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Key Elements of and Materials Performance Targets for Highly Insulating Window Frames

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Abstract

The thermal performance of windows is important for energy efficient buildings. Windows typically account for about 30-50 percent of the transmission losses though the building envelope, even if their area fraction of the envelope is far less. The reason for this can be found by comparing the thermal transmittance (U-factor) of windows to the U-factor of their opaque counterparts (wall, roof and floor constructions). In well insulated buildings the U-factor of walls, roofs an floors can be between 0.1-0.2 W/(m^{2}K). The best windows have U-values of about 0.7-1.0. It is therefore obvious that the U-factor of windows needs to be reduced, even though looking at the whole energy balance for windows (i.e. solar gains minus transmission losses) makes the picture more complex.

In high performance windows the frame design and material use is of utmost importance, as the frame performance is usually the limiting factor for reducing the total window U-factor further. This paper describes simulation studies analyzing the effects on frame and edge-of-glass U-factors of different surface emissivities as well as frame material and spacer conductivities. The goal of this work is to define materials research targets for window frame components that will result in better frame thermal performance than is exhibited by the best products available on the market today.

Key words: Fenestration, window frames, heat transfer modeling, U-factor, thermal transmittance, thermal performance.

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1 Introduction

Demand is growing for energy-efficient buildings that minimize environmental impacts, including carbon dioxide emissions, which are the primary contributors to global warming. A key energy-efficiency strategy is to use optimum materials and components to minimize thermal transmittance (U-factor) of the building envelope, which decreases heat loss from the warm interior to the cold exterior and thereby reduces heating energy use in cold weather. Windows are responsible for about 40 percent of the heat loss through typical building envelopes. Much attention has been given to reducing the impact of windows on building energy use by lowering window frame and glazing unit U-factors.

However, even the most highly insulating frames do not perform as well as highly insulating glazing. The best glazing units currently have U-factors as low as 0.3-0.5 watts per square meter Kelvin [W/(m^{2}K)] (including translucent aerogel products) whereas the best window frames have U-factors as low as 0.6 - 0.8 W/(m^{2}K). Glazing units achieving U-factors of about 0.5 W/(m^{2}K) typically contain three glass panes separated by insulated or thermally broken spacers, krypton or xenon gas fill, and two or more layers of low-emissivity (low-e) coating. The third pane means that these glazing units cost more and are considerably thicker and heavier than standard windows, which has limited their adoption. Window frames with low U-factors normally employ materials with low thermal conductivity as thermal breaks within the structural frame.

Even though today's state-of-the-art windows have considerably lower U-factors than windows of the past, the heat loss per area through windows is still much greater than through building walls and roofs. Walls and roofs can relatively easily achieve U-factors of 0.10 to 0.20 W/(m^{2}K) or lower – much lower than the U-factor of any commercial window. Windows also account for a relatively large fraction of the building envelope in most buildings, and many buildings have large areas of glass. Thus, research on how to further lower window U-factors is essential to further reducing the energy use and environmental impacts of buildings.

This paper describes simulation studies analyzing the effects on frame and edge-of-glass U-factors of different surface emissivities as well as frame material and spacer conductivities. The goal of this work is to define materials research targets for window frame components that will result in better frame thermal performance than is exhibited by the best products available on the market today (see, e.g., Gustavsen et al. 2007).

2 Window Frames

We performed thermal performance simulations on five different window frames: two thermally broken aluminum frames (Frames A and B), one thermally insulated wood frame (C), one solid wood frame (D), and one polyvinyl chloride (PVC) frame (Frame E). Frames A and C had a thermal break of polyurethane (PUR) in the middle. Frame B had a polyamide thermal break in the middle. All the frames were of the inward-opening casement type except Frame B, which was non-moveable.

The frames were simulated with triple glazing, 95 percent argon and 5 percent air filling in the cavity, and two low-e coatings with an emissivity of 0.037. The resulting glazing U-factor was 0.710 W/(m^2K). For all of the frames, the spacer effective conductivity was varied between 0.02 W/(mK) and 10 W/(mK) where the effective spacer conductivity is found by converting the real spacer assembly to a simple rectangular solid as shown in Figure 1. The solid block conductivity is equal to the effective conductivity of the real spacer assembly. Because this effective conductivity is a result of the total spacer configuration, it cannot be directly compared to pure material conductivity. Spacers containing aluminum have an effective conductivity between about 2 and 10 W/(mK), depending on spacer size and the type of sealant used. Stainless steel spacers typically have an effective conductivity of about 0.3 to 1 W/mK, and insulated spacers have an equivalent conductivity of about 0.2 to 0.3 W/(mK). The pure materials used in spacers, e.g., aluminum, stainless steel, and the insulating elements in insulated spacers, have conductivities of 160, 17, and about 0.20 W/(mK), respectively. As a comparison, the best insulating materials have conductivities between about 0.01-0.02 W/(mK) (excluding vacuum insulation panels [VIPs]).

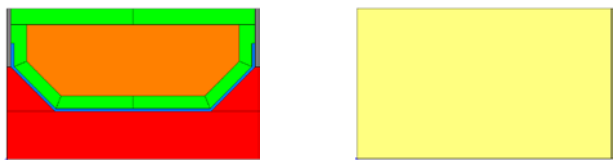

Figure 1. The image on the left shows a typical spacer assembly, and the image on the right is the solid block used in the simulations with an effective conductivity reflecting that of the real spacer configuration.

The spacer conductivity was varied along with the material conductivity and surface emissivity as described below for each frame. Table 1 shows materials and sizes of the simulated frames. The frames are described in more detail in the subsections below, with figures showing their geometry and structural and insulation elements.

Table 1. Materials and sizes of the frames that were used for the numerical simulations.

Frame	Structural material	Thermal break material	Frame height [mm]
A	Aluminum	Polyurethane (PUR)	110
B	Aluminum	Polyamide	56
C	Wood	Polyurethane (PUR)	94
D	Wood		94
E	Polyvinylchloride (PVC)		119

2.1 Window Frame A (Foam-insulated Aluminum)

Window frame A is aluminum with thermal breaks between the frame and sash elements, as shown in the cross-section in Figure 2. A thin layer of aluminum cladding covers solid polyurethane elements, minimizing direct connections between inside and outside. We calculated thermal transmittance values for various configurations of spacers (effective conductivity ranging from 0.02 to 10 W/(mK)) and thermal insulation conductivities from 0.005 to 0.089 W/(mK) for this frame.

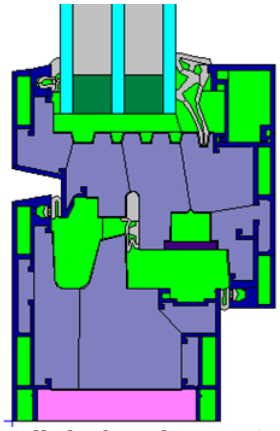

Figure 2. Cross-section of Frame A (thermally broken aluminum). The purple elements show the placement of the polyurethane (PUR) foam. The light green elements show the unventilated cavities within the frame. The dark blue elements show the frame's aluminum skeleton.

2.2 Window Frame B (Thermally Broken Aluminum)

Window frame B is thermally broken aluminum. The internal and external aluminum parts of the frame are connected using a polyamide fastener reinforced with glass fiber. The middle part of the frame is insulated with aerogel (shown in grey in Figure 3). We performed calculations for various combinations of spacer and thermal break conductivities. The spacer effective conductivity was varied from 0.02 to 10 W/(mK), and the thermal break conductivity from 0.005 to 0.1733 W/(mK).

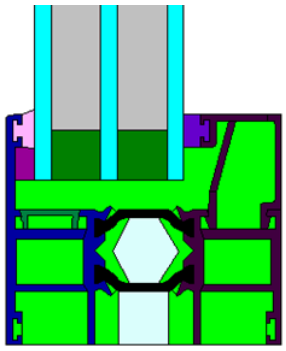

Figure 3. Cross-section of Frame B. The black elements show polyamide thermal breaks, and the light blue area represents the aerogel. The light green elements are the unventilated air cavities within the frame. The blue and dark red elements depict the outer and inner aluminum skeleton, respectively. The outer aluminum skeleton has an emissivity of 0.9, and the inner one (which is painted) has an emissivity of 0.6.

2.3 Window Frame C (Foam Insulated Wood)

Window frame C is wood, insulated with a continuous 17-millimeter-thick layer of PUR foam. We performed calculations for various combinations of spacer and thermal break conductivities. The spacer effective conductivity was varied between 0.02 and 10 W/(mK), and the thermal break conductivity from 0.005 to 0.029 W/(mK).

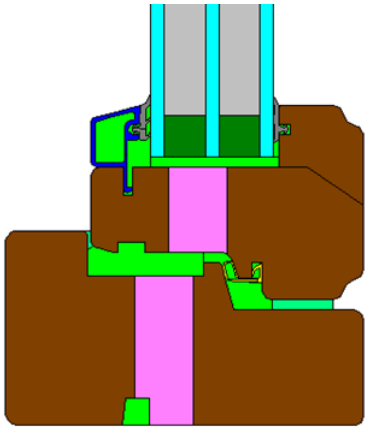

Figure 4. Cross-section of Frame C. The pink areas show the placement of the PUR insulation material, and the brown areas represent the wood areas of the frame.

2.4 Window Frame D (Solid Wood)

Window frame D is also wood but without PUR insulation. We performed calculations for this frame for various spacer and wood conductivities. The spacer effective conductivity was varied between 0.02 and 10 W/(mK), and the wood conductivity from 0.005 to 0.12 W/(mK).

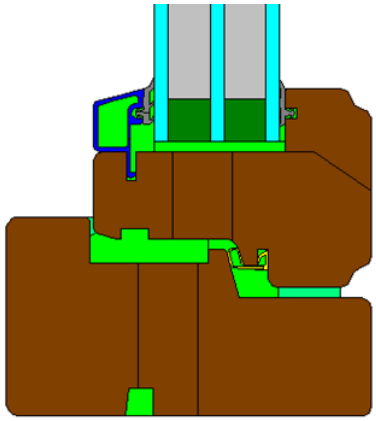

Figure 5. Cross-section of Frame D. Solid core wood is shown in brown. Air cavities are shown in light green.

2.5 Window Frame E (PVC)

Window frame E is polyvinyl chloride (PVC). We performed calculations for various effective spacer conductivities (from 0.02 to 10 W/(mK)) and PVC surface emissivities between 0.02 and 0.9. Originally (see Gustavsen et al., 2010), some of the cavities of this frame were filled with an insulated material, but for the results reported in this paper the cavity filling material was removed because our focus is on the effect of varying surface emissivity.

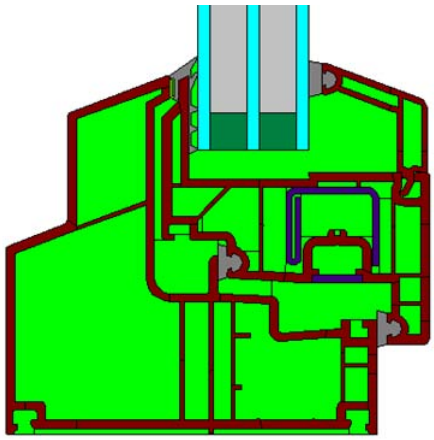

Figure 6. Cross-section of Frame E. The brown areas show the PVC skeleton of the frame, and the light green areas show air cavities. The blue areas show the supporting steel and the continuous parts of the hardware used for opening the frame.

3 Numerical Procedure

We used a finite-element method (FEM) program, THERM (Finlayson et al., 1998), to solve the conductive heat-transfer equation. THERM's quadrilateral mesh is automatically generated. Refinement was performed in accordance with Section 6.3.2b of standard 15099 of International Standards Organization (ISO 15099, 2003). The energy error norm was less than 10 percent in all cases, which has been shown to correlate to an error of less than one percent in the total thermal transmittance of typical windows. More information on the thermal simulation program algorithms can be found in Appendix C in Finlayson et al. (1998). The FEM program uses correlations to model convective heat transfer in air cavities; the program can calculate radiation heat transfer using view factors or fixed radiation coefficients. The convection and radiation coefficients for the frame cavities were calculated according to ISO 15099. These procedures are also reported in Gustavsen et al. (2005) and procedures prescribed by Mitchell et al. (2006).

THERM results have been proven to compare well with experimental results, and, for the version used in this study, we corrected for an error in ISO 15099 for radiation in vertical frame cavities (Gustavsen et al., 2010).

3.1 Material Properties and Boundary Conditions

Table 2 displays the initial material properties used in the numerical simulations. Material data were obtained, if available, from frame manufacturers. When manufacturers did not supply material data, data from ISO 10077-2 were used (EN ISO 10077-2, 2003). As noted above, some of the material data (i.e., surface emissivity, spacer and thermal break conductivity) were varied.

Table 2. Conductivity and emissivity of frame materials.

Material	Frame	Density (kilograms per cubic meter)	Emissivity[3] (-)	Thermal conductivity (W/m-K)
Aluminum	A		0.2/0.9[4]	160
EPDM[1] (all gaskets)	A		0.9	0.25
Polyurethan - Hartschaum ("EP 2718-5", Rohdichte)	A	400[2]	0.9	0.089[3]
Steel, oxidized (hardware)	A		0.8	50
Extruded polystyrene (XPS)	A	33[2]	0.9	0.029
Aerogel			0.9	0.057
Aluminum, painted 0.9	B		0.9	160
Aluminum, painted 0.6	B		0.6	160
Foam rubber	B		0.9	0.06
Polyamide with 25% glass fiber	B		0.9	0.1733
PVC	B		0.9	0.17
Silicone	B		0.9	0.35
Silicone foam	B		0.9	0.17
Aluminum	C, D		0.2	160
EPDM (gasket between frame and glazing)	C, D		0.9	0.25
Nordic pine	C, D		0.9	0.12
Polyurethane 120M	C, D		0.9	0.029
Schlegel QLon (gasket between the solid parts of the frame)	C, D		0.9	0.03
Basotec (frame cavity filler)	E		0.9	0.035
EPDM (all gaskets)	E		0.9	0.25
PVC	E		0.9	0.17
Steel, oxidized (hardware)	E		0.8	50

Notes:

[1]Ethylene propylene diene monomer.

[2]As noted by the manufacturer.

[3]Estimated values – not stated in the documentation or reported by the manufacturer.

[4]Emissivity of 0.9 is used for painted exposed surfaces, and 0.2 is used for untreated (internal) surfaces.

In the simulations, National Fenestration Rating Council (NFRC) 100-2001 boundary conditions were used (see Table 3), as prescribed by Mitchell et al. (2006). The exterior-side boundary condition uses a fixed convection coefficient. In addition, the radiation portion of the surface heat transfer is calculated for each segment as if it views only a blackbody enclosure of the exterior temperature. The interior-side boundary condition also evaluates the radiation exchange for each surface segment separate from a fixed convection coefficient, using a more sophisticated view-factor radiation model that includes the effects of self-viewing frame and glazing surfaces. These NFRC-style radiation boundary conditions were used with -18ºC and +21ºC outside/inside temperatures.

Table 3. Boundary conditions used in the simulations.

Description	Temperature T [°Centigrade]	Heat-transfer coefficient h [W/(m^{2}K)]
FEM simulations (NFRC radiation)		
Frame inside boundary condition	+21.0	2.44 + radiation, with self-viewing
Frame outside boundary condition	-18.0	26 + radiation, with no self-viewing

4 Results

The results from the numerical simulations are presented below in the form of graphical plots of frame and edge-of-glass U-factors as a function of various material properties, i.e., thermal break conductivity, spacer conductivity, and emissivity.

4.1 Frame and Edge-of-glass U-factor as Function of Spacer and Thermal Break Conductivities for Frames A, B, and C

Frame A (aluminum frame with solid thermal breaks between thin layers of aluminum cladding), Frame B (aluminum extrusions separated by polyamide thermal breaks), and Frame C (wood frame with polyurethane thermal break) have in common a thermal break whose function is to reduce what would otherwise be a high thermal transmittance (U-factor). Figure 7, Figure 9 and Figure 11 plot the frame U-factor as a function of thermal break and spacer conductivities for these three frames, respectively. The U-factor is noted on the vertical axis, the thermal break conductivity is noted on the horizontal axis, and the spacer conductivities are represented by different types of lines, as shown in the figure legend. A separate black triangle denotes the performance of a (real) system with material properties as specified in Table 2, for which the effective spacer conductivity is 0.25 W/mK (close to the best performance level found for spacers). Figure 8, Figure 10 and Figure 12 plot the edge-of-glass U-factors for the same three windows, respectively.

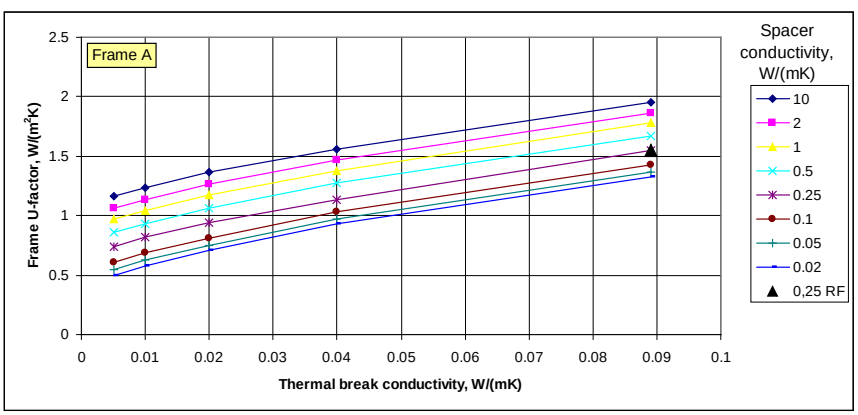

Figure 7. Frame U-factor as a function of thermal break conductivity (horizontal axis) and spacer conductivity (various line types) for Frame A (thermally broken aluminum).

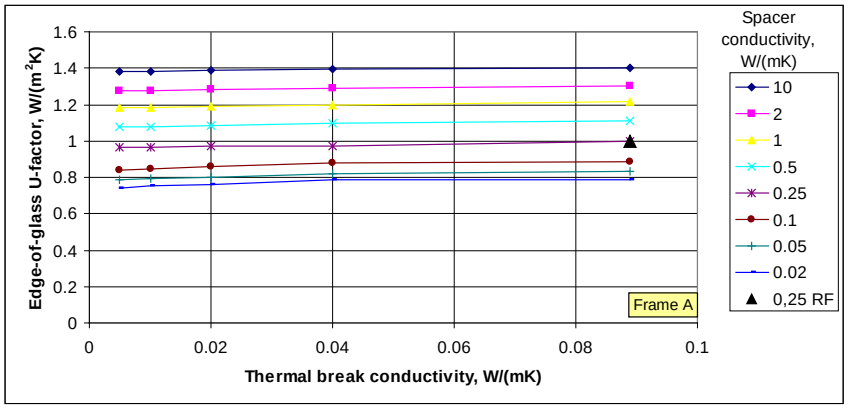

Figure 8. Edge-of-glass U-factor as a function of thermal break conductivity (horizontal axis) and spacer conductivity (various line types) for Frame A (thermally broken aluminum).

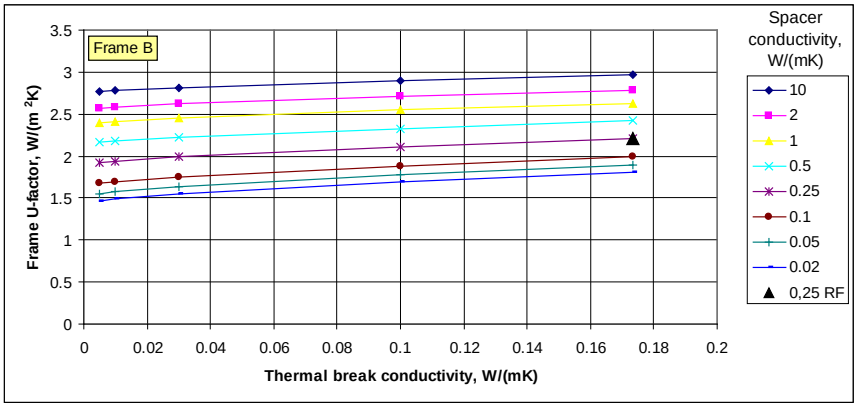

Figure 9. Frame U-factor as a function of thermal break conductivity (horizontal axis) and spacer conductivity (various line types) for Frame B (thermally broken aluminum).

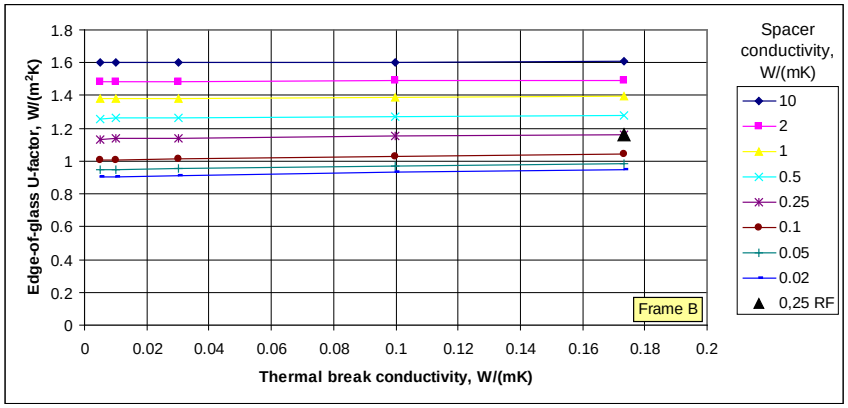

Figure 10. Edge-of-glass U-factor as a function of thermal break conductivity (horizontal axis) and spacer conductivity (various line types) for Frame B (thermally broken aluminum).

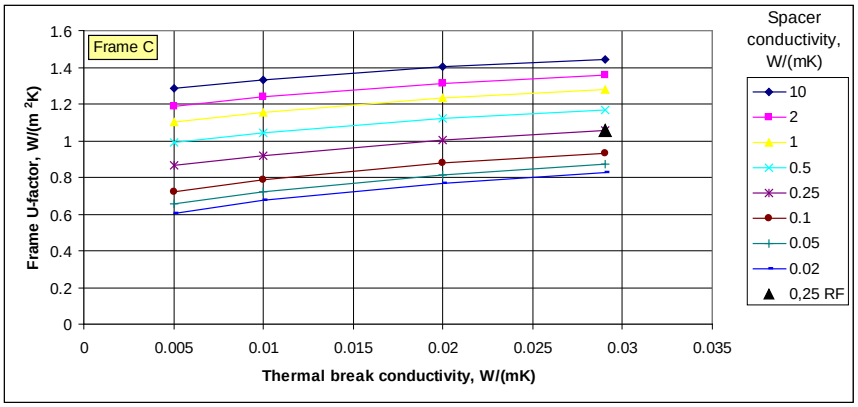

Figure 11. Frame U-factor as a function of thermal break conductivity (horizontal axis) and spacer conductivity (various line types) for Frame C (thermally broken wood).

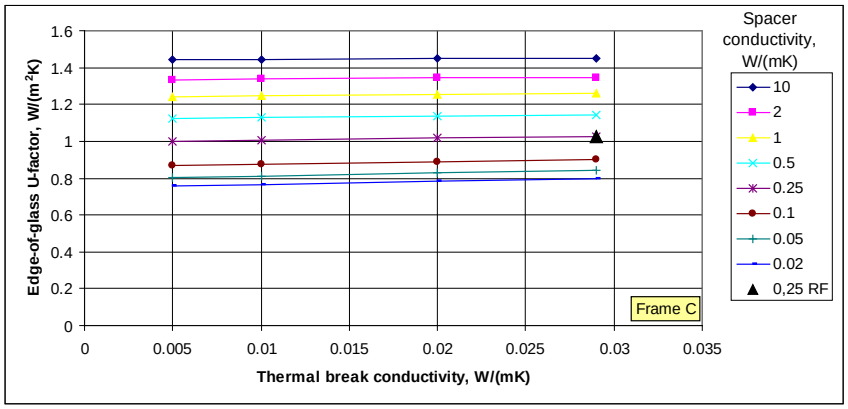

Figure 12. Edge-of-glass U-factor as a function of thermal break conductivity (horizontal axis) and spacer conductivity (various line types) for Frame C (thermally broken wood).

4.2 Frame and Edge-of-Glass U-factors as Function of Spacer and Frame Material Conductivities for Solid Frame D

Frame D was made of wood with a thermal conductivity of 0.12 W/mK, as a starting point. Figure 13 shows the frame U-factor as the frame material conductivity decreases to 0.005 W/(mK) and as a function of spacer conductivity. The U-factor is noted on the vertical axis, the frame material conductivity is noted on the horizontal axis, and the spacer conductivities are represented by separate line types as defined in the figure legend. Figure 14 shows the edge-of-glass U-factor for the same frame. A separate black triangle denotes the performance of a real frame with material properties as specified in Table 2, for which the effective spacer conductivity is 0.25 W/mK.

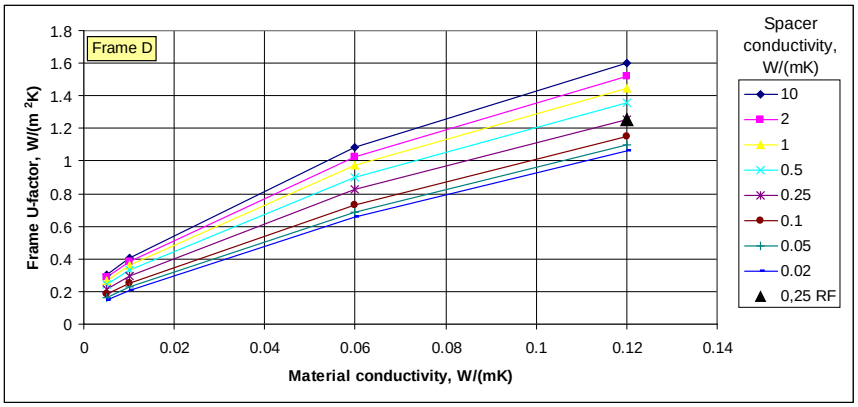

Figure 13. Frame U-factor as a function of frame material conductivity (horizontal axis) and spacer conductivity (various line types) for Frame D (solid wood).

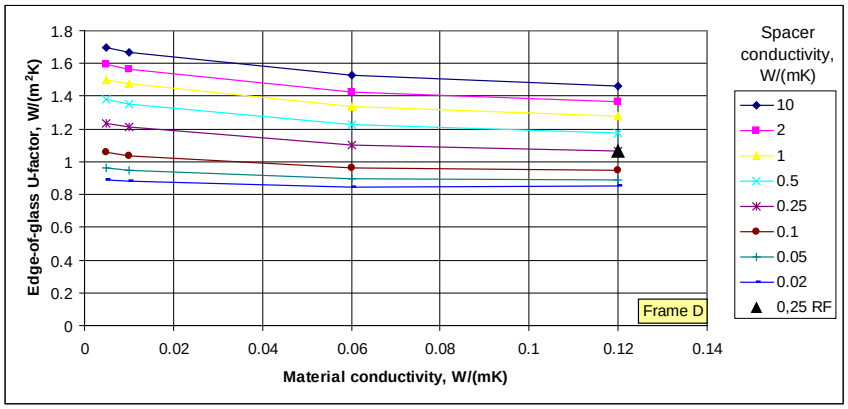

Figure 14. Edge-of-glass U-factor as a function of frame material conductivity (horizontal axis) and spacer conductivity (various line types) for Frame D (solid wood).

4.3 Frame U-factor as Function of Spacer Conductivity and Frame Material Emissivity for PVC Frame E

Figure 15 shows the frame U-factor for the PVC frame (Frame E) as a function of PVC surface emissivity and spacer conductivity. For the PVC to obtain these low emissivities, a surface treatment is necessary. The vertical axis shows the U-factor, the horizontal axis shows the surface emissivity of PVC, and different line types (defined in the figure legend) show the spacer conductivities. A separate black triangle denotes the performance of a real frame with material properties as specified in Table 2, for which the effective spacer conductivity is 0.25 W/mK.

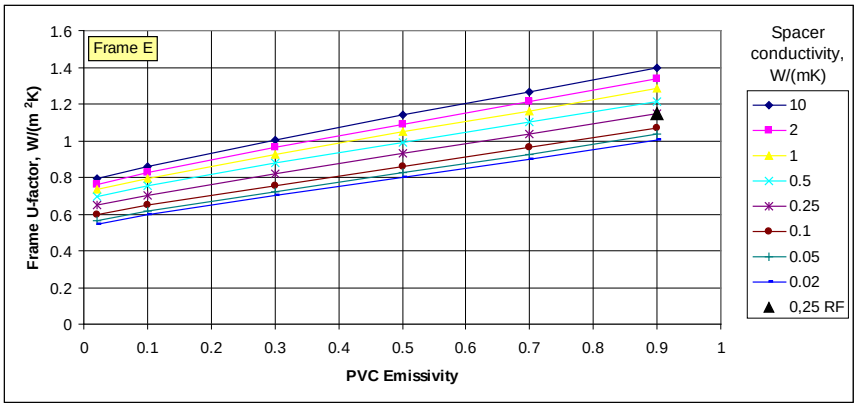

Figure 15. Frame U-factor as a function of frame material emissivity (horizontal axis) and spacer conductivity (various line types) for Frame E (PVC).

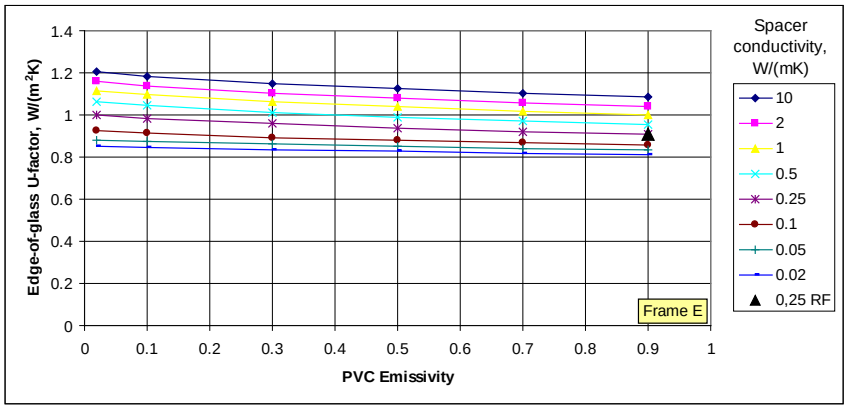

Figure 16. Edge-of-glass U-factor as a function of frame material emissivity (horizontal axis) and spacer conductivity (various line types) for Frame E (PVC).

4.4 Total Window U-factor

Figure 17 and Figure 18 show total window U-factors for windows with the frames studied. All windows are 1.2 meters (m) by 1.2 m with a center-of-glazing U-factor of 0.71 W/(m^{2}K). In each figure, total window U-factor is compared with the center-of-glazing U-factor. Unless otherwise stated, all frames were simulated with standard insulating elements (i.e., thermal breaks and surface emissivity as listed in Table 2). Figure 17 also shows the variation in total window U-factor as a function of spacer conductivity. Figure 18 shows the total window U-factor as a function of material/thermal break conductivity and emissivity. Sections 2.1 to 2.5 denote the maximum and minimum material properties used.

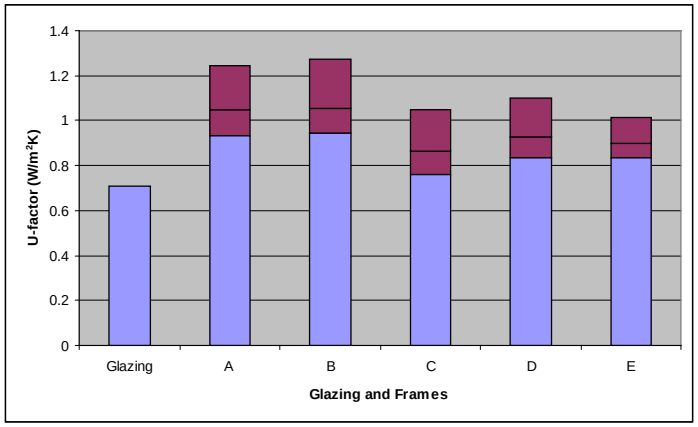

Figure 17. Glazing U-factor and total window U-factor for windows equipped with Frames A-E as a function of spacer conductivity. The blue bar denotes the minimum U-factor for the whole window, i.e. with a spacer conductivity of 0.02 W/(m^2K). The purple bar shows the range of U-factors found by varying the spacer from 0.02 to 10 W/(m^2K), and the bar in the middle denotes the total window U-factor for a window with a good insulating spacer, i.e., with an effective conductivity of 0.25 W/(mK). All frames had glazing with a U-factor of 0.71 W/m^2K, and all frames were simulated with standard frame insulating elements (i.e., thermal breaks and surface emissivity).

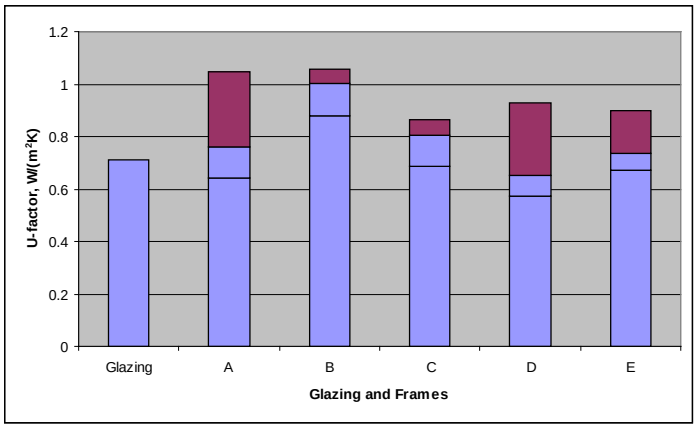

Figure 18. Glazing U-factor and total window U-factor for windows equipped with Frames A-E as a function of material/thermal break conductivity and emissivity. All frames had glazing with a U-factor of 0.71 W/m^2K. The blue bar denotes the minimum U-factor found for the whole window, i.e. with the minimum frame material conductivity or emissivity simulated. The purple bar shows the range of U-factors found by varying the frame material property between the minimum value and the default real material value. A spacer with an equivalent conductivity of 0.25 W/mK is used for these results. The horizontal line in the blue bar denotes the U-factor found when using the minimum material property (emissivity and frame material conductivity) and a spacer equivalent conductivity of 0.02 W/mK.

5 Discussion

5.1 Effect of Spacer Conductivity

All of the figures in the previous section show that both frame and edge-of-glass U-factor decrease as spacer conductivity decreases. Changing the effective spacer conductivity from 10 to 0.25 W/(mK), where 0.25 W/(mK) is close to the effective conductivity for the best available spacers today, results in a decrease in frame U-factor of more than 18 percent for the frames studied here. For some frames, the decrease is as much as 36

percent. The actual percentage depends on frame thermal performance and tends to increase with decreasing frame U-factor. Exceeding the performance of the best spacer technologies available today would further decrease the frame U-factor. For example, reducing the effective spacer conductivity from 0.25 to 0.1 W/(mK) would decrease the frame U-factor by more than 6 percent. A decrease in spacer conductivity from 0.25 to 0.05 W/(mK) results in a decrease in U-factor of more than 10 percent. This result makes clear that windows should use the best spacers available and that research should be undertaken to resolve any manufacturer problems related to using high-performing spacers and to develop alternative and more highly insulating spacer systems.

The results also show that the edge-of-glass U-factor decreases noticeably with decreasing effective spacer conductivity. Reducing the effective spacer conductivity from 0.25 to 0.1 W/(mK) results in an edge-of-glass U-factor decrease of more than 5 percent. A reduction from 0.25 to 0.05 W/(mK) results in a decrease in edge-of-glass U-factor of more than 8 percent.

5.2 Effect of Thermal Break Conductivity (Frames A, B, and C)

Improving the thermal break materials used in window frames (e.g., as in Frames A, B and C) is also a possible strategy to improve the thermal performance of windows. The nominal conductivities of the thermal breaks used in the frames studied here are 0.089 W/(mK) for Frame A, 0.1733 W/(mK) for Frame B, and 0.029 W/(mK) for Frame C. For these frames, we reduced the thermal conductivity of the insulating material from these nominal values to 0.005 W/(mK). Figure 7, Figure 9 and Figure 11 show that decreasing the thermal break conductivity results in lower frame U-factors for Frames A, B, and C, respectively. For Frame A, reducing the thermal break conductivity from 0.089 to 0.04 W/(mK), reduces the frame U-factor by about 27 percent when the spacer conductivity is 0.25 W/(mK). For Frame B, reducing thermal break conductivity from 0.1733 to 0.1 W/(mK) reduces the frame U-factor by 4 percent, and for Frame C, reducing thermal break conductivity from 0.029 to 0.02 W/(mK) reduces frame U-factor by 5 percent, when the spacer conductivity is 0.25 W/(mK).

Reducing the thermal break conductivities does not affect edge-of-glass U-factors in the same way that it affects frame U-factors. Edge-of-glass U-factors remain almost constant as thermal break conductivity decreases. However, a slight decrease in edge-of-glass U-factor with decreasing thermal break conductivity is still observed for the windows that have low spacer conductivity.

5.3 Solid Frame Conductivity (Frame D)

Frame D mainly consists of one material, solid wood. In the simulations, we varied the material conductivity between 0.005 and 0.12 W/(mK); the largest value is typical of wood. For this frame, reducing the conductivity to 0.005 W/(mK) has a much larger effect on frame U-factor than is the case for the other frames. The best U-factor for the other frames is above 0.5 W/(m^2K), but the U-factor for this frame decreases to below 0.2 W/(m^2K). The main reason for this is that the whole frame in this particular specimen is made of the insulating material whereas the thermal breaks are only a part of Frames A, B, and C. This shows that increasing the size of the insulating elements in the heat-flow

direction is a possible alternative strategy for improving window thermal performance, as compared to lowering the thermal break conductivity.

The edge-of-glass U-factor for this solid frame increases with decreasing frame material conductivity, however. The reason for this is probably that the easiest heat-flow path through the window is through the edge-of-glass construction (when the frame material conductivity is low).

5.4 Effect of PVC Emissivity (Frame E)

The emissivity of the interior hollow cavity walls was one of the parameters we varied, between 0.02 and 0.9, for the PVC frame; the typical emissivity of PVC is 0.9. The data show that reducing the emissivity from 0.9 to 0.5 will reduce the frame U-factor by about 19 percent, from 1.15 to 0.93 W/(m^2K) where the spacer effective conductivity is 0.25 W/(mK). A further reduction in emissivity to 0.3 results in an additional 12 percent reduction in frame U-factor, to 0.82 W/(m^2K). For these emissivities to be an option for PVC, either the bulk property of PVC must change, or some surface treatment must be developed. The latter option seems easier although finding a paint or lacquer that can stick to PVC could be a challenge. An alternative could be filling the closed frame cavities with an insulating material. Filling the closed cavities for this frame (where the surface emissivity is 0.9) using an insulating material with a conductivity of 0.03 W/(mK reduces the frame U-factor from 1.15 to 0.86 W/(m^2K) (i.e., this approach is almost as good as having a surface emissivity of 0.3).

The edge-of-glass U-factor for Frame E increases minimally with decreasing PVC surface emissivity because this is now the heat flow path of least resistance.

5.5 Potential for Material Developments

5.5.1 Spacer

For all the frames studied, we varied the effective spacer conductivity between 0.02 and 10 W/(mK). As noted above, the best spacers available today have an effective conductivity of 0.2 - 0.3 W/(mK). In such spacers the insulating part of the spacer has a conductivity of about 0.20 W/(mK). Moreover, the best insulation materials today have conductivities between 0.01 and 0.02 W/(mK), excluding insulating materials/systems like VIPs. Thus, it should be possible to further improve spacer performance.

Two possible routes are envisioned here: 1) Development of spacers with a lower thermal conductivity, and/or 2) development of alternatives to the air and vapor sealant part of the spacer (e.g., the stainless steel or aluminum foil used for high-performance spacers). Both solutions would reduce the effective thermal conductivity of the spacers, and therefore also the frame U-factor, as shown in the figures above. For each of these options, there are two possibilities: finding existing alternative materials with the required properties or developing new materials, e.g., using nanotechnology. Because there is quite a difference between the best insulation materials and the materials used in spacers, looking for alternate existing materials appears to be the easiest immediate option. However, research

should also be undertaken to find solutions that are even better than what is possible using the best materials of today.

5.5.2 Thermal Break

As noted above, the best currently available insulation materials (excluding VIPs) have a conductivity of 0.01 to 0.02 W/(mK). Thus, for Frames A and B, which have thermal breaks with nominal conductivities of 0.089 and 0.1733 W/(mK), alternative existing materials could be sought although finding materials with the right thermal and structural properties might be difficult. In contrast, the thermal conductivity of the break used in Frame C is 0.030 W/(mK), which is close to the performance of the best currently available materials. Therefore, although use of some alternative existing materials might enable performance improvements for this window, new materials should be researched and developed. Concepts for new insulations materials, including Nano Insulation Materials, are noted in Jelle et al. (2010).

5.5.3 Structural Insulating Materials

We investigated Frame D to assess the potential for reducing frame U-factor by using a structural material with a low conductivity. When frame material conductivity is 0.06 W/(mK) and the effective spacer conductivity is 0.25 W/(mK), the frame U-factor is 0.82 W/(m^2K), compared to 1.25 W/(m^2K) when the conductivity is 0.12 W/(mK). Reducing the frame material conductivity to 0.04 W/(mK) results in a frame U-factor of about 0.65 W/(m^2K). Reducing frame material conductivity to 0.02 W/(mK) results in a frame U-factor of 0.43 W/(m^2K). Currently available insulation materials have conductivities as low as 0.02 W/(mK), but materials with appropriate structural properties are difficult to find. New materials with the desired thermal and structural properties should be researched and developed.

5.5.4 Thermal Radiation Properties

The PVC frame simulations show that reducing the surface emissivity is one option for lowering the frame U-factor. Similar results have been found for aluminum frames (Gustavsen, 2001). But, as discussed above, filling the frame cavities with a currently available insulating material might produce U-factors that are almost as low.

5.5.5 Total Performance

Figure 17 and Figure 18 show the effect on total window performance of changing the material properties. From these graphs, it appears that improving the spacer performance could significantly improve the thermal performance of all of the products studied to an approximately equal extent; this is probably a result of having studied an equal spacer conductivity range for all frames. By contrast, the frame material plot (Figure 18) indicates that some material changes show a larger potential for improving total performance than others. For example, improved/new materials that replace a larger portion of the frame (as in Frames A and D) have a larger impact on total performance than new materials/technologies used in smaller parts of the frame (as in Frames B and C).

5.6 Materials Performance Targets

Comparing the thermal transmittance (U-factor) of windows to their opaque counterparts (wall, roof and floor constructions), it is obvious that the U-factor of windows needs to be reduced, even though looking at the whole energy balance for windows (i.e. solar gains minus transmission losses) makes the picture more complex. Still, material performance development targets may be defined based on the simulations performed in this paper. Criteria for finding the targets might however be defined in different ways. Here, we define the criteria in two ways: 1) Setting the frame/spacer material targets based on a frame U-factor reduction of a certain percentage, and 2) Setting an absolute U-factor level that the frame U-factor has to be less than or equal to. In this paper this level is set equal to 0.5 W/(m^{2}K), and it is based on the thermal performance (U-factor) of the best triple glazing units available. This value is similar to the U-factor target found when analyzing the requirements of windows for zero energy residential buildings in US heating dominated climates (Arasteh et al. 2007). Window framing elements should have a U-factor less than or equal to the U-factor of the glazing which is mounted in the frame.

5.6.1 Percentage Value Performance Target

Various percentage reduction levels can be specified, based on various criteria. Instead of setting the exact level, we here report the frame U-factor percentage reduction found by reducing some of the material properties from their default/nominal values to the next nearest lower step calculated in this work. The results are reported in Table 4. The table shows that that reducing the spacer effective conductivity from 0.25 to 0.1 W/(mK) reduces the frame U-factor by between 7 and 12 percent, while, as expected, there is quite some variations for the effect of changing the thermal break/material conductivity and PVC emissivity. The latter is the case because the change in material property is different for each frame and because the frames have very different designs. Thus, setting a common material level for all frames might be difficult. Material targets should instead be specified for each individual frame. For the spacer, it is easier, and a common target may be specified, as this influences the frame and edge-of-glass U-factor similarly.

Table 4. Frame U-factor percentage reduction.

Frame	Material Properties	Percentage Reduction in Frame U-factor [%]
A	λ_{break} = 0.089 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	8
	λ_{break} = 0.089→0.04 W/(mK), $\lambda_{eff.,spacer}$ = 0.25 W/(mK)	27
	λ_{break} = 0.089→0.04 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	34
B	λ_{break} = 0.1733 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	10
	λ_{break} = 0.1733→0.1 W/(mK), $\lambda_{eff.,spacer}$ = 0.25 W/(mK)	5
	λ_{break} = 0.1733→0.1 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	15
C	λ_{break} = 0.029 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	12
	λ_{break} = 0.029→0.02 W/(mK), $\lambda_{eff.,spacer}$ = 0.25 W/(mK)	5
	λ_{break} = 0.029→0.02 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	17
D	$\lambda_{mat.}$ = 0.12 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	8
	$\lambda_{mat.}$ = 0.12→0.06 W/(mK), $\lambda_{eff.,spacer}$ = 0.25 W/(mK)	34
	$\lambda_{mat.}$ = 0.12→0.06 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	42
E	ε_{pvc} = 0.9 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	7
	ε_{pvc} = 0.9→0.7 W/(mK), $\lambda_{eff.,spacer}$ = 0.25 W/(mK)	10
	ε_{pvc} = 0.9→0.7 W/(mK), $\lambda_{eff.,spacer}$ = 0.25→0.1 W/(mK)	16

5.6.2 Absolute Value Performance Target

Comparing the frame U-value to an absolute performance level is another way of finding material research targets. Earlier in this paper we proposed that the window frame U-factor has to be less than or equal to 0.5 W/(m^2K). Looking at the frames in this study (Frames A-E above) it is clear that some of the frames can not reach this level of performance without changing their designs considerably. This is the case for Frames B and C that have minimum frame U-factors of 1.46 and 0.61 W/(m^2K), respectively, even for the lowest thermal break and effective spacer conductivities used, i.e. a spacer conductivity of 0.02 W/(mK) and a thermal break conductivity of 0.005 W/(mK). This tells us that selectively improving the performance of single components (thermal breaks) in a frame is not as effective as overall product performance improvements. Frame E has a slightly larger minimum U-factor (0.54 W/(m^2K)) than the defined criteria. An effective spacer conductivity of 0.02 W/(mK) and PVC emissivity of 0.02 were used to calculate this U-factor. Frame A has a minimum U-factor of 0.5 W/(m^2K) for the minimum spacer and thermal break conductivities used, thus, exactly meeting the defined criteria. Frame D is the only frame where the Frame U-factor can be reduced below the defined criteria by a good margin. For this frame a material conductivity of 0.03 W/(mK) and spacer conductivity of 0.25 W/(mK) results in a frame U-factor of 0.55 W/(m^2K). Reducing the material conductivity to 0.01 results in a frame U-factor of 0.3 W/(m^2K). Thus, for frame designs like Frame D, a material conductivity of slightly below 0.03 W/(mK) should be the target (assuming that the best spacer technologies of today can be used). Applying a material conductivity of 0.03 W/(mK) and reducing the spacer conductivity from 0.25 to 0.1 W/(mK), results in a reduction in frame U-factor from 0.55 to 0.48 W/(m^2K).

6 Conclusions and Further Work

We conclude that several options exist for improving the thermal performance of windows and window frames in particular:

- Development of new spacer technologies – New insulating spacer bars and/or alternatives to the sealant used in the best spacers of today offer a great potential for improving frame energy savings. We propose a materials research target of an effective conductivity for spacers of 0.02 W/(mK).
- Identification of alternative thermal break materials (from existing insulating materials) – Thermal break materials used in aluminum frames have high thermal conductivities; alternatives could be found among existing materials with a conductivity of about 0.02 W/(mK), although materials with the required structural properties might be difficult to find.
- Development of new thermal break materials – Different structural properties are needed for different frames (e.g., for aluminum and wood frames). We propose a materials research target of a conductivity for thermal break materials in aluminum and wood frames of 0.005 W/(mK).
- Development of structural insulating materials – Alternatives to solid wood frames could be developed, for example. We propose a materials research target of a conductivity for solid frame materials of 0.03 W/(mK).

- Development of low-emissivity coatings (or pigments) for PVC/aluminum window frames with many cavities – These coatings could reduce radiation heat transfer in frame cavities. We propose a materials research target of an emissivity for frame surfaces that define hollow cavities of 0.05.
- Development of alternative frame designs/technologies – Frame technologies that are still on the research stage or not yet invented could have better thermal performance then today's technologies. In that regard, this work has identified some research paths for the years to come. One alternative slim window frame profile is presented by Applefield et. al. (2010).
- Alternative window designs. Promising approaches to reducing window energy loss not directly covered in this paper should also be the subject of future work. These include the "Sashlite" spacer-less system where glass and sash are built together without the need for a separate spacer (Sashlite, 2011).

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