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Investigating the Thermal Performance of Expanded Polystyrene as a Function of Core Temperature using Static and Dynamic Thermal Conductivity Values

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Abstract: *When designing and modelling building enclosures, static values for the thermal conductivity of wall materials are used. However, in practice the thermal conductivity of insulating materials is dynamic and increases as temperature increases. Failing to account for the dynamic properties of insulation can introduce errors into the performance simulation of buildings. This paper investigates how the thermal resistance and performance of an expanded polystyrene (EPS) insulation panel varies as a function of core temperature. In order to accomplish this, a guarded hot plate was used. The relationship between thermal conductivity and core temperature was then combined with the Canadian Weather for Energy Calculation data to understand how using a dynamic value for thermal conductivity versus using a static value will affect the heat transferred across the building enclosure. This comparison was accomplished by approximating a wall section using a simplified resistance network model. The results show that considering a dynamic RSI value for EPS results in a 5% difference in predicted yearly heating loads for homes in cold climates such as Ottawa and Edmonton.*

Keywords: Thermal conductivity, RSI value, building envelope, uncertainty, material properties, heat transfer

INTRODUCTION

The building envelope is defined as the barrier between the interior and the exterior conditions. This includes walls, windows, and doors. The primary purpose of the building envelope is to insulate the inside of the building from the outside weather conditions, and consequently, the design of the building envelope has one of the greatest impacts on the heating load of a building. A typical wall section of a stick frame building consists of an outer rain screen, (typically brick or siding), a ventilated air gap, a layer of external insulation, wood sheathing, and loosely packed insulation in the cavities formed by the structural members. The insulating properties of these materials are quantified by their thermal conductivity, which is a measure of the rate at which heat transfer occurs through a material, expressed in units of Watts per meter Kelvin. For building materials, the inverse of thermal conductivity, i.e., thermal resistance (RSI), is commonly used. The RSI value represents the thermal conductivity as a ratio of the material thickness ($\mathrm{m} \cdot K \cdot W^{-1}$).

Most materials used in the construction of typical residential building envelopes are entirely non-conductive solids. In non-conductive solids, heat is transferred primarily through vibrations in the lattice structure (Holman, 2010). As the temperature of a material increases, the intensity of the vibrations in the lattice structure increase. This results in a trend between thermal conductivity and material temperature. As the temperature of a material increases, its thermal conductivity increases linearly (Holman, 2010). This means that the effectiveness of an insulating material within a building envelope changes depending on its average temperature. As a result, the true RSI value of an insulation materials is dynamic, changing as a function of temperature.

Currently, standard practice in building simulation does not account for the dynamic RSI values of insulating materials. Building simulations programs use rated RSI values for the insulating properties of materials, measured at a standard temperature (Swan & Ugursal, 2009). Rated values are measured in accordance to ASTM Standard C518-17, which specify the average testing temperature between the hot and cold surfaces to be 22°C (ASTM International, 2017). Performing simulations based on this rated RSI value introduces inaccuracies into the simulation as components of a building envelope are seldom at 22°C. Throughout a given year, the envelope components have RSI values fluctuating from the rated values at a large enough span to considerably affect the heating loads of the building. This is especially true during times of the greatest heating demand, where temperatures are at their lowest, and thus insulating values at their greatest.

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A key component of the building envelope is the layer of exterior insulation. As minimum insulating values specified within today's building code have increased, external insulation is now required in many locales and building envelope designs. Shown in Figure 1, the exterior insulation is found exterior of the structural members and before the air gap and rain screen. In Canadian building practice, the exterior insulation is typically polystyrene, either extruded (XPS) or expanded (EPS). This study will focus on EPS insulation. In colder climates (such as Canada), the exterior insulation layer is subject to many temperature fluctuations, including very cold temperatures. These temperature fluctuations of the exterior insulation result in measurable changes in the RSI value of the insulation These changes in RSI values have an impact on the heating load of buildings. This impact is not considered in building performance simulation and could be a potential source of inaccuracy.

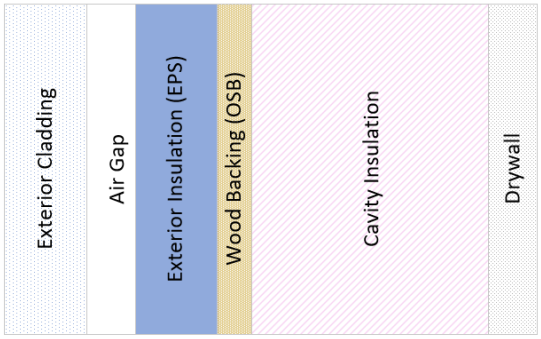

Figure 1: Simplified Wall Estimation

This paper is the first step in an multi-stage project looking at quantifying the impact of dynamic RSI values in building simulation, and will cover three main contributions towards increasing the accuracy of building simulation models:

1. The relationship between temperature and RSI (thermal conductivity) of EPS will be experimentally determined and extrapolated to a useful range;
2. The difference in heat transfer through a wall will be compared using dynamic and static RSI values; and
3. Using weather data for two Canadian cities (Ottawa and Edmonton), the difference in simulated yearly heating demand between dynamic and static RSI values will be compared.

Previous Work

Previous studies have been conducted to examine impact of dynamic RSI values on the cooling loads of buildings. Khouki et al. (Khouki, Fezzioui, Draoui, & Salah, 2016) investigated the impact of temperature dependent thermal conductivity values for polystyrene insulation on the heat transfer through a building envelope. This study consisted of measuring the thermal conductivity of manufactured polystyrene sheets at different temperatures. A linear trend of temperature versus thermal conductivity was created based on the experimental data. Using this trend, Khouki et al (2016). were able to predict the cooling load of a building. An increase in thermal conductivity of 9.4% was predicted for the building walls. A second study, performed by Budawai et al. (2002), investigated how variations of thermal conductivity in insulation materials can impact the envelope-induced cooling loads of a building under different operating temperatures. In the study, Budawai et al. acknowledged that current practice in building energy analysis uses manufacturer rated, static, and thermal conductivity values. This practice fails to account for the changing of thermal conductivity values at different temperatures. The study attempted to quantify how using these values will affect a building's cooling load. A heat flow meter was used to measure thermal conductivity values at different temperatures for a range of building envelope materials, including polystyrene. When considering polyethylene insulation, an estimated change of up to 6% in the cooling load through a building envelope was found.

There is currently no available research on the effect of considering dynamic thermal conductivity of exterior insulation in cold weather climates. As thermal conductivity decreases with temperature, there is potential for the effect of dynamic thermal conductivity to have a significant impact on the simulated heating loads of a building.

Experimental Work

To investigate the effect of dynamic RSI values on building simulation, an experimental trend for RSI values of exterior insulation at varying temperatures was required. This was done using the guarded hot plate at Carleton University. The guarded hot plate was custom built, following ASTM standard

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C177-13 (ASTM International, 2013). The device is shown below in Figure 2.

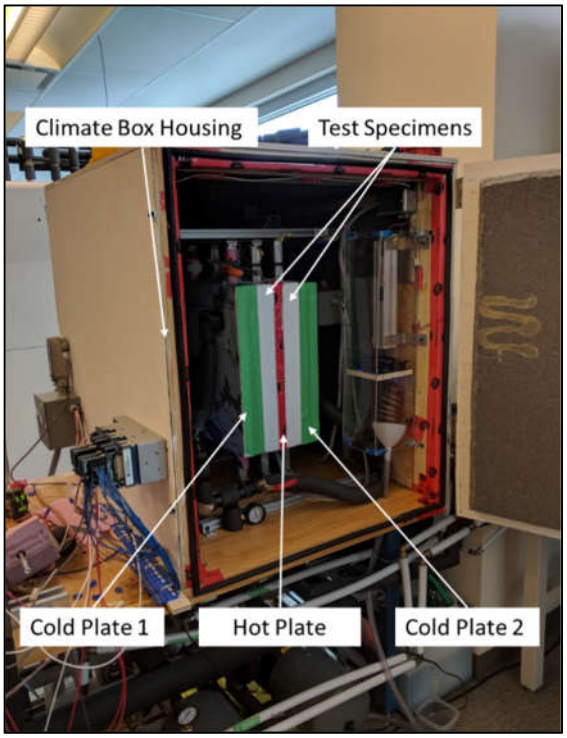

Figure 2: Guarded Hot Plate at Carleton University

A guarded hot plate allows the thermal performance of an insulating material (e.g., RSI) to be accurately measured under controlled, steady state conditions. The guarded hot plate device consists of three aluminum plates. The two outer plates are cooled with a chilled glycol fluid, where the fluid is circulated through the plates at a temperature equivalent to the set-point of the cold plate. The hot plate consists of a center metering plate, which is the area where the thermal resistance of a material is measured over, and a larger guard ring, thermally isolated and surrounding the metering plate. This guard plate is kept at an identical temperature as the metering plate, ensuring 1D heat transfer through the test specimen. Both the metering and guard plates are heated using resistance-based pad heaters embedded within the center of the aluminum plates. A network of thermocouples are installed on both the hot and cold sides of the test specimen to measure the surface temperatures of the test specimen. Two specimens are inserted between the hot and cold plates. A heat flux is introduced across these specimens, and once steady state is reached the average RSI of the two specimens is calculated by measuring the heat input (through the electrical input into the meter plate heater) into the panels, and the temperatures measured by the thermocouples on each face.

This study required the guarded hot plate to create a trend between the EPS center of panel temperature and RSI value. The center of panel is defined as the middle of the insulation panel, halfway between the exterior and interior faces. To obtain this data, two 1.5" EPS specimens were placed inside the guarded hot plate. The thermal conductivity of the specimens was calculated at steady state for a range of center of panel temperature values. Testing was completed at center of panel temperatures of 15°C, 20°C, 25°C, and 30°C. These tests were conducted with different temperature differences across the test specimen to ascertain any influence on overall temperature difference on thermal performance. In total, the test was run 3 times, with temperature differences of 21°C, 30°C, and 40°C.

The results from experimental testing are shown in Figure 3. A linear trendline has been applied to each of the three data sets, and the slopes remain consistent throughout all three test runs. Additionally, the variation in magnitude between the test runs with different temperature differences across the panel was within the uncertainty of the measurement. The values were measured at varying temperature differences to allow for an average RSI to be calculated. The average RSI value was used for every temperature difference experienced in the model. From this point on, temperature differences across the panel are not considered.

To combine the data of the three data sets, an average trendline for RSI values versus center of panel temperatures was created. At each center of panel temperature, the three thermal resistance values were averaged to determine a single RSI value at each center of panel temperature. A trendline was then created using this averaged data set. Since the RSI value of the material changed linearly with temperature (Holman, 2010), the trendline was extrapolated across the complete range of temperatures that the external insulation would typically be exposed to in cold Canadian climates.

Figure 4 provides the trendline for RSI versus center of panel temperature that was used in the analysis. Equation 1 represents the trendline equation used to

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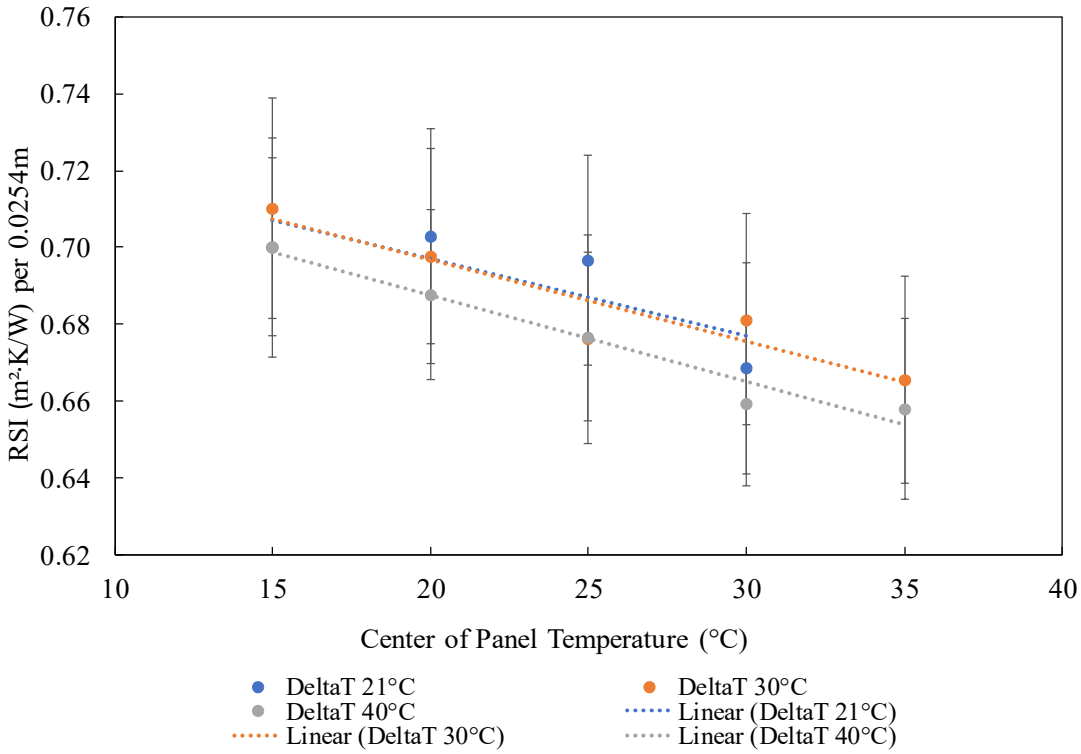

Figure 3:Experimental Data for RSI at Different Center of Panel Temperatures

define RSI as a function of center of panel temperature.

$$RSI = (-0.0021)(T_{\text{Center of Panel}}) + 0.74 \qquad (1)$$

This equation was then implemented into a simplified heat transfer model to determine the impact of the dynamic RSI value on the annual heat loss through a one square meter wall section.

ANALYSIS

The objective of this study was to quantify the difference in heat transfer through the building

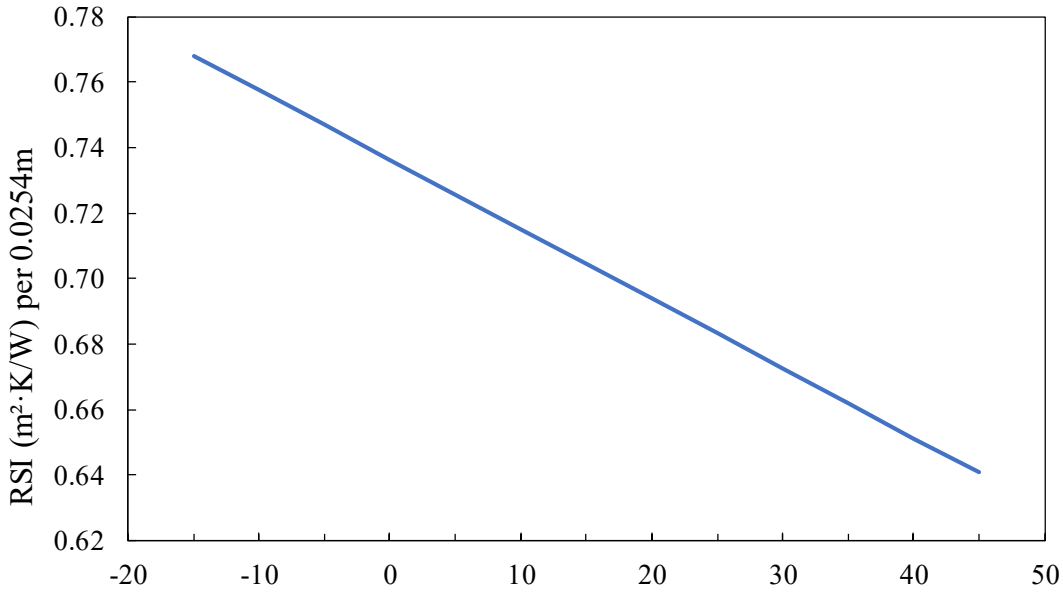

Figure 4: Trendline for RSI at Different Center of Panel Temperatures

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envelope between using rated RSI and dynamic RSI values for the exterior insulation. The heat transfer through the building envelope was predicted using a simplified, 1-dimensional resistance network model for the heat transfer across the building envelope. A generic, one square meter wall section was examined as a proof of concept, and could be extrapolated over the entire surface area of a residential building. The interior surface conditions were kept constant at 22.5°C, while the exterior surface temperature was varied. This simplified model was then first used to determine the center of panel temperature of the EPS, then once the dynamic RSI value of the EPS was determined using the center of panel temperature, the overall heat transfer across the entire wall was calculated.

Using the experimental results from the guarded hot plate, a simplified wall section was used in the analysis. This wall section represented a standard wall section for a stick framed house that would be found in Canada. Table 1 lists the materials and corresponding rated RSI values used in the analysis taken from THERM software. Table 2 provides the convection coefficients used for the interior and exterior environments. The convection coefficients are standard values for interior and exterior surfaces, taken from the THERM software (Lawrence Berkley National Laboratory (NBNL), 2018).

Table 1: Wall Components Thickness and Rated RSI

Material	Rated RSI $[m^2K/W]$	Thickness [m]
EPS (Styrorail, 2018)	2.12	0.07
Plywood (The Engineering Toolbox, 2018)	0.12	0.01
Wall Cavity (16" OC) (Pisupati, n.d.)	1.50	0.09
Drywall (The Engineering Toolbox, 2018)	0.08	0.01

Table 2: Convection Coefficients

Environment	Convection Coefficient $[W/m^2K]$
Interior	2.50
Exterior	25.0

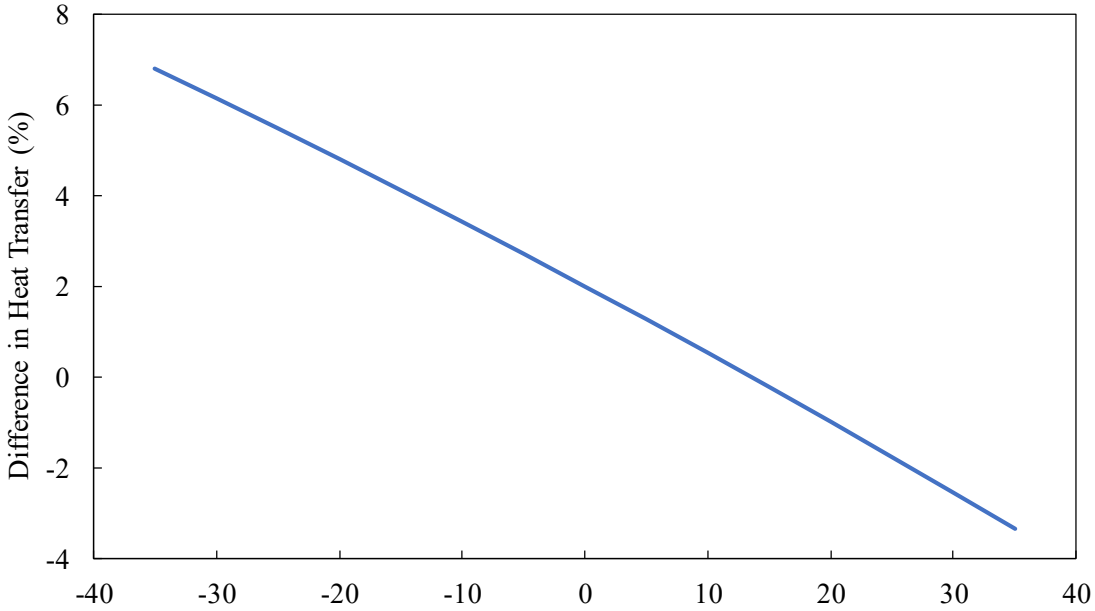

Figure 5:Percent Difference in Predicted Rate of Heat Transfer per Unit Area across a Range of Temperatures

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The first step of the analysis required the rate of heat transfer per unit area, Q in W/m², to be calculated using the rated RSI value. This was done using Equation 2, for a set indoor temperature of 22.5°C and a range of outdoor temperatures from -35°C to +35°C.

$$Q = \frac{\Delta T}{RSI} \quad (2)$$

To determine the true RSI value of the EPS layer, an iterative approach was taken. The first iteration used the rated RSI value for EPS. Once the total heat transfer and temperature profile through the wall were determined, considering both the wall materials and surrounding convection coefficients, a center of panel temperature were obtained for the EPS and a new RSI value for the EPS were found. This was repeated until the RSI value converged, which was defined as a change of less than 0.1%. The final RSI values were then used to calculate the heat transfer through the wall section at the given conditions. This was repeated at intervals of 5°C, from -35°C to +35°C exterior conditions. Figure 5 shows the percent difference between the calculated heat transfers using rated and dynamic RSI values at each temperature interval.

Figure 5 demonstrates that the difference in heat transfer between rated RSI and dynamic RSI approached zero at the temperature in which the rated RSI value was measured. The difference then increases linearly as the temperature moves from the rated point. The largest difference between predicted heat transfers was 7% at an outdoor temperature of -35°C. The average difference in predicted heat transfer across the complete temperature range was 3%.

DISCUSSION

A substantial difference was found in the predicted heat transfer through a wall section when considering temperature dependent dynamic RSI values as opposed to using rated RSI values. Using dynamic RSI values result in a difference in predicted heat transfer of 0.14% per degree from the rated value.

To determine how this variation in RSI influences the overall annual heating load of a building, the annual heating load was approximated. Using hourly temperature data from Canadian Weather for Energy Calculation data sets, hourly exterior conditions were determined. The heat transfer through the wall using both static and dynamic RSI values for EPS was then calculated for two different Canadian cities, Ottawa and Edmonton. The results are shown below in Table 3.

Table 3: Difference in Heating Loads Between Rated RSI and Dynamic RSI

City	Rated RSI [kWh/m²]	Dynamic RSI [kWh/m²]	Difference %
Ottawa	32.6	30.9	5.30
Edmonton	43.8	41.5	5.40

Table 3 shows that if the rated RSI values are used in annual building simulations, the annual heating loads due to losses through the envelope can be overestimated by as much as 5.4%. As building modellers continue to strive for more accurate models, and continue to add more details to models, this can result in a potentially significant inaccuracy in the model results. This demonstrates a relatively simple simulation input that can have a large effect on how close building simulation models emulate real-life buildings.

These two examples are for cold climate locales, where the heating loads are high. this impact could be reduced in locations with less significant heating loads. Additionally, in a traditional stick framed construction, as the one considered in this study, the external insulation contributes a smaller amount to the overall wall RSI. In this study, the EPS made up approximately 55% of the overall wall RSI. In other building techniques, such as insulated concrete forming, nearly all the insulation comes from the exterior EPS layer. This would result in the overall RSI of the envelope being more sensitive to temperature differences, resulting in even higher differences between heat transfers predicted using dynamic RSI versus rated RSI values.

This work has shown that using the dynamic RSI value increases the accuracy of predicted heat loss through

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the building envelope. Implementing this into larger, annual building simulations could significantly increase the computation time as a result of the iterative process required in calculating the dynamic results. As such, the widespread implementation of dynamic RSI values must be done in a way that factors computational limits into consideration.

CONCLUSIONS

This study quantified the error introduced into building simulations by using rated RSI values rather than temperature dependent RSI values for EPS. Using experimental techniques, a linearized trendline for the RSI value of EPS as a function of center of panel temperature was developed. The experimental results were used in a simplified wall analysis to compute the heat transferred through the wall.

Comparing the heat transfer through the building envelope between using the rated and dynamic RSI values for the example wall tested showed an average difference of 3%, or 0.14% per degree from the rated temperature. Heating loads due to losses through the envelope were estimated using both rated and dynamic values, for Ottawa and Edmonton, and a 5% difference in yearly heat loss through the building envelope was found. Since effort is taken in building simulation to achieve results comparable to actuality, considering dynamic RSI values is a relatively simple way to reduce error in heating loads by over 5%.

FUTURE WORK

This paper has shown that using a rated, static RSI value to calculate the heat loss through a wall section can introduce a significance error, particularly at low exterior temperatures. Although this has been proven in a generic one square meter wall section, the overall impact on the heating load, while factoring in surface area of the walls, and heat loss through other methods including air infiltration must be determined. To do this, the dynamic thermal resistance model will be implemented into a complete house model in EnergyPlus. This model will then allow the impact on simulations of using dynamic RSI values in comparison to static values.

Additionally, this study looked at only a single insulating material in EPS and assumed the impact of temperature was negligible on the remaining materials, including the insulation installed in the structural cavities. Future work will examine the impact of temperatures on all material layers and wall designs, with different ratios of inboard to outboard insulation.

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