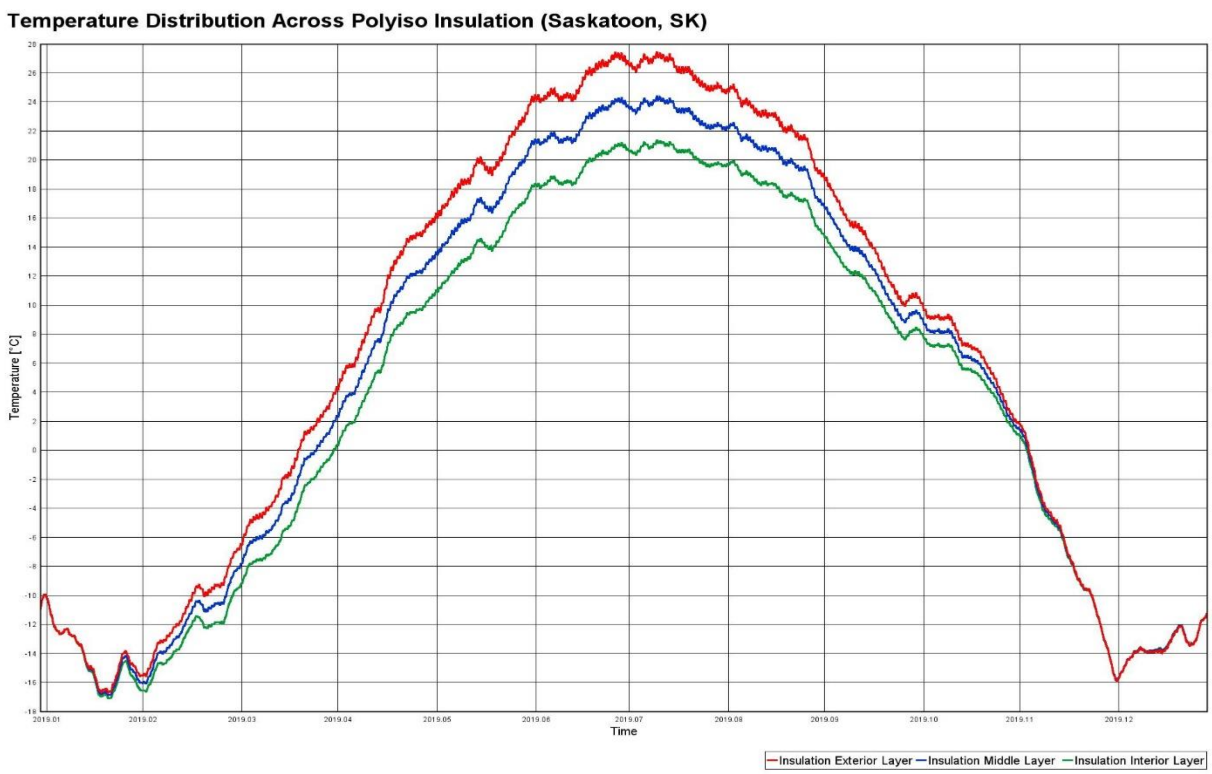

Figure 62 In-service boundary temperature distribution across polyiso insulation for Saskatoon, SK

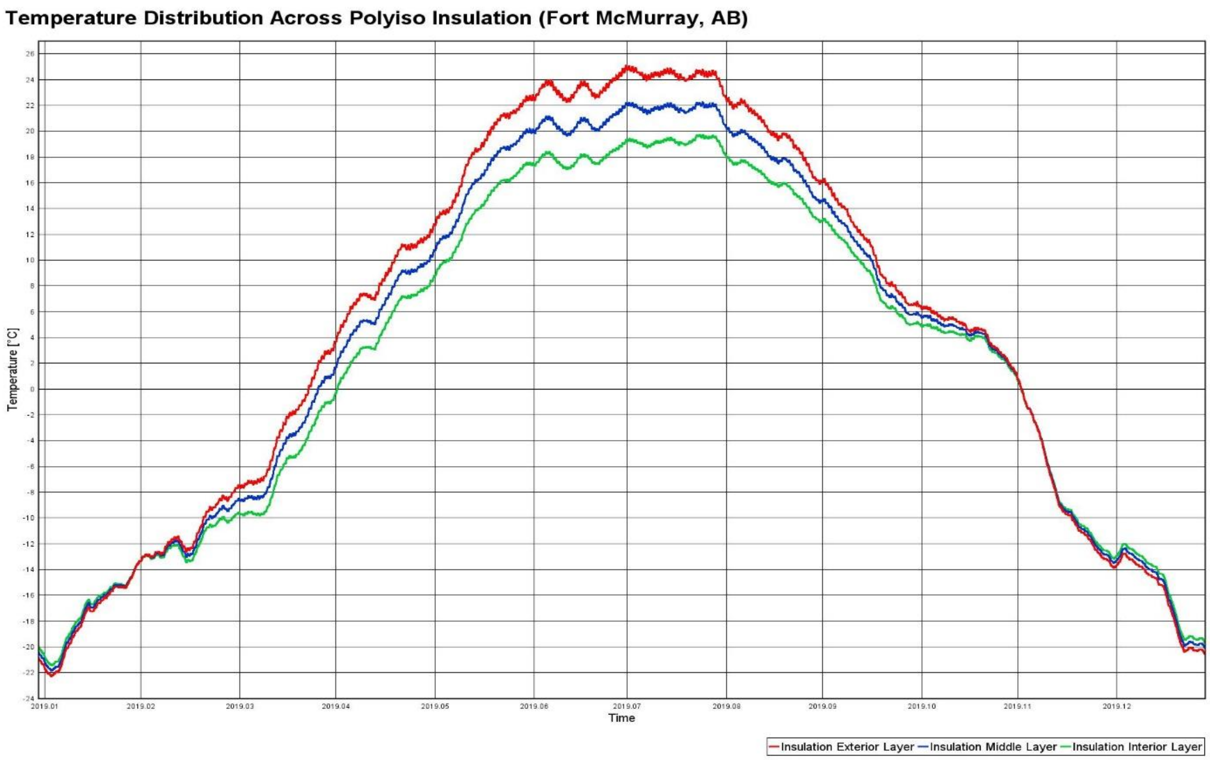

Figure 63 In-service boundary temperature distribution across polyiso insulation for Fort McMurray, AB

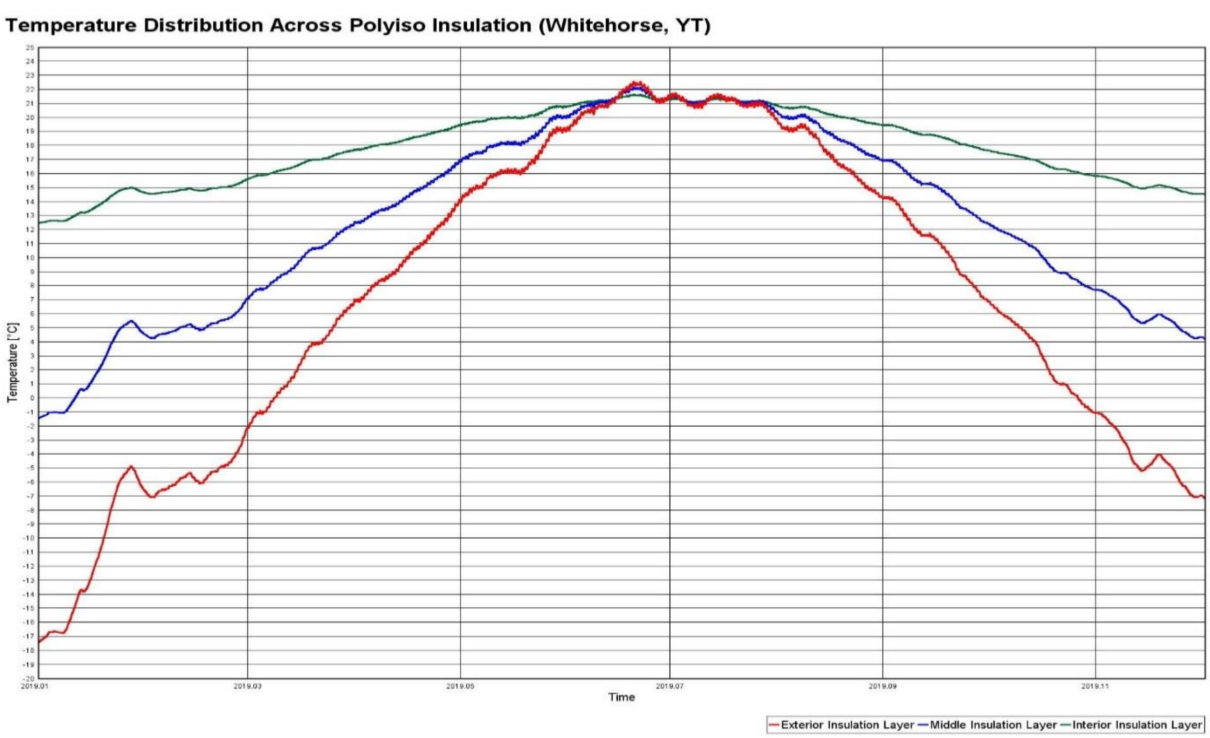

Figure 64 In-service boundary temperature distribution across polyiso insulation for Whitehorse, YT

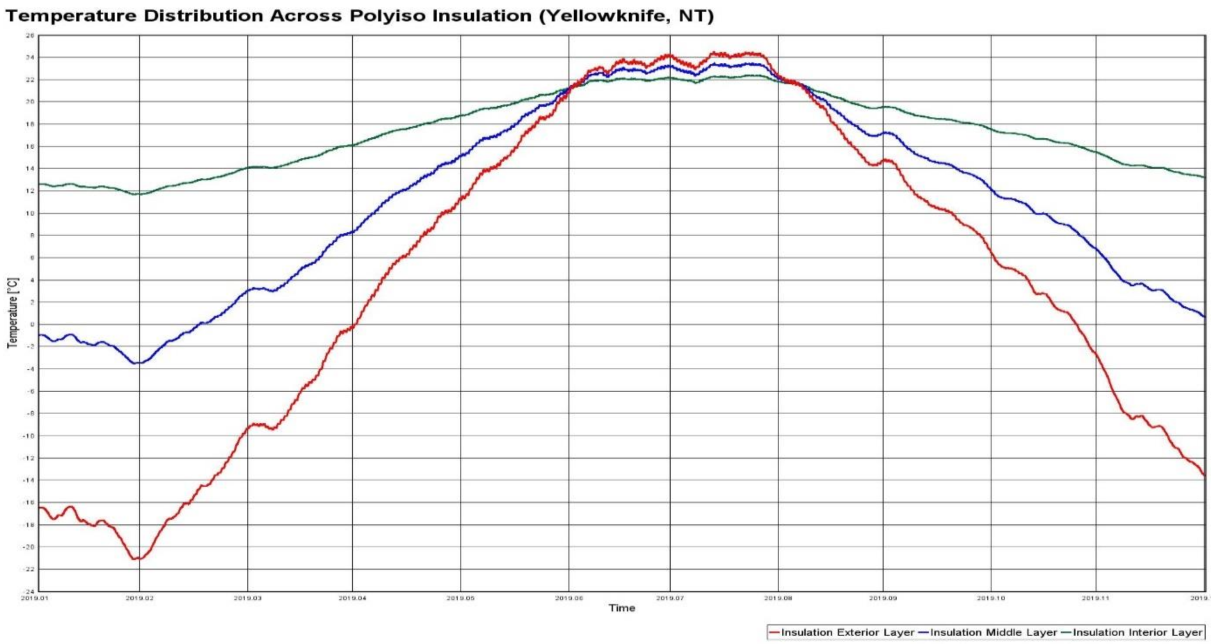

Figure 65 In-service boundary temperature distribution across polyiso insulation for Yellowknife, NT

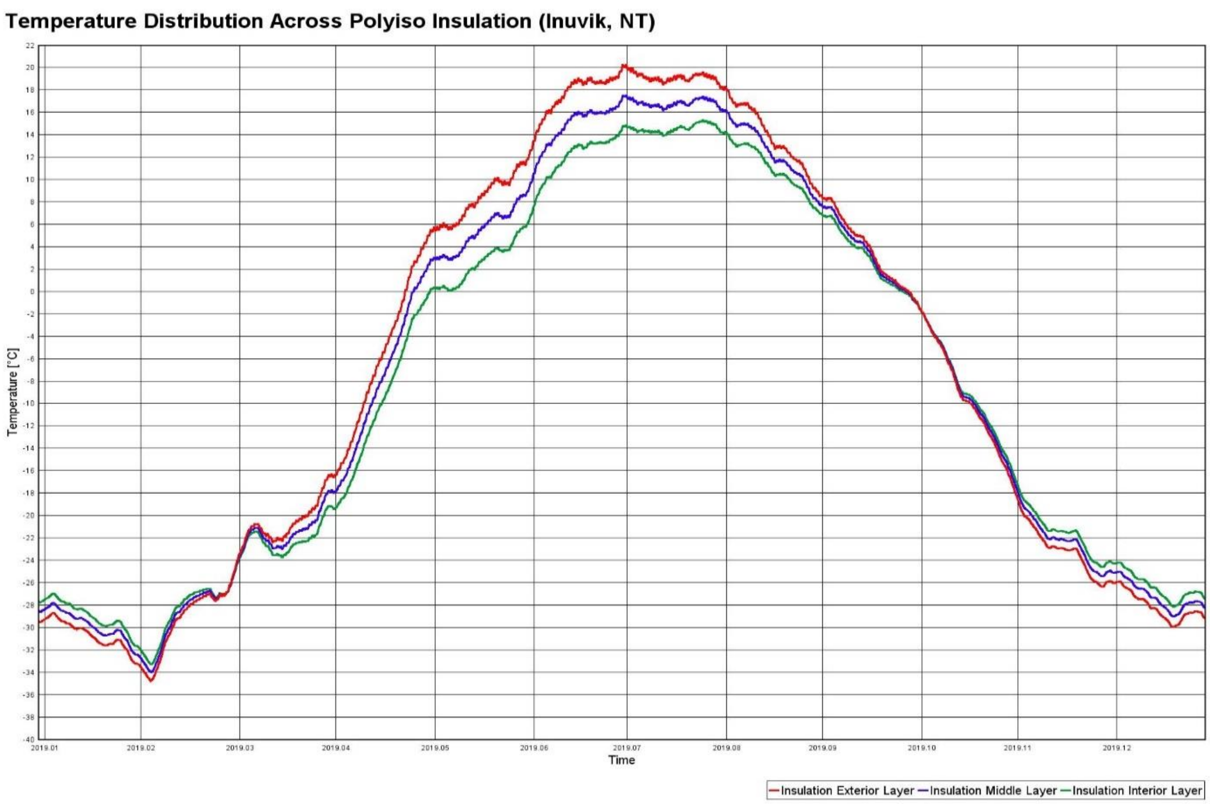

Figure 66 In-service boundary temperature distribution across polyiso insulation for Inuvik, NT

Appendix D Laboratory setup and polyiso insulation

Figure 67 Laboratory testing equipment (Heat flow meter and polyiso insulation)

Appendix E: In-service boundary temperature of selected Canadian cities

In-service boundary temperature across polyiso roof insulation determined from hygrothermal simulations of ten Canadian locations

Table 10 In-service boundary temperature conditions across polyiso insulation

Cities	Vancouver (BC)				Toronto (ON)				Saint John (NB)				Calgary (AB)				Edmonton (AB)			
HDD	2825				3520				4570				5000				5120			
Insulation Layer	EL	ML	IL	Total	EL	ML	IL	Total	EL	ML	IL	Total	EL	ML	IL	Total	EL	ML	IL	Total
Jan	7	12	18	12	1	9	16	9	0	8	16	8	-2	7	16	7	-5	5	15	5
Feb	5	11	17	11	0	8	16	8	-1	8	16	8	-7	4	15	4	-7	4	14	4
Mar	10	15	19	14	4	11	17	11	2	10	17	10	-1	8	16	8	0	8	16	8
Apr	13	16	19	16	8	13	18	13	8	13	18	13	10	15	19	15	9	14	18	14
May	17	19	20	19	19	20	21	20	12	16	19	16	16	18	20	18	16	18	20	18
Jun	23	22	22	22	24	23	22	23	18	19	20	19	23	23	22	23	22	22	21	22
Jul	23	22	22	22	27	26	24	26	24	23	22	23	22	22	21	22	24	23	22	23
Aug	27	25	23	25	26	25	24	25	20	21	21	21	23	23	22	23	23	22	22	22
Sep	23	22	22	22	22	22	22	22	18	19	20	19	20	21	21	21	16	18	20	18
Oct	15	17	20	17	16	18	20	18	15	17	19	17	10	14	18	14	12	15	19	15
Nov	11	15	19	15	10	14	18	14	8	13	18	13	6	12	17	12	3	10	17	10
Dec	5	11	17	11	6	12	17	12	3	10	17	10	-4	6	15	6	-3	7	15	7

Table 11 In-service boundary temperature conditions across polyiso insulation

Cities	**Saskatoon (SK)**				**Fort McMurray (AB)**				**Whitehorse (YT)**				**Yellowknife (NT)**				**Inuvik (NT)**			
HDD	5700				6250				6580				8170				9600			
Insulation Layer	**EL**	**ML**	**IL**	**Total**	**EL**	**ML**	**IL**	**Total**	**EL**	**ML**	**IL**	**Total**	**EL**	**ML**	**IL**	**Total**	**EL**	**ML**	**IL**	**Total**
Jan	-6	5	15	5	-14	0	13	0	-18	-1	12	-2	-17	-1	13	-1	-19	-2	12	-3
Feb	-9	3	14	3	-7	4	15	4	-6	5	15	5	-21	-3	12	-4	-23	-4	11	-5
Mar	-1	8	16	8	-2	7	16	7	-2	7	16	7	-9	3	14	3	-15	0	13	-1
Apr	8	13	18	13	8	13	18	13	7	12	18	12	0	8	16	8	-9	3	14	3
May	18	19	20	19	15	18	20	18	14	17	20	17	11	15	19	15	9	14	18	14
Jun	25	24	23	24	24	23	22	23	19	20	21	20	21	21	21	21	16	18	20	18
Jul	27	26	24	26	26	24	23	24	21	21	21	21	24	23	22	23	22	22	22	22
Aug	25	24	23	24	23	23	22	23	20	20	20	20	22	22	22	22	19	20	21	20
Sep	20	20	21	20	17	19	20	19	14	17	19	17	15	17	19	17	11	15	19	15
Oct	12	15	19	15	9	14	18	14	7	12	18	12	6	12	17	12	2	10	17	10
Nov	5	11	17	11	4	11	17	11	-1	8	16	8	-3	7	15	7	-11	2	14	2
Dec	-9	3	14	3	-7	4	14	4	-7	4	14	4	-14	0	13	0	-17	-1	13	-2

In-service boundary temperature across PVC membrane roof under Canadian climates

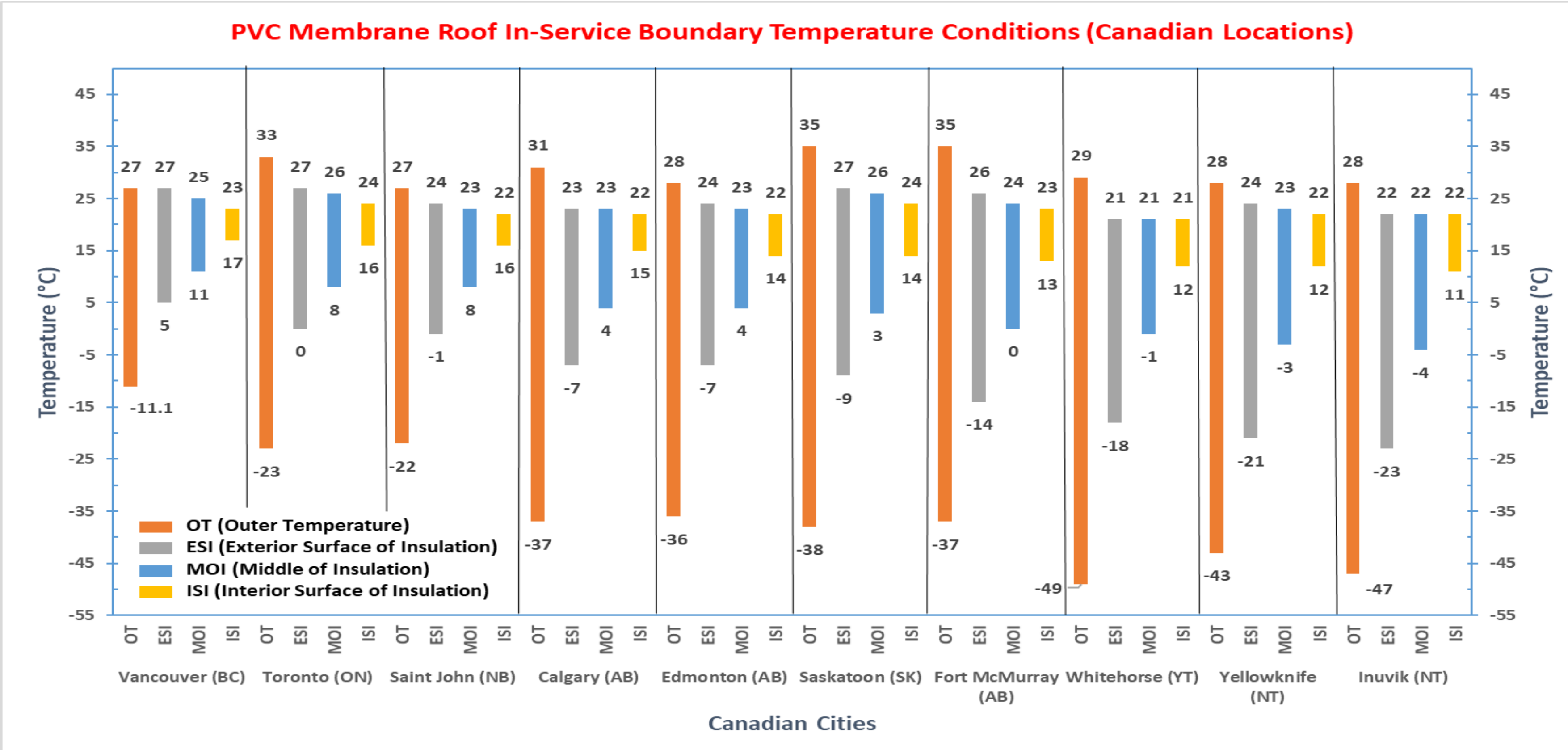

Figure 68 In-service boundary temperature conditions (PVC Membrane Roof)

Appendix F: Thermal conductivity integral (TCI) method

R-value/inch calculations as per TCI Method explained in ASTM C1045

Thermal Conductivity Integral (TCI) Method

T MEAN	T2	T1	k avg	T2 SQ	T1 SQ	T2 CU	T1 CU	T2 QU	T1 QU	X	Y	Z
-4	10	-18	0.026715	100	324	1000	-5832	10000	104976	-4.0	81.3	-848.0
4.5	18.5	-9.5	0.024665	342.25	90.25	6331.625	-857.375	117135.063	8145.063	4.5	85.6	973.1
10	24	-4	0.024247	576	16	13824	-64	331776	256	10.0	165.3	2960.0
24	38	10	0.024781	1444	100	54872	1000	2085136	10000	24.0	641.3	18528.0
43	57	29	0.028383	3249	841	185193	24389	10556001	707281	43.0	1914.3	87935.0

A			
1.0	-4.0	81.3	-848.0
1.0	4.5	85.6	973.1
1.0	24.0	641.3	18528.0
1.0	43.0	1914.3	87935.0

B
0.033611
0.029754
0.027033
0.029795

-4	0.033611
4.5	0.029754
10	0.027967
24	0.027033
43	0.029795

A^-1			
-2.6463E-03	1.2922E+00	-3.4870E-01	5.9146E-02
-1.0172E-01	8.9053E-02	1.8537E-02	-5.8722E-03
6.3951E-03	-9.8774E-03	4.1953E-03	-7.1297E-04
-8.9448E-05	1.5678E-04	-9.6428E-05	2.9092E-05

Variables	
3.0695E-02	a
-4.4301E-04	b
1.3221E-05	c
-8.1427E-08	d

$$k(T) = a + b \cdot T + cT^2 + dT^3$$

Figure 69 Thermal conductivity integral method

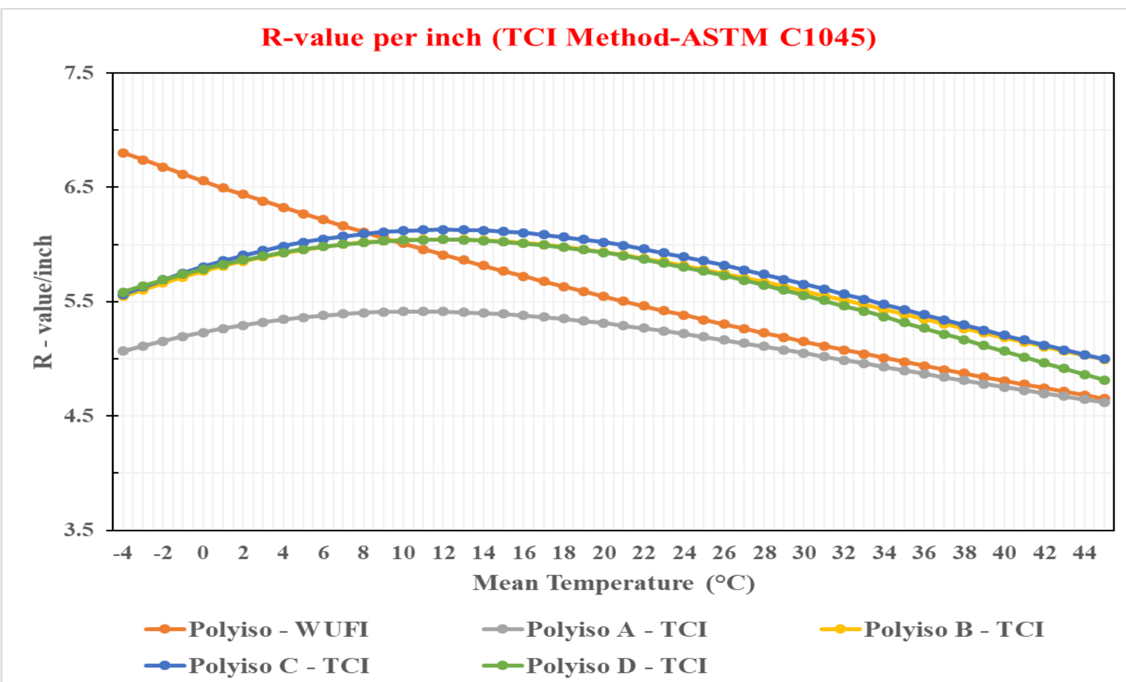

Figure 70 R-value/inch vs mean temperature (ASTM C1045)