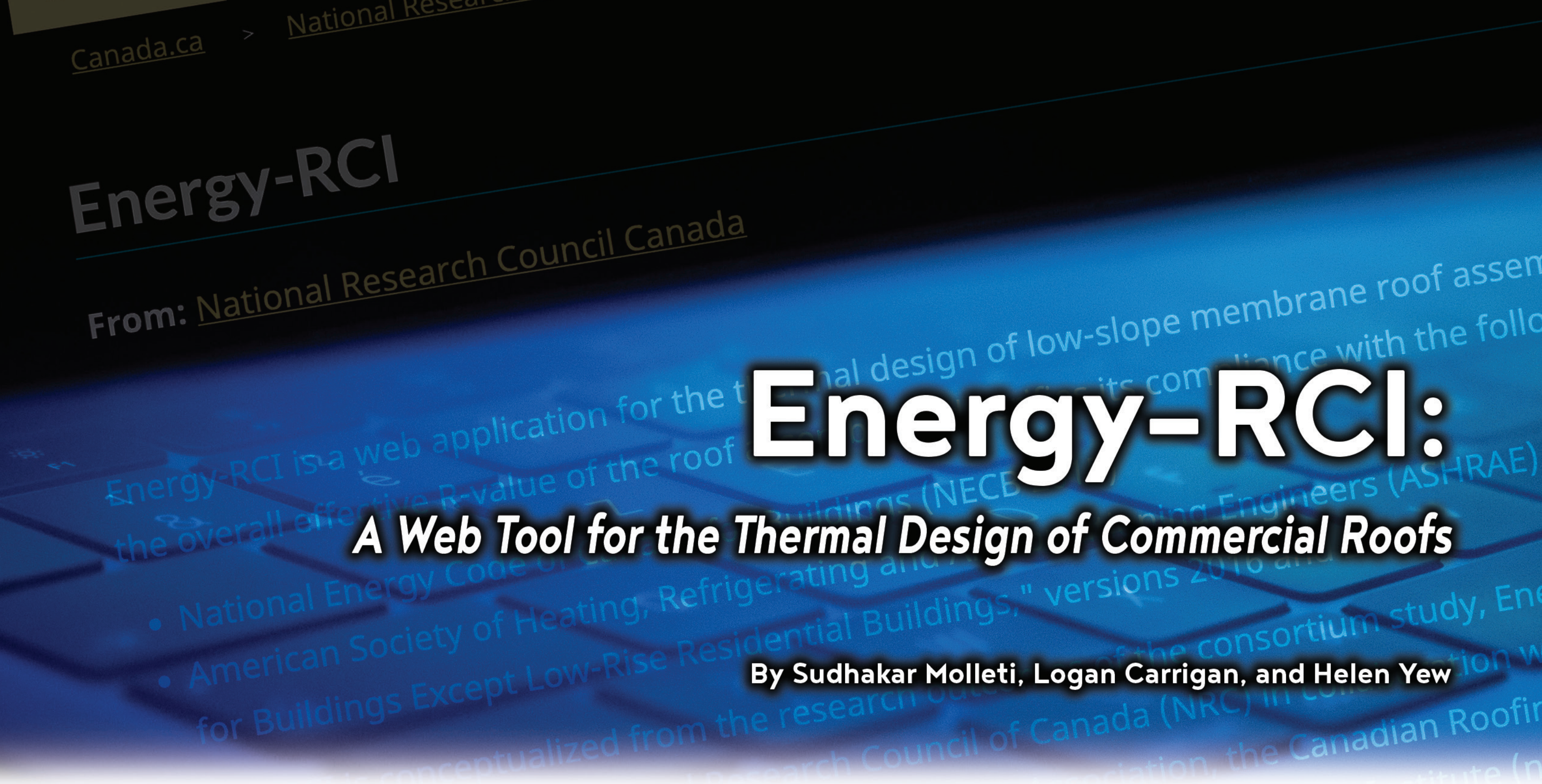

Energy–RCI:

A Web Tool for the Thermal Design of Commercial Roofs

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Energy-RCI is a National Research Council (NRC) Canada web application tool developed for the thermal design of commercial roofs. Available at https://nrc.canada.ca/en/research-development/products-services/software-applications/energy-rci, the aim of Energy-RCI version 1.0 is to provide design solutions for thermal bridging of mechanical fasteners in roof thermal performance. This paper seeks to briefly explain the functions and capabilities of Energy-RCI and how it benefits the Canadian and US roofing industries. Additionally, the existing web-based applications are briefly compared.

DEVELOPMENT OF THE ENERGY-RCI WEB TOOL

Building energy codes, such as ASHRAE 90.1,[1,2] the *International Energy Conservation Code*,[3] and the *National Energy Code of Canada for Buildings* (NECB),[4] provide minimum performance requirements for designing energy-efficient building systems, including roofing systems. However, these codes and standards have mainly focused on the insulation requirements and placed less emphasis on thermal impact factors such as thermal bridging and thermal bypass and their effect on energy loss.

Thermal bridging occurs in roof assemblies in areas where the uniform thermal resistance of the assembly is changed by the inclusion of materials with relatively higher thermal conductivity, such as the mechanical fasteners. For example, in low-slope membrane roofing systems, mechanical fasteners are used to secure the individual components and provide resistance against wind uplift forces. The three standard roofing system types that fall into this category are the mechanically attached roofing system (MARS), partially attached roofing system (PARS), and induction welded roofing system (IWRS). The number of fasteners or fastener density in each system depends primarily on the required wind uplift resistance that the system must sustain to meet the prescribed design loads.

Currently, in the roofing industry, documents such as ANSI/SPRI-WD1[5] and FM 1-29[6] provide performance-based fastener densities for mechanically fastened roof assemblies. For assemblies where these criteria are not specified, fasteners can be added prescriptively or based on specifications from roofing manufacturers. Based on current industry practice, the fastener densities in MARS, PARS, and IWRS can range from 0.15 to 1 fastener per square foot (1.6 to 10.8 fasteners per square meter). However, the thermal bridging resulting from these fastener densities is not currently addressed in the thermal design of roof assemblies.

As part of efforts to enhance the energy efficiency of the commercial roofs, the NRC developed the Energy Resistance of Commercial Roofs (ERCR) industry consortium. The consortium partners include IIBEC, National Roofing Contractors Association, Canadian Roofing Contractors Association, Roofing Contractors Association of British Columbia, Sika, Trufast, EPS Industry Alliance, Rockwool, Soprema, 2001 Company, and Natural Resource Canada's Program of Energy Research and Development.

The ERCR consortium conducted a comprehensive experimental study to quantify the thermal bridging of fasteners in standard configurations within widely implemented roof assemblies. The designed roof assemblies are consolidated into three effective *R*-value categories—R-26, R-31, and R-36—which represent the seven climatic zones in North America. More than 100 experiments were conducted to quantify the impacts of fastener density, fastener location, fastener diameter, and fastener penetration depth on the thermal performance of the designed roofing assemblies. From the experimental data, the thermal bridging of fasteners was quantified in terms of the "relative" decrease in effective *R*-value (**Fig. 1**) and Chi factors (χ). The Chi factor is a point transmittance of the fasteners used in the particular assembly (watt/kelvin). It corrects the thermal transmittance at each of the fastener densities used in the roof design.

To identify the additional thermal resistance required to compensate for the thermal bridging losses, fastener compensation factors were also developed in the ERCR consortium study. For example, the thermal resistance of an R-31 roof assembly designed with a fastener density of 0.625 fasteners/ft^2 must be increased by roughly 15%, to approximately R-36, to meet the target design value after compensation.

The NRC developed Energy-RCI to facilitate the calculation of thermal bridging losses in roof thermal design. The application allows users to quickly determine whether their roof thermal design meets energy standard or code (ASHRAE 90.1[1,2] or NECB[3]) requirements and, if not, what adjustment to the *R*-value is needed to account for the thermal losses.

The purpose of codes and regulations is to enact changes in industry practices that benefit society at large. However, to achieve this societal benefit, code requirements must be easily understood by those individuals who implement them. Thus, NRC and its industry partners found that simply amending the codes would be insufficient, and providing additional guidance to help facilitate change would be the best approach. To that end, Energy-RCI can be used to help determine whether a low-slope roof design is code compliant while also considering the influence of thermal bridging.

USING THE ENERGY-RCI APPLICATION

The Energy-RCI application collects data from the user and generates results with five general steps. At each step, the user must input or choose parameters for the construction of the low-slope roof assembly such as location, assembly type, and material selection. The application uses these inputs and a database of material hygrothermal properties, climate data, and correlations derived from the ERCR consortium study to calculate the thermal performance of the designed roof assembly.

Step 1: Unit Selection

The user first selects the preferred units of measure, Imperial or metric, for the data input and results.

Step 2: Code and Building Location Selections

The user then assigns a project name and selects the energy code, (NECB,[3] ASHRAE 90.1-2016,[1] or ASHRAE-2019[2]) with the thermal requirements that they want the roof assembly design to meet. The user also selects their building's location by choice of city in either Canada or the United States.

Then, depending on the energy code and the building climatic zone location, the application will generate three important indexes: Climate Zone, U-factor requirement, and effective *R*-value requirement.

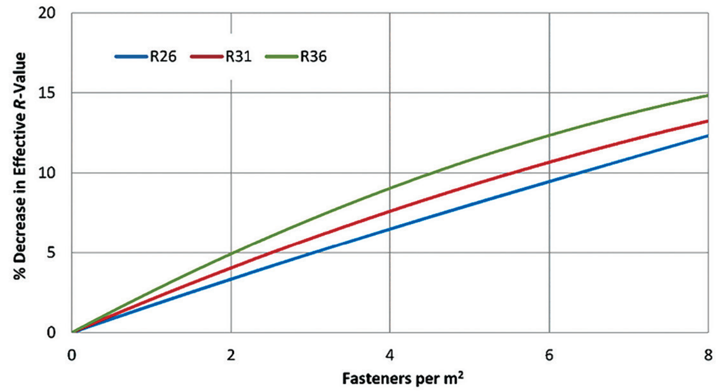


***Figure 1.** Decrease in thermal resistance as a function of fastener density using #14 fastener. Note: 1 m^2 = 10.8 ft^2.*

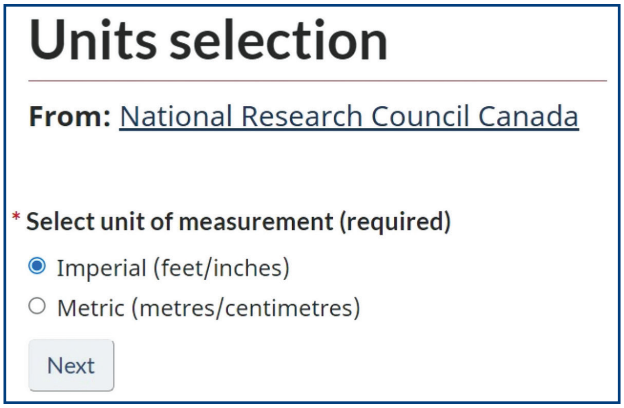


Figure 2. Unit selection screen.

Step 3: Roof Assembly Type

The design of the actual roof assembly begins in step 3. The user starts by choosing the type of roofing system from the following options:

- Adhesive-applied roofing system (AARS): A system in which the roof membrane is bonded to the substrate using adhesives, and all other components below the roof membrane are attached with adhesives
- MARS: A system in which the roof membrane is intermittently attached to the deck using fasteners
- PARS: A system in which the roof membrane is bonded to the substrate using adhesives, and a minimum of one component below the membrane is intermittently attached to the supporting structure using fasteners
- IWRS: A system in which the insulation is fastened to the deck using a fastener and coated plates, and a roof membrane is attached from above to each plate using an electromagnetic induction tool

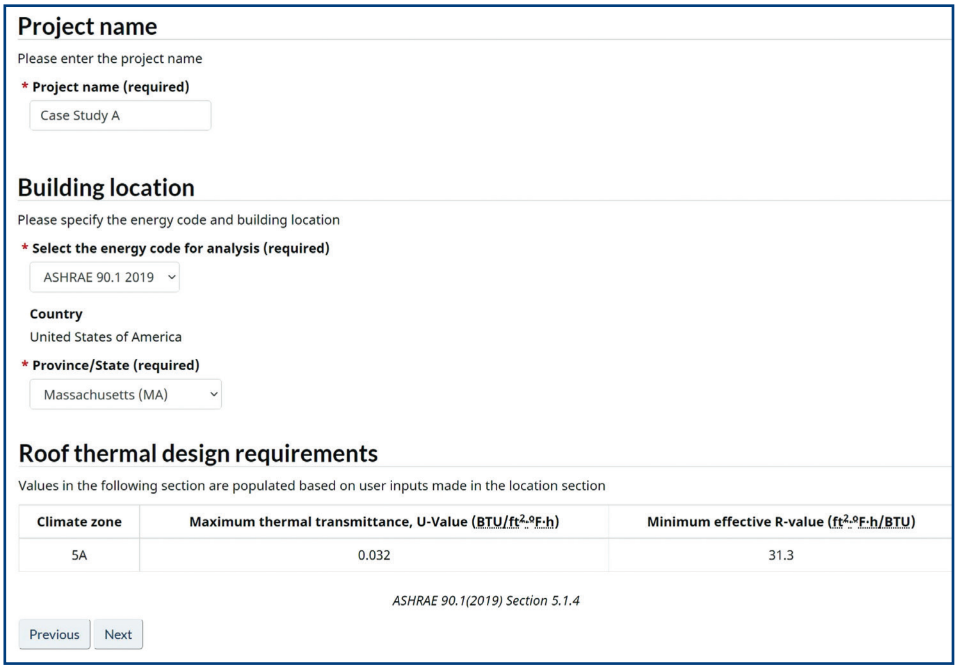


Figure 3. After assigning a project name the user selects an energy code and enters location information, leading to the automatic generation of thermal design requirements. Note: U-Value = U-factor.

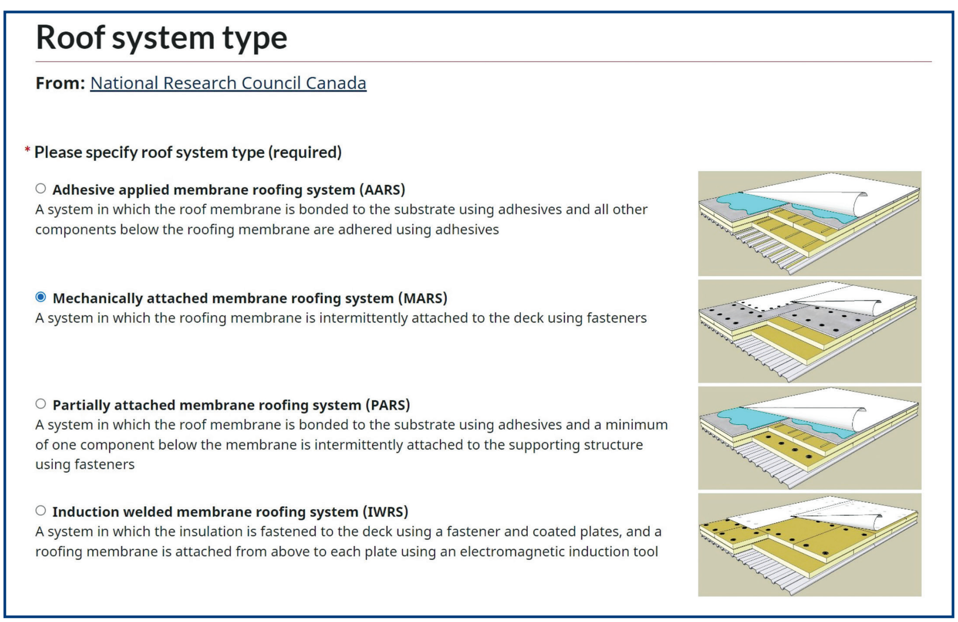


Figure 4. Selecting a roofing system type.

Step 4: Roof Assembly Components

Depending on the roof assembly type selected in step 3, the user is prompted to input the roof components' parameters and their attachment details. Energy-RCI allows the user to configure six components: membrane, cover board, insulation, vapor barrier, deck, and attachment parameters. For example, for cover board and insulation, the user can input the specific thickness within the bounds of thicknesses tested by the ERCR study. Furthermore, in the insulation configuration, the number of layers (up to three) and the dimension of the boards (as this pertains to fastener layout) can be selected.

The attachment details contain predefined fields for users to select the fastener type and fastener layout for MARS, PARS, and IWRS. The fastener density (the number of fasteners per square foot or square meter) is calculated based on the user selection. AARS designs do not use fasteners; therefore, no input is required.

For MARS and PARS designs, Energy-RCI requires additional specific parameters relating to those system types. For PARS, the fastened layer is configurable, allowing the user to select either through one or through multiple layers of insulation. The thermal bridging effects of fastening through all layers and fastening only the bottom layer differ considerably, so different correlations are used. For MARS, the membrane sheet width, fastener spacing along the seam, and the number of membrane seams per cover board or insulation board are all configurable and used to determine the proper fastener density.

Step 5: Thermal Calculation (Results)

In the final step, the application calculates the thermal performance of the user's designed roof. The application displays a tabulated summary of data collected in the previous steps, a schematic of the cross section of the assembly design, the calculation for the *R*-value of the opaque assembly, the decrease in *R*-value according to any thermal bridging losses based on the fastener diameter and fastener density, and the final effective *R*-value of the roof assembly.

Finally, the calculated effective *R*-value is converted to a U-factor and compared to the design U-factor prescribed by the energy codes. For example, suppose the roof design meets the code design U-factor. In that case, the calculator will indicate that the design is an acceptable design. However, if the design does not meet the code design U-factor, the calculator will provide the additional *R*-value required (fastener compensation loss) to meet the target design value.

CASE STUDY

To illustrate the functionality and output of the Energy-RCI application, we present a simple case study. For the time being, thermal bridging from parapet, pipes, and curbs is not factored into the calculation but will likely be incorporated in a future version of Energy-RCI.

This case study considers the thermal bridging of fasteners in a traditional MARS roof assembly for a building with a low-slope roof of standard construction. A commercial building in Boston, Massachusetts, is proposed to be designed with MARS. The roof configuration comprises a steel deck, self-adhesive membrane as a vapor barrier, polyiso insulation, asphaltic core board, and modified bituminous membrane. The fastener attachment for the cover board is 12 fasteners per board, and the membrane layout is designed with a fastener spacing of 12 in. (305 mm) on center.

Step 1

The first step is to select between Imperial and metric units of measure for all inputs and outputs (**Fig. 2**). For this case study, the Imperial system will be used.

Step 2

In the design criteria fields, the user begins by assigning a project name. This name can identify the results if a user has multiple projects to examine. For example, for this case study, the project name is "Case Study A" (**Fig. 3**).

Next, the user identifies the building location and selects the relevant energy code (Fig. 3). The options are NECB 2015,[3] ASHRAE 90.1-2016,[1] and ASHRAE 90.1-2019.[2] The case study uses ASHRAE 90.1-2019.

Note that when an energy code is selected, the geographical regions are reduced to those where that code applies. For NECB 2015,[3] the options for the Province/State field are Canadian provinces, and for ASHRAE 90.1 2016[1] or ASHRAE 90.1-2019,[2] only US states are selectable.

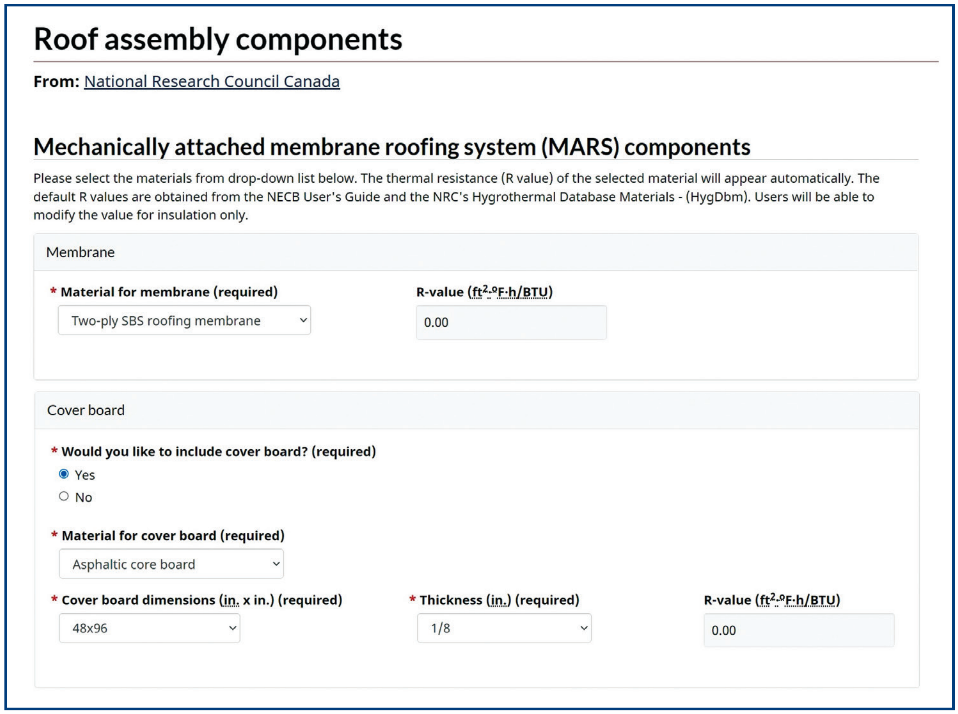


Figure 5. Selecting the membrane type and cover board.

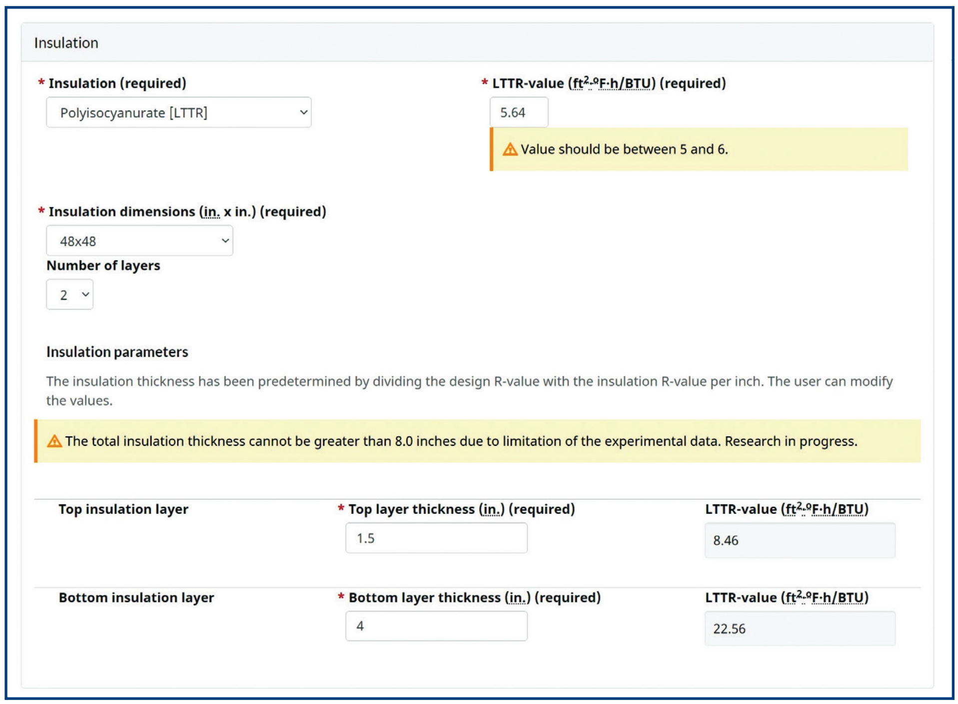


Figure 6. Selecting the insulation.

The city for this case study is Boston. However, because all of Massachusetts is in one climate zone, the only option is All City (which is not shown in Fig. 3), which represents all cities in the state.

The roof thermal design requirements are then presented in a table taken from the selected energy code. Boston falls in climate zone 5A with a maximum design U-factor of 0.032 BTU/ft^2·°F·h (0.184 W/m^2·K) and minimum effective *R*-value of 31.3 ft^2 °F h/BTU (5.43 m^{2}K/W), as shown in Fig. 3.

Step 3

The next step is to select the roofing system type (**Fig. 4**). The defining trait of Case Study A is that the roofing system is a MARS type. This step affects how the following roof configuration and final calculation steps proceed.

Figure 7. Selecting the vapor barrier and deck materials.

Step 4

Step 4 identifies the components and their parameters for the case study's MARS.

Membrane

First, the membrane material is selected (**Fig. 5**). Options include two-ply or three-ply SBS (styrene-butadiene-styrene), single-ply EPDM (ethylene propylene diene terpolymer), single-ply TPO (thermoplastic olefin), or single-ply PVC (polyvinyl chloride) roof membranes. For the MARS, two-ply SBS is selected as the roof membrane type.

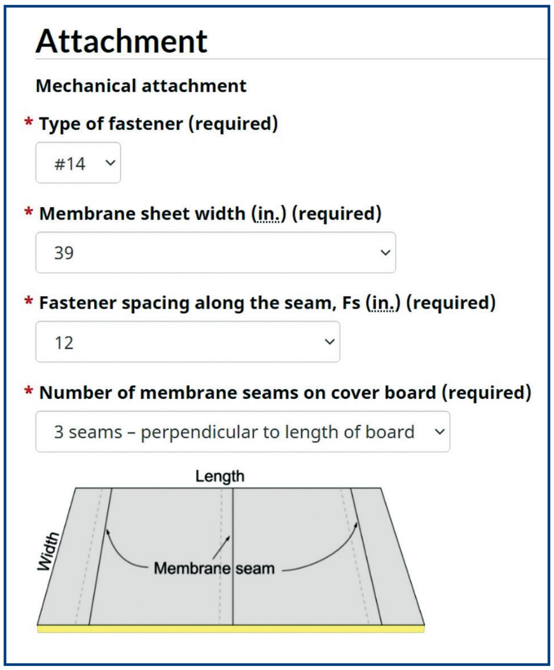


Figure 8. Finalizing the attachment details.

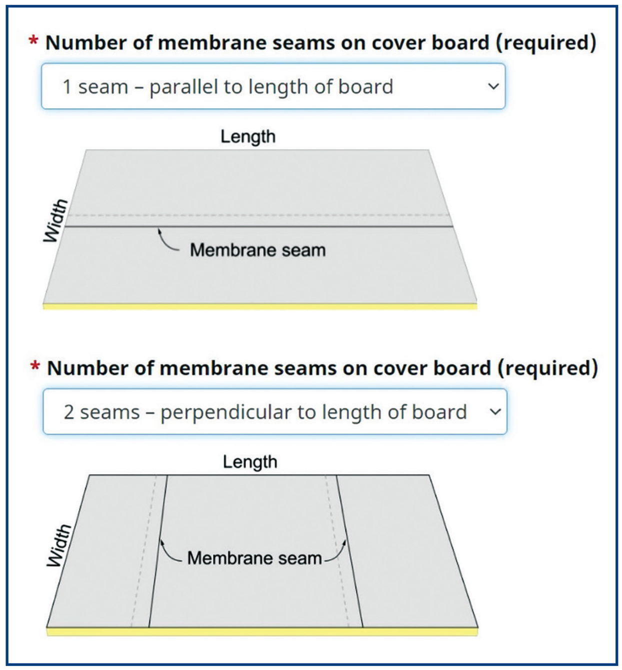


Figure 9. Diagrams for one- and two-seam membranes on cover boards.

Cover Board

Next, the user may choose the option to include a cover board. Cover boards will be used in this case, which causes the subsequent selections to appear (**Fig. 6**).

The user then selects the material for a cover board. Options are glass mat-faced gypsum, fiber-cement board, wood fiberboard, and asphaltic core board.

The user also selects the dimensions and thickness of the cover board. Dimension options are 40 × 80 in. (1 × 2 m), 48 × 48 in. (1.2 × 1.2 m), 48 × 60 in. (1.2 × 1.5 m), and 48 ×

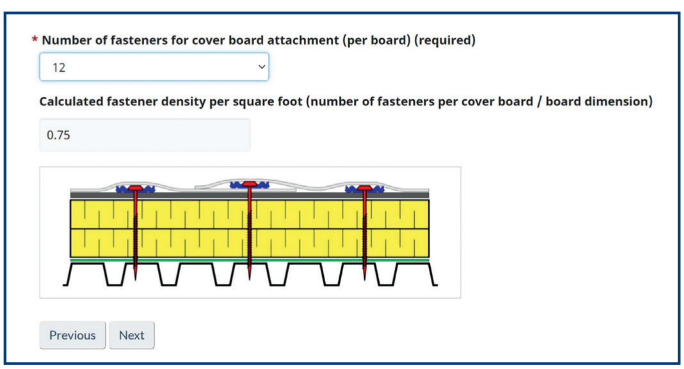
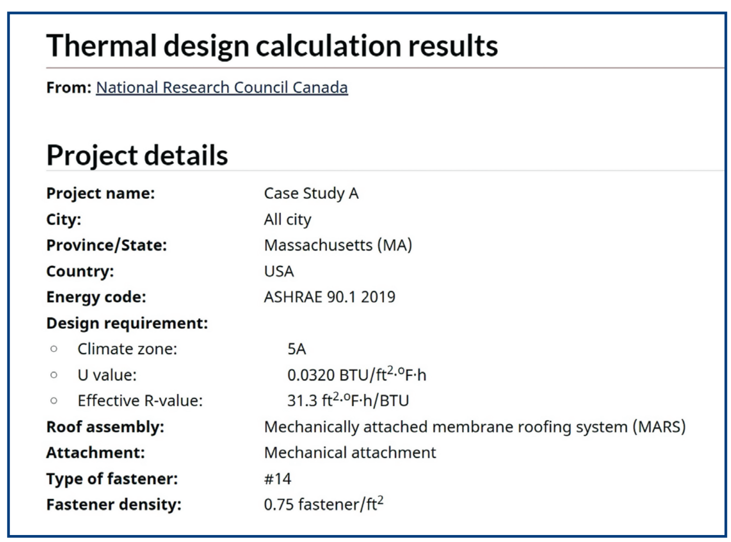


Figure 10. After the user inputs the attachment details, fastener density per square foot or square meter is automatically calculated. A cross-sectional diagram of the roofing system with fasteners is provided.



Thermal design calculation results

From: National Research Council Canada

Project details

Project name:	Case Study A
City:	All city
Province/State:	Massachusetts (MA)
Country:	USA
Energy code:	ASHRAE 90.1 2019
Design requirement:	
◦ Climate zone:	5A
◦ U value:	0.0320 BTU/ft²·°F·h
◦ Effective R-value:	31.3 ft²·°F·h/BTU
Roof assembly:	Mechanically attached membrane roofing system (MARS)
Attachment:	Mechanical attachment
Type of fastener:	#14
Fastener density:	0.75 fastener/ft²

Figure 11. The thermal design calculation results include the project details from the case study.

96 in. (1.2 × 2.4 m). Thickness options are ⅛ in. (3.2 mm), $\frac{3}{16}$ in. (4.8 mm), ¼ in. (6.4 mm), and ½ in. (12.7 mm). For the case study, an asphaltic core board is selected with the dimensions of 48 × 96 in. and a thickness of ⅛ in.

Insulation

The user selects insulation next (Fig. 6). Options are polyisocyanurate (LTTR [long-term thermal resistance]), expanded polystyrene (EPS type II), and stone wool.

For insulation, the *R*-value or LTTR are automatically provided using the NRC's Hygrothermal Database Materials. The user may input their own values, but the results will note this change.

The user next selects the insulation dimensions and the number of insulation layers. Dimension options are 48 × 48 in. (1.2 × 1.2 m) and 48 × 96 in. (1.2 × 2.4 m). Layer options are two and three layers.

Then, the thicknesses of each insulation layer (top, middle, and bottom in the case of three layers) are automatically selected to meet the conditions given by roof thermal design requirements from step 2, but without compensating for thermal impact factors. The user can manually alter the thicknesses.

For the case study, the design layout uses two layers of polyisocyanurate insulation boards with thicknesses of 1.5 in. (38 mm) (top) and 4 in. (102 mm) (bottom). The selected boards are 48 × 48 in. (1.2 × 1.2 m) with an LTTR-value of 5.64 ft^2 °F h/BTU (0.99 m^2K/W) per inch.

Vapor Barrier and Deck

The user selects the vapor barrier from four options: permeable felt, plastic sheet, two-ply felt and asphalt, and self-adhesive membrane. For the case study, a self-adhesive membrane is selected as the vapor barrier (**Fig. 7**).

The user also selects the structural substrate (the deck). For the case study, the only option is metal deck.

Attachment Details

The next task is to finalize the attachment details (**Fig. 8**). First, the user selects the type of fastener (fastener diameter). Options are #12, #14, and #15. This case study will use #14.

Next, the user selects the membrane sheet width. Because modified bituminous membranes are manufactured in a standard sheet width dimension of 39 in. (1 m), the user in the case study has only one option to select. If the selected membrane type is single-ply TPO, PVC, or EPDM, the options for membrane sheet width range from 48 to 146 in. (1.2 to 3.7 m).

MARS

Components	R-value ($ft^2 \cdot {}^oF \cdot h/BTU$)	Thickness (in.)
Air film: Exterior	0.17	-
Membrane: Two-ply SBS roofing membrane	0.00	-
Cover board: Asphaltic core board	0.00	0.125
Insulation: Polyisocyanurate [LTTR]	-	-
Top insulation layer	8.46	1.5
Bottom insulation layer	22.56	4
Vapour barrier: Self adhesive membrane	0.00	-
Deck: Metal deck	0.00	-
Air film: Interior	0.63	-

Figure 12. The thermal design calculation results include the original inputs for the mechanically attached roofing system (MARS) from the case study.

Results summary

Total effective R-value

Effective R-value ($ft^2 \cdot {}^oF \cdot h/BTU$)	31.82
Thermal transmittance, U ($BTU/ft^2 \cdot {}^oF \cdot h$)	0.0314

Fastener impact factor

Decrease in effective R-value	14.21%

Final calculation

Overall effective R-value ($ft^2 \cdot {}^oF \cdot h/BTU$)	27.30
Overall thermal transmittance, U ($BTU/ft^2 \cdot {}^oF \cdot h$)	0.0366

Design check

Calculated overall thermal transmittance (U=0.0366)	>	ASHRAE 90.1 2019 thermal transmittance (U=0.0320)

Observation: The calculated U-value is greater than the maximum ASHRAE 90.1-2019 U-value for roofs (Table 5.14).

To account for thermal bridging losses, an additional 5.36 $ft^2 \cdot {}^oF \cdot h/BTU$ is required to reach the ASHRAE 90.1-2019 U-value for roofs.

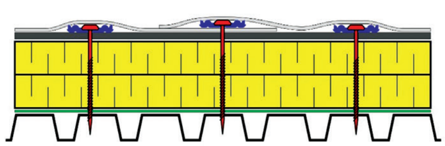


Figure 13. Thermal design calculation results using the original inputs from the case study.

The user selects the fastener spacing along the seam. Options are 12 in. (305 mm) and 18 in. (460 mm). For this case study, 12-in. fastener spacing is selected. For single-ply TPO, PVC, or EPDM membranes, the fastener spacing of 24 in. (610 mm) is also an option.

The user selects the number of membrane seams on the cover board. This step helps determine the membrane fastener density. Options are one, two, and three seams. For each option, a diagram illustrates the physical layout (Fig. 8 and **9**). This case uses the three-seam layout (Fig. 8).

Next the user selects the number of fasteners for cover board attachment per board (**Fig. 10**). The options available depend on the cover board dimensions selected previously. For 48 × 96 in. (1.2 × 2.4 m) cover board, the options are 6, 8, 10, and 12 fasteners. For 48 × 48 in. (1.2 × 1.2 m) cover board, the options are 4, 5, 6, and 8 fasteners. This case study uses 12 fasteners per board.

The inputs are used to calculate the fastener density per square foot or square meter. In this case, the final fastener density count is 0.75 fasteners per square foot (8.07 fasteners per square meter). The application also provides a cross-sectional diagram of the MARS that shows the membrane and cover board fasteners

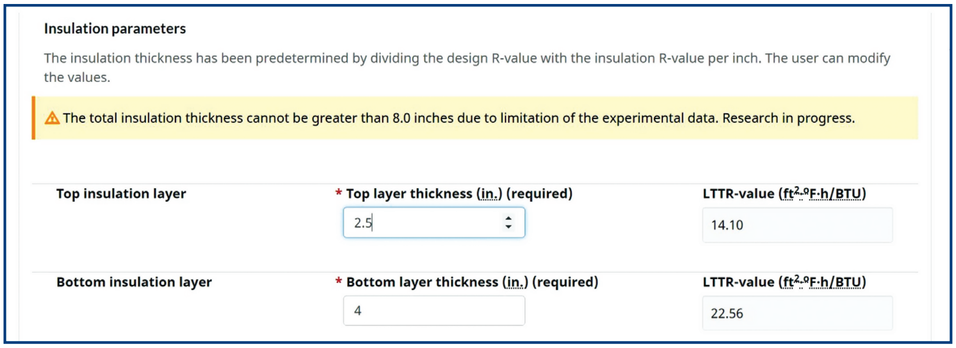


Figure 14. Increasing the insulation thickness.

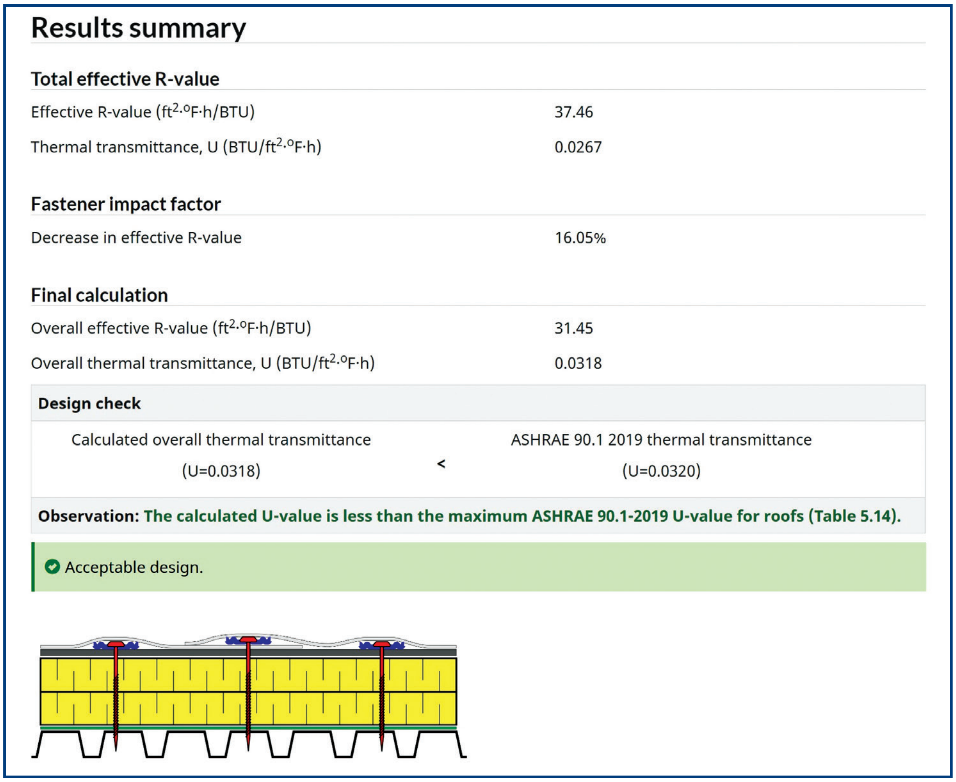


Figure 15. Thermal design calculation results summary for the adjusted inputs.

penetrating through all insulation to the metal deck (Fig. 10).

Step 5

Step 5 provides the thermal design calculation results. The "Project details" table (**Fig. 11**) presents the details input in steps 1 through 4. When the results from this page are printed or published, this table provides a complete summary of the underlying design requirements.

The results (**Fig. 12**) list all selected components and their respective thicknesses (if applicable) and contributing thermal resistances. Exterior and interior air films are included in this summary because they are used to calculate the effective thermal resistance of the assembly.

In the "Results summary" (**Fig. 13**), the calculated total effective thermal resistance of the opaque assembly (without any fasteners) is given. In this case study, the results were an *R*-value of 31.82 ft^2 °F h/BTU (5.59 m^{2}K/W) and a U-factor of 0.0314 BTU/ft^2·°F·h (0.179 W/m^{2}K).

Based on the insulation selected, insulation thickness, fastener type, and resulting fastener density, the application determines the fastener impact factor (the decrease in effective thermal resistance). In this case study, the resulting thermal bridging losses are 14.21%.

The final calculation applies the impact factor to the opaque assembly's effective thermal resistance to yield the overall effective thermal resistance. In the case study, this calculation adjusts the effective *R*-value result of 31.82 ft^2 °F h/BTU (5.59 m^{2}K/W) to an overall effective *R*-value of 27.30 ft^2 °F h/BTU (4.80 m^{2}K/W). In terms of the U-factor, the effective value of 0.0314 BTU/ft^2·°F·h (0.179 W/m^{2}K) is adjusted to an overall effective value of 0.0366 BTU/ft^2·°F·h (0.208 W/m^{2}K).

The application then runs a design check between the calculated U-factor and the code design U-factor. For the case study, the application warns that the calculated U-factor of 0.0366 BTU/ft^2·°F·h (0.208 W/m^{2}K) is more than the ASHRAE 90.1-2019 prescribed U-factor of 0.0320 BTU/ft^2·°F·h (0.184 W/m^{2}K). It advises the user that to account for thermal bridging losses, an additional 5.36 ft^2 °F h/BTU (0.86 W/m^{2}K) is required to meet the ASHRAE 90.1-2019 U-factor for roofs.

The application allows users to return to the previous step without losing their design progress. By doing so, the user can alter their design parameters to attain the design requirements. For example, in this case, the thickness of the top insulation layer is increased to 2.5 in. (63.5 mm) from the original value of 1.5 in. (38 mm) (**Fig. 14**).

After making adjustments, the user proceeds to the results page. The updated results summary (**Fig. 15**) indicates that with the increased thickness of the insulation boards, the opaque assembly effective *R*-value has increased to 37.46 ft^2 °F h/BTU (6.59 m^{2}K/W) with a U-factor of 0.0267 BTU/ft^2·°F·h (0.152 W/m^{2}K). Because the insulation thickness changed, the fastener impact factor also changed, from 14.21% to 16.05%. The new final calculation shows a thermal resistance of 31.45 ft^2 °F h/BTU (5.53 m^{2}K/W) and a U-factor of 0.0318 BTU/ft^2·°F·h (0.1807 W/m^{2}K).

After the design check, the application shows that the new design U-factor is less than the code value and thus gives an acceptable design approval.

CONCLUSION

Energy-RCI is a web-based application to determine whether the thermal design of a low-slope roof meets code requirements while also considering the influence of thermal bridging of mechanical fasteners. Currently, the energy codes do not have design provisions for fastener thermal bridging in commercial roofs. The ERCR research and this application are intended to bring the impact of thermal bridging on the effective thermal resistance of roof assemblies to the forefront of industrial practices, and to support the amendment of the codes to require fastener thermal bridging considerations in the thermal design of commercial roofs.

While there are many tools for calculating the thermal performance of a roofing assembly, the Energy-RCI application is the only tool that incorporates thermal bridging in the roof thermal design. **Table 1** provides a brief comparison of these tools.

The NRC is continuing the ERCR consor-

Feature available	Calculis	Ubakus	Building Envelope Campaign	Energywise	Energy-RCI
R-value calculation	✓	✓	✓	✓	✓
Roofing-assembly specific	×	×	×	✓	✓
Building/energy code comparison	×	×	✓	✓	✓
Roofing system thermal designs:					
• AARS	×	✓	×	✓	✓
• MARS	×	×	×	×	✓
• PARS	×	×	×	×	✓
• IWRS	×	×	×	×	✓
Thermal bridging loss	×	×	×	×	✓
Thermal bridging compensation	×	×	×	×	✓

Note: AARS = adhesive-applied roofing system; MARS = mechanically attached roofing system; PARS = partially attached roofing system; IWRS = induction welded roofing system.

Table 1. Tools for calculating the thermal performance of a roofing assembly.

tium project investigating the impact of thermal bridging on new U-factor requirements prescribed by the codes and quantifying the thermal losses in rooftop penetrations. In this capacity, it seeks to further develop the Energy-RCI application to accommodate any significant thermal impact factors it finds and expand the database to include the ever-evolving thermal requirements of the energy codes.

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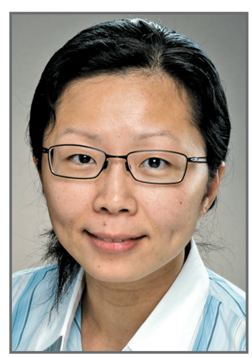

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