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Highly Insulating Window Panel Attachment Retrofit

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The Green Proving Ground program leverages GSA's real estate portfolio to evaluate innovative sustainable building technologies and practices. Findings are used to support the development of GSA performance specifications and inform decision-making within GSA, other federal agencies, and the real estate industry. The program aims to drive innovation in environmental performance in federal buildings and help lead market transformation through deployment of new technologies.

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I. Executive Summary

BACKGROUND

Nationwide, the energy savings potential for replacing the existing windows on commercial buildings with high-performance triple pane windows is about 1 quadrillion BTUs (Apte 2006), which equals just over 1% of the total energy consumption by the United States in 2011. One quadrillion BTUs is also known as 1 “quad” and is equivalent to the energy consumed by 5.5 million U.S. households (US EIA 2012). By using insulating window retrofits installed over existing glass and framing systems to achieve performances levels similar to triple glazing, it should be possible to reduce heating and cooling energy use by two thirds of the previous value for typical existing construction, on average. Larger savings can potentially be achieved by retrofitting buildings with the poorest performance windows in the coldest climates.

OVERVIEW OF THE TECHNOLOGY

This study evaluates a high-performance insulating window retrofit technology that was installed on the interior side of each original single pane glass window in a GSA office building in Provo, Utah. A total of 21 windows were retrofitted with a combined glass surface area of about 231 sq. ft. and a wall-to-window area ratio of 10 to 1. The highly insulating window retrofit product (Hi-R panel) tested is a pre-manufactured, framed window unit featuring three glazing layers that enclose two hermetically sealed Argon filled gaps. The thermal insulating performance of windows resulting from an indoor-outdoor temperature difference, not direct solar gain, is reported as a conductance (U-factor), where a smaller number is a better insulator. The mathematical inverse, the R-value, which is typically used to report thermal performance of walls, is also provided (in IP units) for comparison. When installed over an existing single pane window, the resulting four-layer assembly has a U-factor of 0.14 BTU/hr-ft²-F (R-7.1) at the center of glass, and 0.27 BTU/hr-ft²-F (R-3.7) for the whole window, including the frame. By comparison, the original single pane glass window with an aluminum frame had a U-factor of 0.98 BTU/hr-ft²-F (R-1) for both the center of the glass and the whole window, because the original glass and frame performance are roughly the same. While the four-layer glazing reduces the heat transfer of the central glass area to 1/7 of its previous value, the whole window heat transfer, including the frame effect, is reduced overall to approximately 1/3 the previous value.

PROJECT RESULTS/FINDINGS

As measured over the winter months with the highest heating load, the total building heating load reduction was 34-41% for the Provo office, following the installation of the Hi-R panel window retrofit. By scaling the measured results by heating degree-day data for the entire year, we can project the annual savings for the retrofit as reduced consumption of natural gas by 108 MBTUs, which leads to reduced carbon dioxide emissions of 6.4 tons. Although this type of retrofit can also result in cooling energy savings, a measurable cooling impact was not apparent in this building. Existing deep window overhangs already provided effective shading that reduced solar heat gain through windows.

In addition to reduced energy consumption, the improved thermal performance of the insulating window retrofit results in warmer room-side glass surface temperatures under cold winter conditions, improving thermal comfort for the occupants and increasing usable office space near windows. Following the retrofit installation, after a winter and summer season of working in the building with the new windows, a web-based survey was distributed to occupants of the office to acquire feedback regarding their thermal comfort

before and after the retrofit. Occupants noted improvements in their winter thermal comfort, and personal portable space heater use was reduced or eliminated to maintain comfort after the retrofit installation.

Condensation was not observed behind the window retrofit panels during the monitoring period of this study. The compressed rubber seal of the retrofit panel against the existing window opening appears to have been adequate to avoid moisture transmission to the colder original glass layer and thus avoid condensation. However, the dry climate of Provo, Utah, and the absence of a building humidification system made this particular case a weak test of condensation sensitivity for this type of product. Evaluation of condensation potential for retrofit window panels should be conducted for individual applications as they are considered, by modeling surface temperatures, establishing expected humidity conditions and building an understanding of the efficacy of the gasket to impede moisture transport.

The rate of payback of the initial investment in this particular retrofit window improvement was estimated to be approximately 9 years. Payback will vary as a result of initial window performance, climate and other application specific factors. A thermal modeling comparison for the Provo, Utah, case showed that a retrofit window panel choice with a different configuration and slightly less insulating performance could have a faster payback, by reducing the initial cost without significantly reducing the thermal performance and energy/cost savings over time. A double pane Hi-R panel with two low-emissivity (low-e) coatings, while significantly less expensive, achieves a 51% energy savings compared to the triple panel Hi-R panel with one low-e that achieves a 53% savings.

CONCLUSIONS

- Twenty-one existing single pane, aluminum-framed windows (total 231 sq. ft., and 1:10 window to wall ratio) were retrofitted in a GSA single-story office building in Provo, Utah, using interior fixed Hi-R window panels consisting of triple pane, single low-e glazing fitted in its own narrow aluminum frame. The installation maintains a similar window aesthetic to the base window, and can be performed quickly with minimal disruption to building occupants.
- Measured total building heating load reduction was 34-41% for winter months. Projected annual savings are estimated as 108 MBTUs of natural gas annually, resulting in 6.4 tons of CO₂ emissions.
- In addition to reduced energy consumption, this retrofit resulted in improved thermal comfort for the occupants and increased usable office space near windows.
- Condensation was not observed behind retrofit panels during the monitoring period of this study in a dry climate (Provo, Utah).
- The rate of payback of the initial investment in this retrofit window improvement was estimated to be approximately 9 years for this particular building and climate. Application specific factors, including initial window performance, wall-to-window area ratio, climate, and energy cost, will influence the payback period for other projects.
- Based on thermal modeling results for the Provo, Utah, retrofit, a double glazed, double low-e, interior Hi-R panel retrofit would provide a better value and faster payback than the triple layer, single low-e configuration that was installed. The energy savings associated with these two configurations is nearly identical, but the initial cost of the triple layer Hi-R panel is significantly higher.

II. Background

A. WINDOW ENERGY SAVINGS OPPORTUNITY

Windows present a significant energy load to buildings, especially for older buildings with windows comprised of a single layer of glass and highly conductive, non-thermally broken metal frames. Previous work by LBNL has shown that, averaged over the contemporary building stock in the United States, roughly 39% of heating energy BTUs consumed in commercial buildings annually, or 0.96 quadrillion BTUs (quads) out of 2.45 quads, is associated with windows (Apte 2006). The same work estimated that the use of highly insulating triple pane low-e windows could reduce window-related commercial building heating use down to 0.25 quads, or a quarter of the previous amount (see Table 1). For context, the entire U.S. annual energy consumption has been close to 100 quads for several recent years, and one quad is equivalent to the energy consumed by roughly 5.5 million U.S. households (US EIA 2012).

While it is possible to replace existing windows with triple glazing to improve energy efficiency, it can also be complicated and expensive, depending on the design of the existing construction. It is, therefore, important also to consider retrofit options that provide equivalent thermal performance gains while making use of the existing installed glass and framing. The case for energy savings associated with highly insulating windows is compelling enough for the average U.S. building stock. However, the energy savings potential is often much higher in heating-dominated climates of the U.S., such as the northern Midwest and Northeast, especially when the building still utilizes older, low-performance window products. Buildings in the most demanding winter climates with the least insulating existing window products (such as single-pane glass in metal frames with no thermal break) present the most compelling cases for retrofitting with Hi-R panel window attachments.

Table 1. U.S. Annual Commercial Building Window Energy Use - reported in quadrillion BTUs (quads) of primary (source) energy. For context, the U.S. total annual energy is ~100 quads

	Building HVAC energy consumption	Window-related energy consumption	Percent of building HVAC energy-related to windows	Window-related energy consumption for triple glazing performance	Building HVAC energy savings for triple glazing
Heating	2.45	0.96	39%	0.25	29%
Cooling	1.90	0.52	28%	0.21	16%
Total	4.35	1.48	34%	0.46	23%

The U.S. General Services Administration (GSA) is a leader among federal agencies in aggressively pursuing energy efficiency opportunities for its facilities and installing renewable energy systems to provide heating, cooling, and power to these facilities. GSA's Public Buildings Service (PBS) has jurisdiction, custody or control over more than 9,600 assets and is responsible for managing an inventory of diverse Federal

buildings totaling more than 354 million square feet of building stock. This includes approximately 400 buildings listed in or eligible for listing in the National Register of Historic Places, and more than 800 buildings that are over 50 years old. GSA has an abiding interest in examining the technical performance and cost-effectiveness of different energy-efficient technologies in its existing building portfolio, as well as in those buildings currently proposed for construction. Given that the large majority of the GSA's buildings include office spaces, identifying appropriate energy-efficient solutions has been a high priority for GSA, as well as for other Federal agencies. It is expected that GSA's large portfolio of buildings has a significant energy savings potential associated with Hi-R window panel retrofits. However, there is significant variability in the existing window framing configurations in this portfolio and no single Hi-R panel design is expected to be applicable in all cases. A variety of Hi-R window panel retrofit mounting solutions will be needed for widespread deployment.

While the predominant focus of this study is the potential heating energy reduction associated with higher performance windows, it is important to keep in mind that windows interact strongly with both heating and cooling loads in buildings. In comparison to heating energy demand, windows are responsible for about 28% (0.52 out of 1.90 quads) of cooling energy used in commercial buildings (Apte 2006). Furthermore, windows provide valuable natural daylight services to buildings by displacing electric lighting loads, which results in further energy savings.

While the supporting data is sparse, it has been estimated that roughly half of the United States installed commercial window stock has double pane glass, with the remainder single pane, and the majority are mounted in aluminum frames (Apte 2006). As a large commercial building owner with diverse holdings, it is a reasonable assumption that the GSA window stock has a similar percentage of single and double glazed windows. On average, the combined heating and cooling energy associated with windows is about 34% (1.48 out of 4.35 quads), and the energy savings potential in existing commercial buildings retrofitted to high performance triple low-e windows is about 1 quad (Apte 2006). Using this level of insulating window retrofit, it should be possible to reduce heating and cooling energy use associated with windows by two-thirds of the previous value. With 34% of a building's heating and cooling energy attributable to windows, this represents a potential 11% reduction of the entire heating and cooling energy requirements for GSA buildings. Retrofitting the poorest performance windows in the coldest climates will result in even larger savings at specific sites.

B. STATE OF THE ART WINDOW TECHNOLOGY

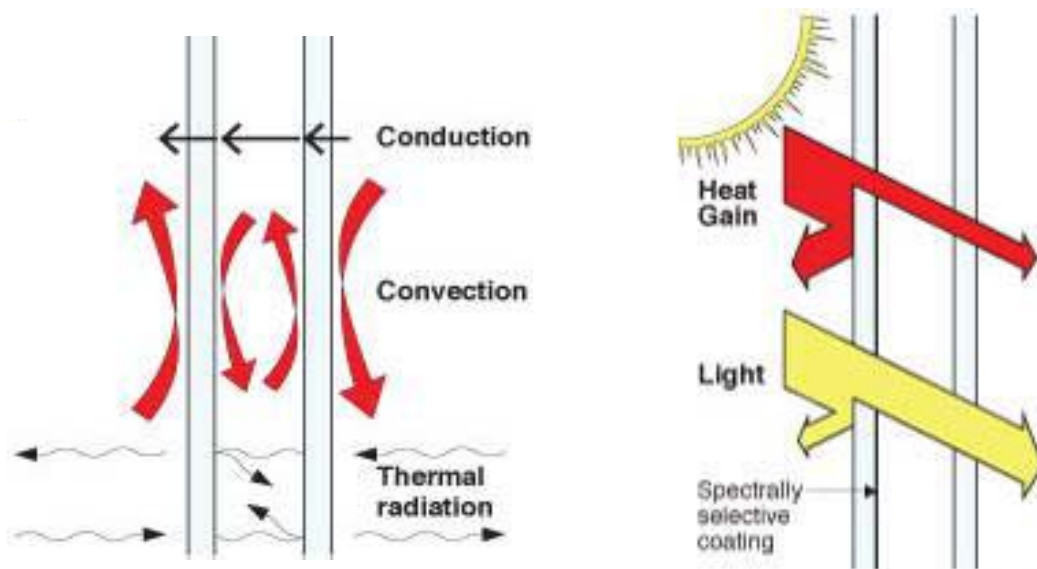
Many years of high-performance window technology development have achieved significant reductions of heat flow through windows by means of controlling thermal conduction, convection, and radiation (see Figure 1, left). Some of the established high-performance design elements include multiple glazing layers that enclose hermetic insulating gas layers to reduce conduction and convection, low-emissivity (low-e) coatings to reduce radiant heat exchange between the layers and more insulating frames and edge of glass spacer materials to reduce conduction at the perimeter of the glass area. These measures address the thermal transfer due to interior-exterior temperature difference, typically reported as a resistance (R-value) for walls, or as a U-factor (inverse of R-value) for windows. A smaller U-factor signifies a better insulator.

Compared to opaque wall insulations, windows have additional performance criteria to consider. Windows can transmit a large fraction of directly incident solar radiation into the interior. The amount of this type of

energy flow through the window is reported by the solar heat gain coefficient (SHGC), a unitless number from zero to one that represents the fraction of solar energy incident on the exterior of a window and frame that is transmitted to the interior. Another factor to consider is the visible light transmission (VT) of a window. Visible light transmission through windows can reduce electric lighting loads and improve the quality of light and occupant enjoyment of the space, while too much direct light transmission can cause discomfort from glare. Air infiltration, or leakage around joints and gaskets, is also important and highly variable, especially in older buildings with worn operable windows. Retrofit panels can help improve air tightness without replacing the entire window. The room-side glass surface temperature that a window reaches under typical environmental conditions is an indicator of thermal comfort for occupants when they are near the windows. A more insulating window will have a room-side glass surface temperature closer to room temperature, providing a more comfortable work space near the window and effectively increasing usable space in the building. The room side window surface temperature also determines the likelihood that condensation will form on the glass under various indoor air humidity conditions.

Low-emissivity coatings, which improve the insulating performance (*i.e.*, lowering U-factor) of a window by reducing the long wave infrared radiation exchange between glazing layers, can also be designed to reflect portions of the solar spectrum, resulting in lower solar heat gains. A spectrally selective, or low solar gain, low-e coating preserves the clear view of uncoated glass, while reflecting most of the invisible, near-solar infrared portion of sunlight, which carries about half of radiant solar energy (see Figure 1, right). This combination of properties, available in low-e coatings, reduces both heating and cooling loads in buildings, leading to energy savings in both winter and summer. Rejection of solar gain when direct sunlight falls on a window also reduces peak cooling loads at the time of day when electrical demand on the grid is at its maximum. However, low solar heat gain windows are not always the most optimal energy choice.

Figure 1. Heat transfer through windows. Conduction, convection, and radiation modes of heat transfer resulting from an indoor outdoor temperature difference (left). Direct solar heat gain and reflection using a spectrally selective or low solar gain low-e coating (right).



Some buildings in appropriate climates will benefit from high solar gain low-e coatings, which can help offset heating energy demand, by providing passive solar gain. For best results, the building typically also will take advantage of seasonal shading geometry or a means of deployable window shading to control unwanted solar gain during hotter periods of the year. Commercial buildings with high internal heat loads from people and equipment are often dominated by cooling energy in many climates and are, thus, not frequently considered for accepting passive solar gain. As revealed by the data in Table 1, however, more energy is consumed nationally to heat commercial buildings than to cool them, suggesting potentially large opportunities to take advantage of passive solar heating in commercial buildings. In the case of a retrofit, it is also important to determine if a building is already benefiting from passive solar gains that will be eliminated by the selection of a low solar gain retrofit. Selection of high solar gain windows must be accompanied by consideration for mitigating that gain when it is undesirable. Passive solar gain should only be selected when the building, window orientation, shading, and climate are well suited to this practice. Whole building annual energy analysis of particular buildings under local conditions is advised, including assessment of seasonal shading or other means to control solar gain at the appropriate time.

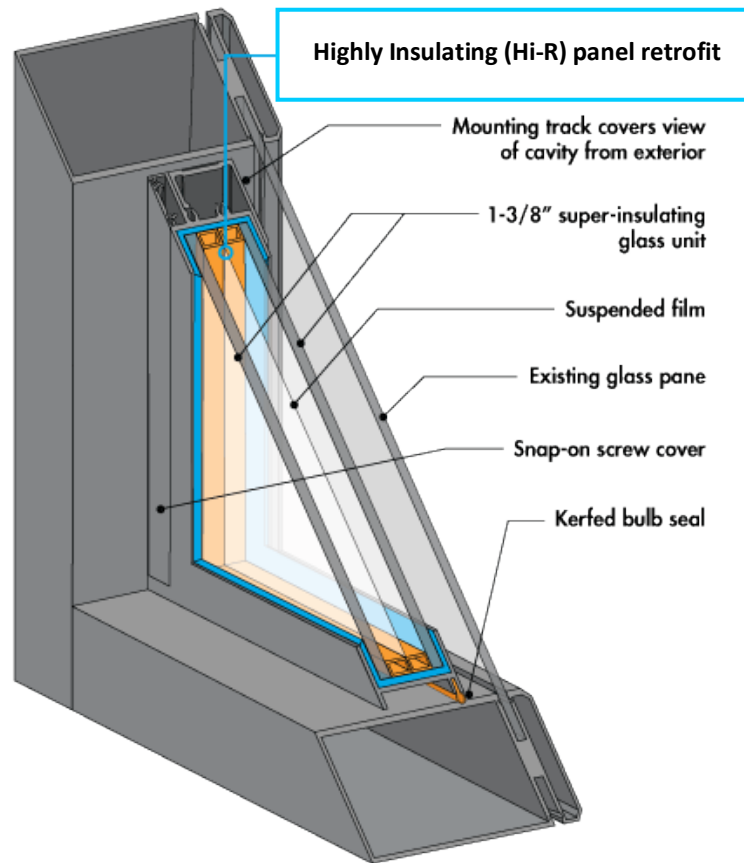
It should be recognized that a single window performance criteria (*e.g.*, U-factor, SHGC, or VT) is never the optimal choice for all conditions of building type, climate, orientation, and local shading. It is best practice to evaluate window performance choices for particular climates and individual building applications. The high degree of variability in commercial building design favors the use of whole-building annual energy simulations using local climate data when selecting the optimal window properties for a building, making use of the specific climate, orientation, and shading criteria for the application.

III. Project Installation and Evaluation

A. OVERVIEW OF RETROFIT TECHNOLOGY

The highly insulating window retrofit product (Hi-R Panel) tested in this study is a new and relatively unique retrofit product offering. It takes the traditional storm window concept that has been used for residential windows for more than a hundred years and reconfigures it as a highly insulating retrofit for commercial building applications, where there remains a large stock of buildings with low performance single glazing. A major distinction from traditional storm windows is that the Hi-R panel can be comprised of a two- or three-layer, hermetically sealed insulated glazing unit (IGU), with integrated high performance low emissivity (low-e) coatings, rather than the traditional storm panel that is a single glass layer and often not low-e coated (see Figure 2).

Figure 2. Corner cross section of the three-layer, highly insulating framed retrofit panel fitted inside the larger frame of an existing single glazed façade.



The Hi-R panel is installed on the interior (*i.e.*, the room side) of an existing low-performance window instead of the exterior, which is where residential storm panels are typically located. Installation can be completed quickly and without significant disruptions to building occupants (see Figure 3a). Aluminum rails

are fastened with a self-adhesive gasket seal and screws to the existing window frame jambs (*i.e.*, the sides of the window pocket) (see Figure 3b, left). The aluminum-framed retrofit glazing panel is then attached to the frame rails with screws (see Figure 3b, right), and an integrated rubber gasket around the perimeter of the pane seals the air pocket between the original glass and the retrofit Hi-R panel. The four corners of the retrofit panel were sealed with silicone caulk to complete the seal of the panel where there is a small gap between the vertical mounting rail and the sill and head of the original window pocket.

Figure 3a. Installation of highly insulating panel retrofit



Figure 3b. Highly insulating panel retrofit frame attachment details



Side mounting rail attachment to jamb, left.

Side mounting rail cross-section with Hi-R panel frame installed, right.

As a commercial building-oriented product addressing a market in which many windows are not operable, the particular Hi-R window panel design used in this study is not intended to accommodate operable windows, although alternative designs could accommodate operable windows. In this case, the Hi-R panel is best suited for installation over fixed windows or operable windows where it is acceptable to disable the

operating hardware and no longer make use of windows for air ventilation. The fixed nature of the Hi-R panel design used in this study makes it easier to secure and seal air flow around the retrofit panel, structurally allowing support for heavier, multiple-layer retrofit panels while improving the thermal performance and condensation resistance compared to operable Hi-R panel configurations. The retrofit framing design and placement location of the Hi-R panel and other similar retrofit panels favor a more cost-effective, high-performance window product and less labor-intensive installation, compared to replacing the original windows and framing with new high-performance windows. The Hi-R window panel can be equally compelling for storefront and curtain wall applications and adapts well to wood/drywall returns. Furthermore, a retrofit insulating panel maintains the existing windows and frame materials rather than putting them into a waste stream and uses less new material than a replacement window would, while achieving comparable performance.

In addition to the heating and cooling energy savings associated with the improved insulating value of high performance retrofit window panels, the room-side window surface temperature will be closer to indoor air temperature, which results in a significant improvement in thermal comfort for occupants. Sitting near a poorly insulating window in winter is uncomfortable because of extra heat loss from the windows in the form of cold air drafts and thermal radiation exchange. A more insulating window, with a higher room-side temperature in the winter, will be much more comfortable, thus increasing the usable space in the building. There are corresponding thermal comfort benefits in hot summer conditions when the temperature difference across the window is reversed and it remains cooler by the window.

Just as hermetically sealed replacement windows provide a range of low-e coating choices, a high-performance retrofit panel comprised of one or more additional layers will include low-e coatings to achieve optimal performance. In the case of the three-layer Hi-R panel tested in this study, only one of the sealed gas gaps had a surface that was low-e coated. Window thermal performance is specified as a U-factor (thermal conductance), where lower numbers are a better insulator, however R-values in IP units are also provided as a comparison to wall insulation values. The U-factor for the center of glass of the installed Hi-R panel is 0.14 BTU/hr-ft²-F (R-7.1), and 0.27 BTU/hr-ft²-F (R-3.7) for the whole window, including the frames.

As in all windows, low-e coatings can also include solar control properties that reduce solar heat gains (and thus air conditioning loads) when direct sun falls on the windows. The solar heat gain coefficient (SHGC) of the retrofit panel, including the original single layer of glass with a bronze-tinted applied film, is 0.24, down from about 0.57 for the original glass without the retrofit. The solar heat gain rejection achieved with a low-e coating is a static property that remains the same in hot summer months, when low SHGC is highly desirable, as well as cold winter months, when some passive solar heating benefit could be realized from higher SHGC. Commercial buildings often benefit more from the reduced air conditioning load in the summer than from the passive heating in the winter, but it is worth considering higher solar heat gain low-e coatings for climates and façade orientations that are well suited to favoring higher passive solar gains to offset heating energy demand. This is especially viable when the direct solar control in the summer can be controlled by another means, such as seasonal shading. Products like the Hi-R retrofit panel are available with both low solar gain and higher solar gain low-e coatings. It should also be mentioned that the sound attenuation benefits of the Hi-R window panel were found to reduce exterior sound in the work place.

B. DEMONSTRATION PROJECT LOCATION AND DESCRIPTION

The project site is a 6,347 square foot single-story GSA office building in Provo, Utah (see Figure 4 below). The building, built in 1971, has modest building envelope insulation levels characteristic of that time. The masonry block walls with brick veneer have, at most, 1" mineral wool insulation on the interior (see Figure 5), and there are 21 tall, slender (approximately 2-feet wide by 5-feet, 9-inches high) single-pane windows spaced semi-regularly around the four facades (mostly on the West and North orientations). The original single-glazed windows have an applied film with a bronze tint on the interior and utilize louvered, horizontal mini blinds. The wall-to-window area ratio is approximately 10:1, averaged over the four orientations. The majority of office workspaces are in close proximity to windows, as shown in Figures 5 and 6 (where the window locations are circled in red). Central forced air heating (natural gas) is augmented by perimeter baseboard radiators served by a central hot water boiler (also natural gas). Some office workspaces were observed to have portable electric space heaters for supplemental heating. The building's roof top air conditioner and ventilation fans represent the electric space-conditioning load. There are multiple control zones in the conditioned interior space and a separate information technology utility closet housing computer servers that receives conditioned air from a smaller, dedicated rooftop system.

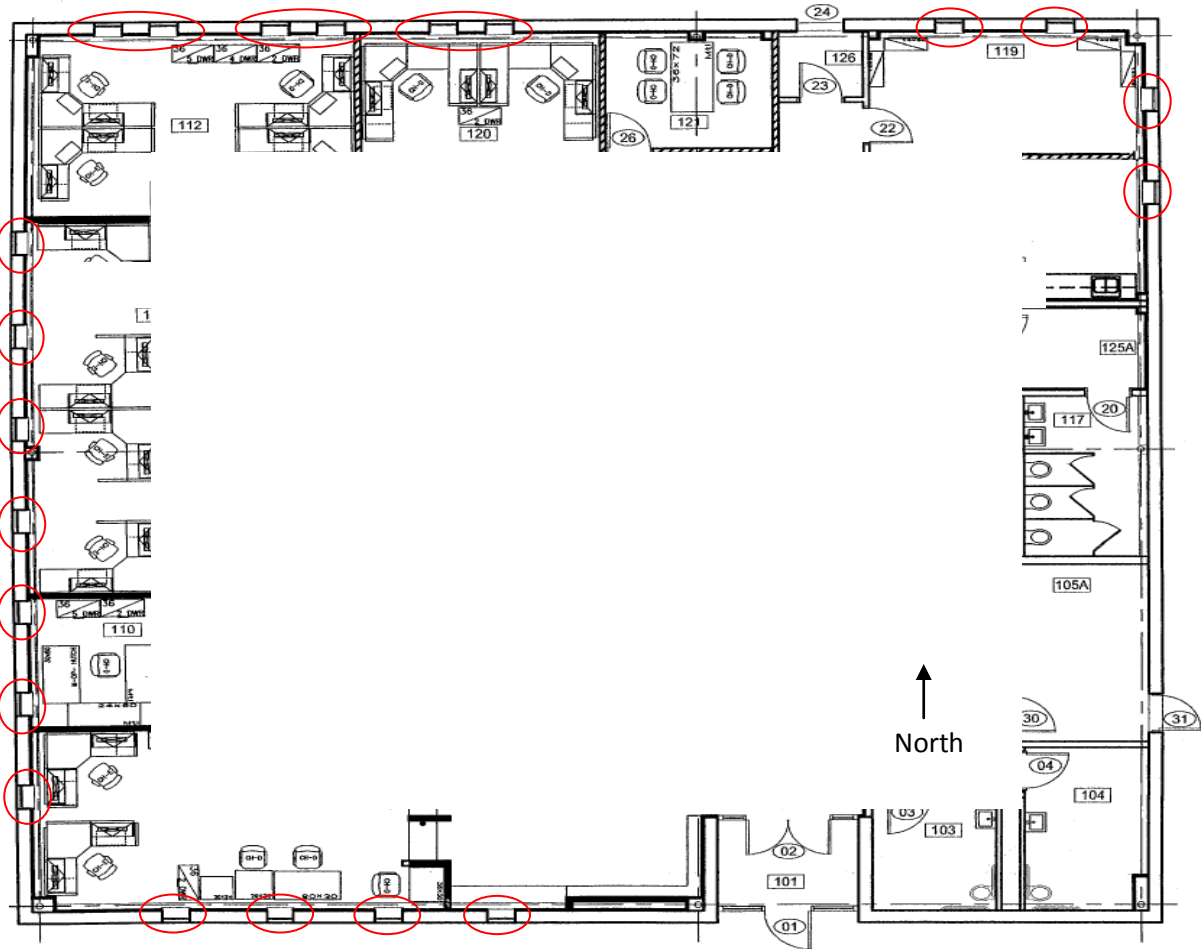
Figure 4. Exterior view of the west side of the Provo office building showing window configuration and overhang



Figure 5. Typical work space adjacent to window, left. View of insulation on block wall above drop ceiling, right.



Figure 6. Provo office floor plan. Red ovals highlight the 21 window locations. North direction is located up.



C. TEST AND INSTRUMENTATION PLAN

To compare the performance of the insulating window panel retrofit to the existing condition of the subject building, a period of monitoring was conducted on the original configuration of the building before retrofit, during the winter, from December 15, 2011, through February 17, 2012. The window retrofit panels were installed on February 18, 2011. The ideal timing of the installation would have been earlier in the winter to ensure more comparable pre- and post-retrofit winter conditions; however, this schedule provided adequate data without waiting another year for the next winter season.

A series of autonomous datalogging sensors were deployed over the pre- and post-retrofit period. The post-retrofit monitoring period extended into July to explore the performance during the warmer spring and summer seasons as well as the winter; however, there was no direct measurement of pre-retrofit warm season conditions because of the limited schedule available to conduct the study. In addition to the direct measurements using sensors deployed by this research effort, GSA staff provided utility bills and detailed electricity and natural gas data from the existing building energy management system. This data was provided for both the warm and cold seasons of 2011 and 2012, before and after the retrofit.

Table 2. Pre-retrofit datalogging sensor descriptions

Quantities measured	Location of measurement
Temperature	East baseboard heater (to monitor runtime)
Temperature	North baseboard heater (to monitor runtime)
Temperature (thermocouple)	West center of glass
Temperature (thermocouple)	West frame
Temperature, relative humidity, plus 2 external temperature probes	Desk height west office, west wall, west baseboard heater (to monitor runtime)
Temperature, relative humidity	Break room thermostat
Temperature, relative humidity	Lobby thermostat
Temperature	South baseboard heater (to monitor runtime)
Temperature, relative humidity	Outside building in utility cage adjacent to boiler room

During the winter baseline period, nine small autonomous datalogging devices with five-minute logging intervals were deployed, as reported in Table 2. In addition to the basic ambient weather conditions, the focus of measurements during this period included interior glass, wall and window frame surface temperatures, relative humidity (RH), as well as monitoring the baseboard heater cycles to understand

when and how long they were active. Two lighting sensors that counted the hours of operation of the room lights, were also deployed during this period to understand the lighting schedule in the building.

During site visits in December 2011 and February 2012, an infrared camera was used to measure window and wall surface temperatures. The quantitative thermography laboratory techniques described in previous thermography work (Griffith 2000) were adapted under the constraints of the field test environment. Global infrared background corrections were made assuming a relatively uniform room enclosure surface temperature, and absolute temperature offset was confirmed by comparison with a surface mount thermocouple at a single reference point, rather than using a controlled reference emitter. Argon gas fill measurements were performed with a glow discharge instrument to confirm the gas fill in the new sealed retrofit panels.

During the post-retrofit logging period from February to July, 25 autonomous datalogging sensors were deployed to make detailed measurements of the retrofit panels on all orientations of the building. While most of the autonomous datalogging sensors stored months of data that was read out upon completion, some of the sensors used wireless transmission to a laptop computer operating in the building. This computer provided a remote connection that allowed monitoring of some of the data on a daily basis. The second logging period was several months longer than the first. As a result, the post-retrofit measurement interval increased from 5 minutes to 10-30 minutes (depending on the device), to avoid filling the memory before completion. The post-retrofit measurements focused on room-side and non-hermetic enclosed gap surface temperatures between the retrofit panel and the original glass layer. Measurement of temperatures and relative humidity in the gap allowed examination of the condensation potential between the retrofit and the original glass. One retrofitted window on each façade was instrumented with eight separate sensors, as shown in Figure 7 and described in Table 3. Two additional windows on the west and north facades also were instrumented to allow comparison of the condensation potential when a small hole is drilled through the original window frame to provide more moisture diffusion toward the outside condition compared to the inside condition. Wall and baseboard heater temperatures continued to be monitored to observe cycle time and duration.

Table 3. Summary of logged measurements over six months, February to July

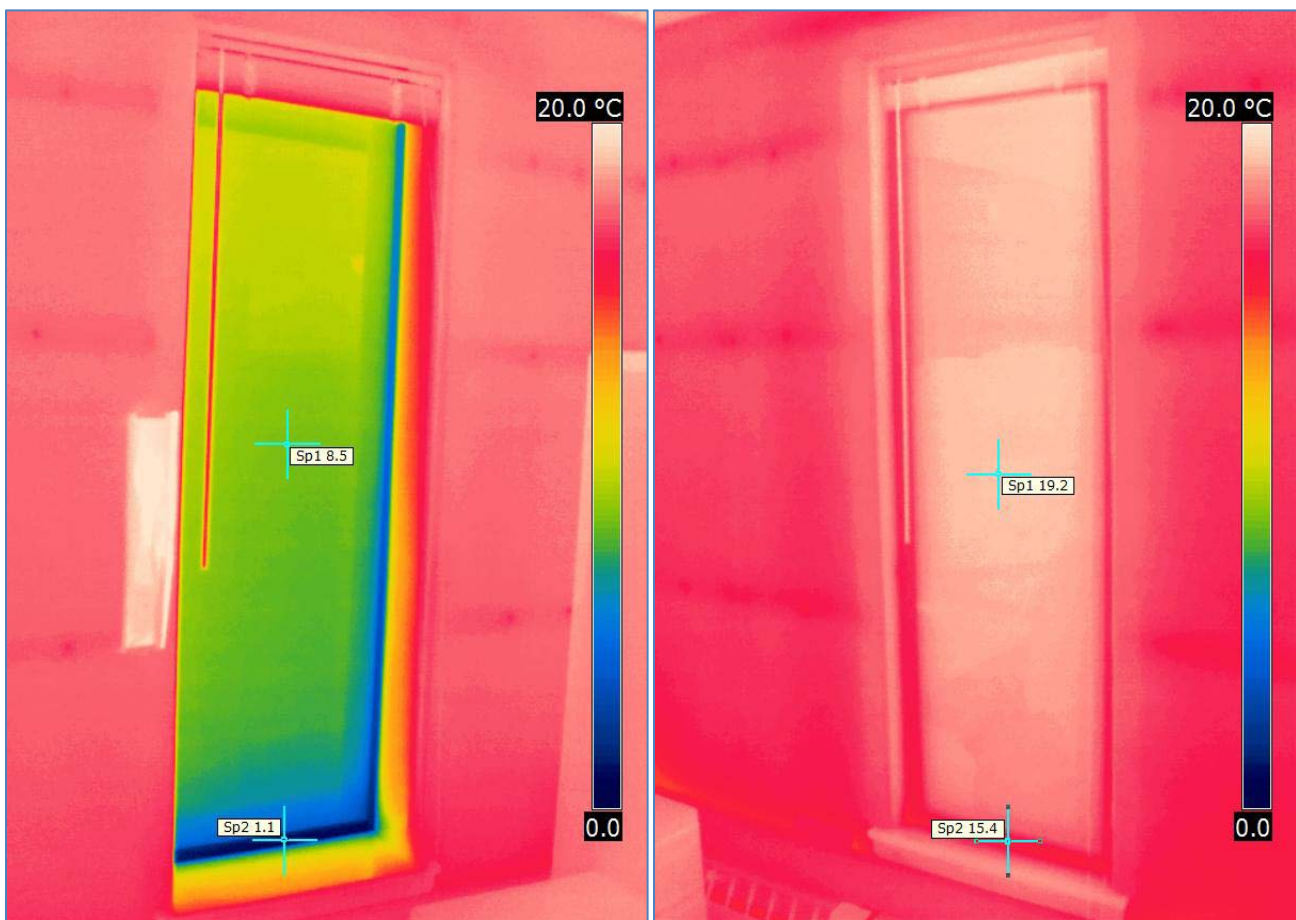
Location	Sensor Placement	Measurements Taken
Exterior	Utility Cage	<ul style="list-style-type: none"> Temp/RH
One window on each of the four facades (West and North wireless, East and South not wireless)	Room/Wall	<ul style="list-style-type: none"> Room side center of glass temperature Room side frame temperature Wall temperature Baseboard temperature
	Window Gap	<ul style="list-style-type: none"> Temperature/relative humidity in cavity between single pane glass and Hi-R panel retrofit Center of glass surface temperature of single glazing Frame temperature
Two drilled window frames (single and double holes)	Room/Wall	<ul style="list-style-type: none"> Room side COG temperature Room side frame temperature
	Window Gap	<ul style="list-style-type: none"> Temperature/relative humidity in cavity between single pane glass and Hi-R panel retrofit Center of glass surface temperature of single glazing
Inside Core	Thermostat, South lobby	<ul style="list-style-type: none"> Room temperature
	Thermostat, Break room	<ul style="list-style-type: none"> Room temperature
	North West open office	<ul style="list-style-type: none"> Room temperature, relative humidity
	West open office	<ul style="list-style-type: none"> Room temperature, relative humidity Light Floor temperature
	North East office	<ul style="list-style-type: none"> Room temperature, relative humidity Light Floor temperature
	North West office	<ul style="list-style-type: none"> Light on/off
	Break room	<ul style="list-style-type: none"> Occupancy Light on/off

IV. Project Results/Findings

A. DIRECT MEASUREMENTS

Using both infrared thermography and contact sensor surface temperature measurements, it is readily apparent that center-of-glass performance of the Hi-R panel retrofit is highly insulating and a dramatic improvement over the previous condition. Figure 8 depicts the side-by-side surface temperature comparison captured with an infrared camera. Although the indoor and outdoor temperature difference is not identical in these two images, the relative performance compared to the wall clearly shows the large improvement. In fact, the window insulation level now exceeds that of the modestly insulated masonry wall, as indicated by the slightly warmer glass temperature compared to the wall temperature in the right image.

Figure 8. Infrared camera room side window surface temperature measurements before (left) and after (right) Hi-R panel retrofit, taken during the February 2012 installation site visit.



**Before - Outdoor 1°C, Indoor 20°C (left).
After - Outdoor 7.8°C, Indoor 21°C (right).**

Figure 9 shows two retrofitted windows side by side with a smaller (5°C) temperature span, making it easier to read the higher temperature of the glass relative to the wall, and revealing more detail in the

temperature patterns of the wall. The subtle thermal bridging of the furring strips and fasteners are visible in the wall area, for example.

Contact surface temperature probes attached to the data logging sensors also confirm the dramatically improved thermal performance, as shown in Figures 10 and 11. During cold, nighttime conditions, when there is no influence from directly absorbed sunlight, and no cycling of the perimeter baseboard wall heaters to influence the surface temperatures, the room-side surface of the retrofit layer is about 10C° warmer than the original glass under the same outside freezing condition (0°C). Under this condition, the 8°C single-pane glass surface temperature rose to 18°C after the retrofit, approaching the room temperature of 21°C. The room-side glass surface after retrofit is again shown to be warmer than the interior surface of the wall by about 1-2 degrees Celsius. Thus, the glass area of the retrofit window system is now a better insulator than the existing wall construction.

Figure 9. Infrared thermogram of two windows measured after the retrofit with a small temperature span scale (5°C), demonstrates detailed temperature variation between the glazing, frames and wall.

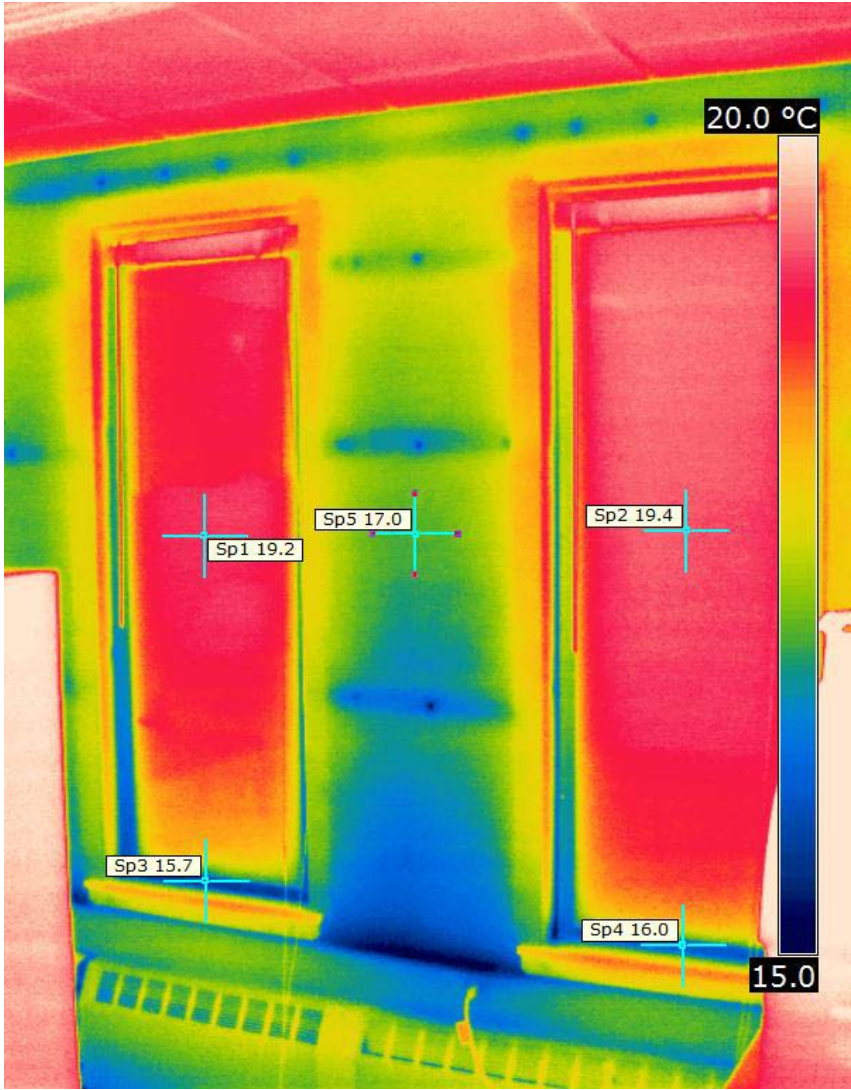


Figure 10. Pre-retrofit logged window glass and frame surface temperatures, with indoor/outdoor conditions and wall temperature comparison.

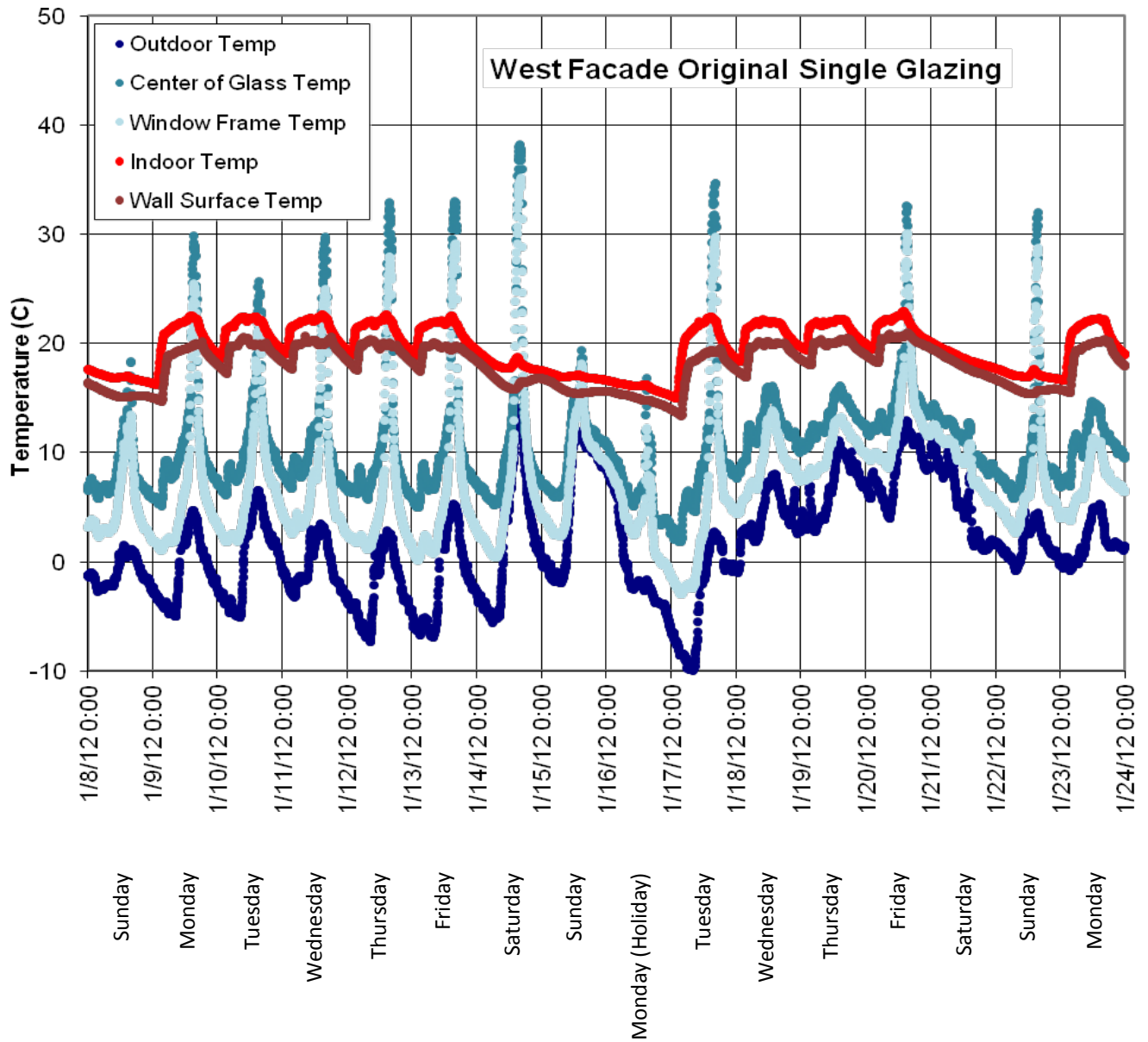
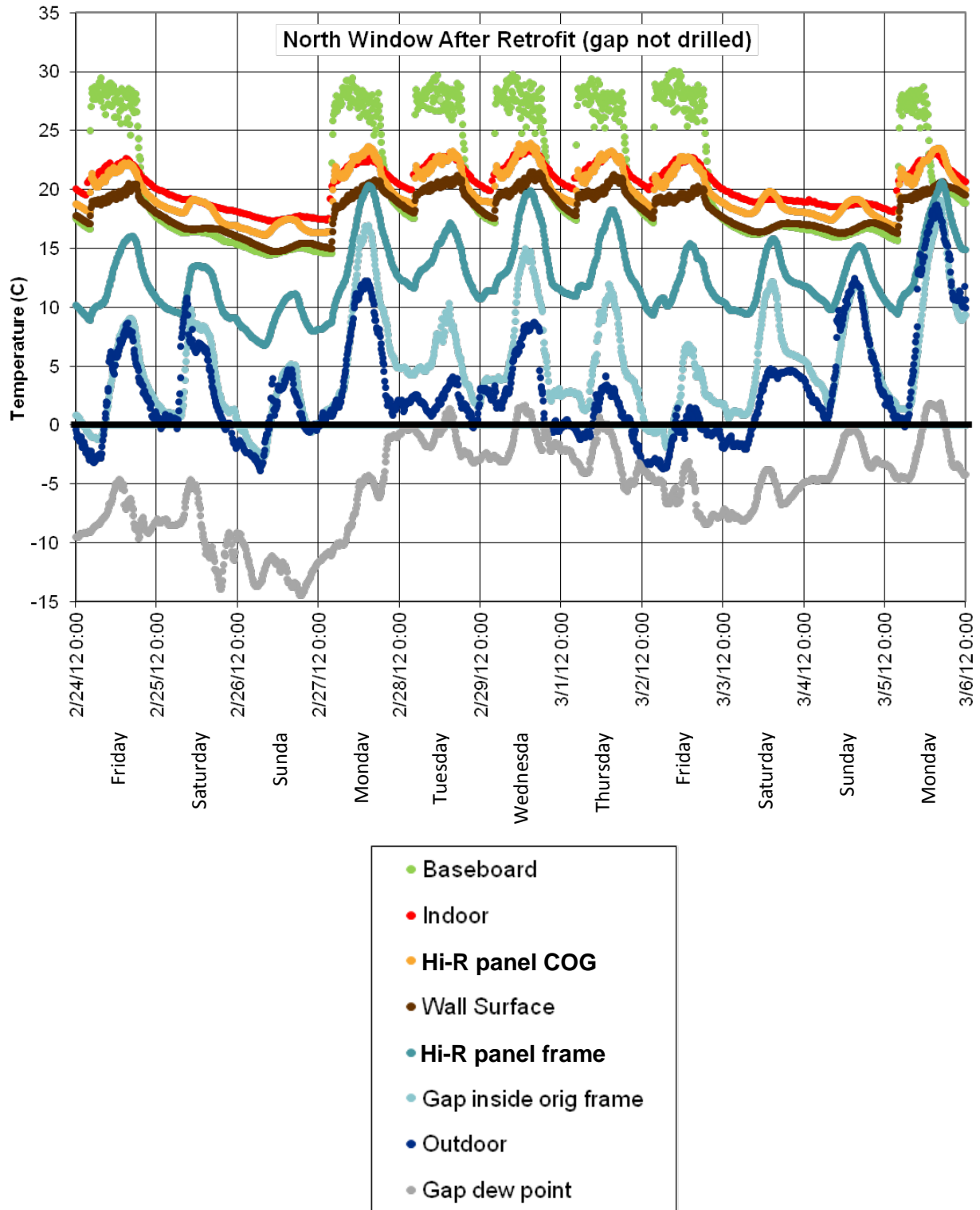


Figure 11. Post-retrofit logged window glass and frame surface temperatures including non-hermetic gap facing surface of original frame, and wall temperature comparison. Baseboard heater is on when green data points labeled Baseboard are above 20°C.



B. MODELED WINDOW PERFORMANCE RESULTS

The window/glazing and frame performance computer simulation software tools WINDOW and THERM, which were developed with the support of the US Department of Energy and are available at no cost to users, are valuable and well-established tools to rate the U-factor, solar heat gain coefficient (SHGC) and visible transmittance (VT) of windows. These software tools are regularly used for thermal and solar-optical performance modeling of windows by window manufacturers, National Fenestration Rating Council (NFRC) researchers and others. These tools also are applicable to the selection and design of high-performance window panel retrofits, including calculating U, SHGC and VT for the retrofit assembly and informing the design of frames and retrofit attachment systems with minimal thermal bridging at the perimeter of the highly insulating panel.

Although the modeling techniques for multi-layer specular glazings and coatings are mature and well validated, the accuracy and utility of the models is further demonstrated by comparison to the measured results of this project for the case of window retrofit panels. Glass surface temperatures predicted by the computer models were compared to the surface temperature measurements using the same environmental conditions (*i.e.*, the model boundary conditions were matched to the measured environmental conditions). The modeled surface temperatures for center of glass were mostly within 0.5-1°C of the measured values (see Table 4). In the few cases where the difference between measurement and model were as much as 3°C, the modest error is likely a result of incomplete knowledge of the environmental conditions, such as external wind speed, as well as non-steady state measurement conditions deviating from those used in the model, including the slow trends of environmental conditions over time and thermal storage in the masonry walls.

Although, in this case, the surface temperature output of the software tool, WINDOW, was used as a comparison, the primary performance output reported by WINDOW is U-factor and SHGC. The close correspondence between measured surface temperatures and the computer-modeled surface temperature results provides confidence that the product is being accurately modeled and that the U-factor reported by WINDOW is also reliable. For consistency with NFRC ratings, the U-factors are reported for standard conditions in NFRC100 (-18°C and 21°C) rather than the measured environmental temperature difference used to confirm surface temperature agreement. Using the WINDOW to calculate the center-of-glass performance of the three-layer Hi-R panel installed over single glazing, the complete assembly was shown to have a center of glass U-factor of 0.14 BTU/hr-ft²-F (R7.1).

Table 4. Summary of measured versus modeled surface temperatures (all temperatures in °C)

Date/time MST	Outdoor Air	A. Measured Surface 2 COG	WINDOW modeled surface 2 COG	B. Measured inside original frame (sill)	THERM Modeled inside original frame (sill)	C. Measured surface 3 COG	WINDOW modeled surface 3 COG	D. Measured surface 3, 15mm above sill sightline	THERM Modeled surface 3, 15 mm above sill sightline	E. Measured surf 8 COG (room side)	WINDOW modeled surface 8 COG	F. Measured room side of HI-R panel frame	THERM Modeled room side of HI-R panel frame	G. Measured room side wall surface	THERM Modeled room side wall surface	Indoor Air
12/26/11 4:35	-5.6	3.7	4.7	-0.8	-1.5	-	-	-	-	-	-	-	-	14.3	13.8	15.7
1/8/12 22:00	-1.8	6.6	6.9	2.9	4.1	-	-	-	-	-	-	-	-	15.2	14.7	16.5
1/15/12 4:00	-1.6	6.2	7.4	2.8	4.5	-	-	-	-	-	-	-	-	16.4	15.3	17.2
1/20/12 20:20	10.3	14.7	15.3	13.1	13.7	-	-	-	-	-	-	-	-	20.0	20	21.1
2/12/2012 4:50	4.6	10.6	11.2	8.9	8.9	-	-	-	-	-	-	-	-	18.0	17.2	18.7
2/26/12 2:30	-2.3	-1.1	-0.3	-0.9	2.5	3.8	3	4.3	6.4	16.6	15.7	8.1	8.7	15.7	15.7	18
3/4/12 4:00	2.0	3.2	3.6	2.6	6	7.3	6.4	7.7	9.1	17.8	17	10.9	11.2	16.9	17.1	19
3/11/12 3:30	4.1	4.2	5.6	4.5	7.6	7.9	8	8.3	10.5	18.1	17.5	11.4	12.3	17.6	17.6	19.3
5/14/2012 3:40	9.8	9.2	10.9	9.1	12.5	12.8	12.8	12.9	14.7	20.5	20.2	15.6	16.1	21.0	20.3	21.6

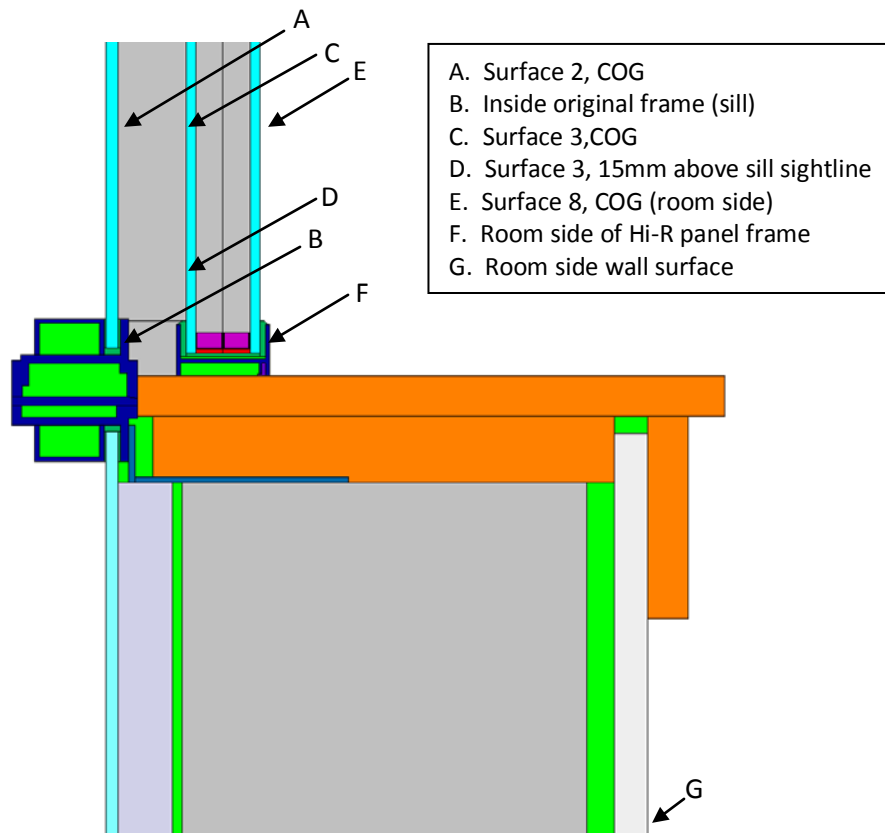
C. FRAMING EFFECTS

There is a direct conduction path through the high-thermal-conductivity aluminum frame of the original window and the retrofit panel. As a result, the room-side of the retrofit panel aluminum frame is significantly cooler than the center of glass. Observed winter minimums fell below 10°C, as seen in Figure 11. However, this is a significant improvement compared to the original frame, which was measured to have minimum interior surface temperatures <0°C under similar winter weather conditions, as seen in Figure 10. As in the case for center-of-glass room-side temperatures, it was important to look at these frame temperatures when the building room temperature was drifting down on thermostat setback, because the wash of perimeter heat delivered by the baseboard heaters makes it difficult to measure the surface temperature associated with steady state heat flow through the window. In Figure 11, periods when the baseboard heater cycles off (*i.e.*, green data points fall below 20°C) are the most reliable for comparison to modeling results. THERM, the two-dimensional heat-transfer simulation used in the NFRC rating system to predict the performance of the window framing, was used to model the retrofit window panel in the context of the original glass and wall (see Figure 12), to allow comparison of modeled and measured frame surface

temperatures, as well as to calculate the frame U-factor. A summary of modeled surface temperature compared to measurement are reported in Table 4.

There is more deviation between some of these frame/edge values compared to the center-of-glass values, with the gap-facing side of the original frame up to 3C° higher than measurements. Again, an unknown exterior wind speed (which was not measured along with ambient temperature; the model assumed zero wind speed) may be partially responsible. The models are also calculated at steady-state conditions (unchanging interior and exterior environmental conditions). It is possible that slow trending of the environmental conditions combined with the thermal storage behavior of massive materials like the cinderblock walls lead to a non-steady state measurement condition that is different than the modeled conditions. It is also complicated to gather the exact geometry and material properties for frame simulations, especially for existing construction with limited documentation. Still, the close agreement offers confidence in using existing window modeling tools to predict the overall U-factor with the addition of Hi-R panel retrofit assemblies. The THERM frame properties are combined with the center-of-glass model results in WINDOW to calculate a whole-window U-factor that includes the area weighted effect of the frame, resulting in a U-factor of 0.27 BTU/hr-ft²-F (R-3.7) for the whole window assembly. The retrofit assembly has less than 1/3 the heat loss associated with the original window. While this remains a favorable U-factor for a complete retrofit assembly and is comparable to the U-factor of a new high performance replacement double-glazed window with a highly insulating frame, this result demonstrates the value of addressing both glass and frame performance in a coordinated fashion, as the benefits of a glazing can be diminished significantly by relatively poor frame performance.

Figure 12. THERM heat transfer model cross section of retrofit window and sill frame with wall section. Letters correspond to measurement labels in table 4.



At high levels of glazing performance, the incremental cost to increase the insulating glass performance further may be better directed to improving the frame performance. However, optimizing the frame performance is challenging in many retrofit situations, especially if installing into an aluminum curtain wall configuration (where it is generally not feasible to add insulation or a thermal break to the framing), when there is a dimensionally deep, highly conductive frame already in place. If an aluminum-framed retrofit is installed with direct contact to an aluminum curtain wall, there is minimal change in original frame performance.

In this study, the retrofit aluminum frame was fastened into a wooden jamb, rather than installing it to the original outer aluminum frame. An intentional gap of $\frac{3}{8}$ " was left between the two frames to allow mounting datalogging equipment between the original glass and the retrofit panel, and it also served to improve the thermal break between the inner and outer aluminum frames. If the retrofit frame had been installed in direct contact with the original frame, the retrofit frame temperature would have been lower and the whole-window U-factor less insulating. The manufacturer suggested touching the frames in typical installation as a means to minimize paths for moisture transport through the wood and its joints to the non-hermetic gap. However, for the best thermal performance, it is worth considering measures to minimize the direct conduction path between a thermally unbroken original frame and the retrofit frame, if the retrofit frame also is highly conductive.

D. POTENTIAL FOR CONDENSATION

Under winter ambient weather conditions, very low surface temperatures (*i.e.*, below freezing) were observed on the original glass layer facing the gap to the retrofit product, as well as on the original frame facing the gap to the retrofit (see Figure 11). The original center-of-glass and aluminum-frame temperatures tracked together closely when there was no direct solar radiation, so only the frame temperature is presented in Figure 11. It is expected that a highly insulating interior retrofit panel will support a large temperature difference by itself. Therefore, the outer, original pane and frame will reach thermal equilibrium close to that of the outdoor ambient air temperature. This cold surface temperature enclosing the non-hermetic gap between the retrofit panel and the original glass layer raises concern about condensation. Although there is a rubber seal on the Hi-R panel that is designed to minimize air and moisture transport from the interior room air of the building around the panel to the gap between the Hi-R panel and original window, there remains the potential for relatively warm, moist interior room air to migrate around the retrofit panel and potentially condense on the cold surfaces of the original glass and frame. Despite this potential, no indications of condensation in the gap between the original single pane and retrofit product were observed (logged surface temperatures never dropped below the dew point), suggesting that the compressed rubber seal supplied with the retrofit panel was adequate to prevent condensation.

One contributing factor to this outcome was the extremely dry air conditions at the test site. Building interior relative humidity (RH) ranged between 15 and 25% for most of the winter. This low humidity helped avoid potential condensation issues in the non-hermetically sealed gap, but it should not be considered a typical building condition. ANSI/ASHRAE standard 62-2001 recommends maintaining room RH levels between 30% and 60%. The Provo, Utah, climate is notably dry compared to other U.S. climates. Also, buildings in cold dry climates are often humidified for occupant comfort and health. While this pilot study observed no condensation for a building in a dry climate without supplemental indoor humidification, it is recommended that attention should be given to condensation potential as part of the design process for interior Hi-R window panel retrofit installations, especially when there is an expectation of higher indoor air humidity. Reviewing the RH conditions of a particular building in advance of a potential retrofit should include a coordinated analysis of expected surface temperatures in the assembly, most likely with a frame-heat-transfer simulation tool such as THERM. It is difficult to predetermine the amount of moisture transport that will be able to diffuse past a compressed rubber bulb seal, both initially, as well as over time, as the seal ages. There may also be a variable degree of inadvertent air leakage introduced by the inconsistency of the installation or the air seal and insulation condition of the existing window. As a result of these uncertainties and the dry conditions of this test, it is recommended that this type of panel system be proven under winter conditions in a building with a higher room RH before adopting widespread deployment in such conditions.

As a potential winter condensation mitigation strategy, modest venting of the cavity toward the exterior was tested on two instrumented windows on the north and west facades of the building. A small hole, 1/8" in diameter, was drilled through the original aluminum frame to provide a minimal venting path from the new, non-hermetic gap enclosed by the retrofit panel to the exterior air. For each of the two drilled test windows, an adjacent window was also instrumented, allowing side-by-side comparisons between drilled and undrilled configurations on both the west and north orientations. This venting measure is potentially useful for maintaining lower relative humidity in the non-hermetic gap and avoiding condensation by providing a

more direct moisture diffusion path toward the cold dry exterior instead of toward the relatively warm moist interior. For the Provo, Utah, location, the winter data did not show significant differences in gap moisture levels between the drilled and undrilled cases; however, the conditions were very dry overall and no condensation was observed. Therefore, the value of this mitigation technique may not have been fully demonstrable under these conditions. Intentional exterior venting would probably be more important for a higher interior RH condition or a case where the retrofit panel seal was not optimal because of a material flaw or installer error. It is important to note that drilling the hole to “vent” the cavity preferentially toward the exterior introduced no degradation of thermal performance of the window retrofit assemblies. The room side glass surface temperatures remained identical between the drilled and non-drilled cases, indicating they provided identical thermal insulation. While a biased moisture diffusion path toward the exterior is potentially useful in a cold dry climate with a building that has a high internal moisture load, it might actually exacerbate condensation in hot humid summer conditions when the outside moisture traveling through the drilled hole would more readily condense on the framing of the retrofit panel cooled by interior air conditioning.

E. OBSERVED ENERGY SAVINGS

Utility bills and detailed building electrical and gas meter data were provided by GSA for both 2011 and 2012 and used to assess energy consumption changes following the retrofit. Table 5 reports the energy consumption for the five months of the monitoring period following the retrofit, as well as data for corresponding months of the previous year before the retrofit. While there were not supplemental sensors in place from February through June 2011, the utility figures with the monthly heating degree days (HDD) for each year provide a good basis for comparison. Because the retrofit was installed on February 18, 2011, February HDD are only reported for the 18th to the 28th, but the MBTUs are reported for the whole month in a corrected fashion, as though the retrofit were in place the entire month. The heating savings in percent values are adjusted proportionally by the year-to-year HDD ratio to correct for weather differences. Table 8 extrapolates the data in Table 5 to an annual savings projection based on scaling the heating demand by typical HDD values for the whole year. The annual estimate projects 108MBTU of heating savings per year, and 6.4 tons of avoided carbon dioxide emissions.

Table 5. Electrical and Gas Utility Usage before (2011) and after 2012) retrofit, with heating degree days

	2011 Measured Electricity (kWhs)	2012 Measured Electricity (kWhs)	Electrical Savings	2011 Measured Gas (MBTU)	2012 Measured Gas (MBTU)	Heating Savings	2011 Actual Weather HDD 18°C	2012 Actual Weather HDD 18°C
Feb	1,2342	7,740	-37%	51.2	31.7*	-38%	194*	249*
March	1,3333	7,631	-43%	36.6	23.3	-41%	367	393
April	1,2624	7,129	-44%	31.6	12.0	-34%	448	258
May	1,2454	7,356	-41%	19.8	3.1	-38%	243	61
June	1,2187	7,850	-36%	6.1	1.6	-67%	24	19

*** Feb. 2012 is corrected for leap year and a mid-month retrofit installation (HDD reported are for Feb 18 - 28)**

The weather-corrected heating savings ranged between 34 and 41% for the winter months with the most heating. This result exceeds the average commercial building expectation for highly insulating windows presented in the background section of this work. This is likely a result of the low starting window performance and the relatively cold winter climate. It is also possible that the thermostat set point adjustment (adjusted following the retrofit) contributed to further savings that were not directly related to avoided window heat transfer, but were enabled by the improved thermal comfort provided by the window retrofit. Building operators lowered the heating set point 3-5 degrees in late February after observing the building behavior with the retrofit panels installed and concluding it was possible to have equal comfort with a lower set point. Likewise, the cooling set point was raised 2-4 degrees in late May or early June.

The substantial 30-40% drop in electrical savings (from Table 5) from 2011 to 2012 is primarily associated with an LED lighting retrofit that was installed in October 2011, as a separate energy efficiency measure from this research project. This lighting retrofit took place between the pre-retrofit summer conditions and the post-retrofit summer conditions, making it difficult to resolve any electrical savings associated with reduced cooling load from the utility data. The seasonally consistent electrical savings suggest it is predominantly associated with the lighting change. The building already had somewhat low sensitivity to solar gain as a result of the deep window overhangs providing good shading, as well as the relatively low window-to-wall ratio. The large LED lighting savings likely obscures a potentially smaller change in air conditioning energy usage. The annual energy modeling results can be examined to understand the expected trends in cooling energy savings.

Despite the large observed heating energy savings, it is possible that a portion of the window savings is obscured by the change in the electrical lighting load. Lighting energy generally ends up as heat within the conditioned space, adding to the air conditioning load during hot weather, and removing load from the heating system during cold weather. If the roughly 40% electrical savings, or about 5,000 kWh/mo, ultimately provided heat to the space preceding the lighting retrofit heating, that is a significant portion of heating energy that will have to be made up by another source and that will make it appear that the

windows have saved less energy than they actually have. Whether the reduced load was due to lighting or included other plug loads, it is equivalent to 17MBTU of heating energy, or roughly half the measured heating consumption in the winter. If this effect is even partially active, the energy savings associated with the window retrofit could be substantially larger than reported.

F. ANNUAL ENERGY SIMULATION SAVINGS

Two annual energy simulation techniques were utilized to support this work, both based on the EnergyPlus simulation engine. The EFEN software front end to EnergyPlus simulated the whole building, while the COMFEN software front end is designed to typically simulate a single zone portion of a large commercial façade. In this case, COMFEN was used to create an effective “whole building” model, by piecing together multiple models of the four different façade orientations as well as a core zone without windows. Annual energy models in general, and particularly COMFEN, are also useful tools to explore the relative energy savings implications for different retrofit Hi-R window panel performance levels.

A summary of monthly heating energy is presented in Table 6. The Table includes data based on the measured heating savings that has been scaled by a TMY-3 weather file heating degree days (HDD) to extrapolate to the full year, in comparison to both COMFEN and EFEN annual energy results. All data is for the post-retrofit condition, with a difference column that can be used to get back to the original configuration consumption. The EFEN absolute values are not exact, but reasonably close, while the EFEN percent difference shows more deviation than the COMFEN results. Without detailed work to calibrate the model, it is difficult to simulate all the aspects of a particular building to the point that the results closely match the utility bill. For instance, the COMFEN results have a large absolute offset, which is not surprising since it is not really a complete multi-zone model of a building and this was an experimental attempt to build a full model from pieces using COMFEN. However, COMFEN agrees well on the relative percent change, even though the absolute value of the before and after difference is an order of magnitude different than the measured value. On the other hand, the absolute value of the before and after difference for both COMFEN and EFEN are nearly the same. The apparent inconsistencies should not discourage the use of such tools. For the complexity of the problem and the relatively modest modeling detail, these results are informative and meaningful. Furthermore, it is not typical to compare multiple models to measured values; one of the most valuable applications is exploring relative changes within one software package for a particular application, where the self consistency of the simulation code gives informative trend indications and incremental changes.

User-friendly annual energy computer-simulation tools with an emphasis on a particular building component, like COMFEN, are well suited to exploring the relative impacts of different glazing choices in the façade of a building. While it is difficult to set all of the assumptions accurately enough to achieve an exact match between model building energy and measured building energy, this type of modeling more readily provides relative comparisons, such as the savings associated with double versus triple glazing, or the incorporation of a shading system. Therefore, to broaden the discussion of retrofit panels beyond the particular product explored in this study, a brief comparison using COMFEN simulation results is presented to explore the annual energy implications of moving from the original single-glazed pane to double-, triple- and quadruple-glazed assemblies (see Table 7). The results in Figures 13 and 14 clearly show that the largest energy savings gains are achieved with the initial change from a single- to a low-e double-layer assembly. It is also possible to assemble a three-layer system with two low-e layers, based on a two-layer sealed retrofit

panel, that has nearly the same U-factor and annual energy consumption as the single low-e, three-layer retrofit, creating a quadruple-layer assembly. It is likely that a two-layer retrofit with two low-e layers (to make a triple assembly) is significantly less costly to produce than the three-layer, suspended film retrofit panel and will have a notably shorter payback period.

Table 6. Measured annual heating data scaled by TMY-3 HDD versus two annual energy simulations

	TMY-3 Provo HDD	Measured heating of retrofit with TMY-3adj., MBTU	Measured heating with TMY-3 adj., Difference, MBTU	savings %	COMFEN model of retrofit, MBTU	COMFEN retrofit heating difference, MBTU	savings %	EFEN model of retrofit, MBTU	EFEN retrofit heating difference, MBTU	savings %
Jan	594	35.6	17.8	33%	8.2	3.1	27%	33	2	6%
Feb	493	29.6	14.8	33%	6.9	2.8	29%	22	2	8%
Mar	386	23.2	15.4	40%	3.1	1.7	35%	15	1	6%
April	269	13.5	5.4	29%	0.8	0.4	33%	9	1	10%
May	131	6.6	3.9	-	0.0	0.0	-	4	0	-
June	42	3.4	7.1	-	0.0	0.0	-	2	0	-
July	3	0.2	0.5	-	0.0	0.0	-	1	0	-
Aug	2	0.1	0.1	-	0.0	0.0	-	1	0	-
Sept	69	3.5	1.4	-	0.0	0.0	-	3	0	-
Oct	251	15.1	10.0	40%	1.3	0.7	35%	9	1	10%
Nov	458	27.5	13.7	33%	4.8	2.4	33%	19	2	10%
Dec	609	36.5	18.3	33%	9.8	3.8	28%	30	2	6%
Total	3307	194.6	108.5	36%	35.0	14.9	30%	148	11	7%

**Table 7. Alternative Hi-R panel retrofit performance levels.
U factor, Solar Heat Gain Coefficient (SHGC), and Visible Transmission (VT)**

	Glazing System Name	Description	U-factor (BTU/h-ft-F)	SHGC	VT
1	Bronze Base Case	Original single pane window with bronze applied film	0.98	0.62	0.53
2	Bronze + 1 (low-e)	Single layer retrofit, exposed (durable) low-e=0.15 coating toward gap (effective double assembly)	0.35	0.46	0.47
3	Bronze + 2 (two low-e)	Two layer IG retrofit, exposed (durable) low-e=0.15 coating toward unsealed gap, low-e=0.04 toward IG gap (effective triple assembly)	0.15	0.31	0.37
4	Bronze + 3 (one low-e)	Three layer suspended film triple IG retrofit, one low-e=0.04 toward one inner IG gap (Hi-R panel retrofit as installed, effective quadruple)	0.14	0.27	0.34

Figure 13. COMFEN example screen showing comparison results for four window configurations

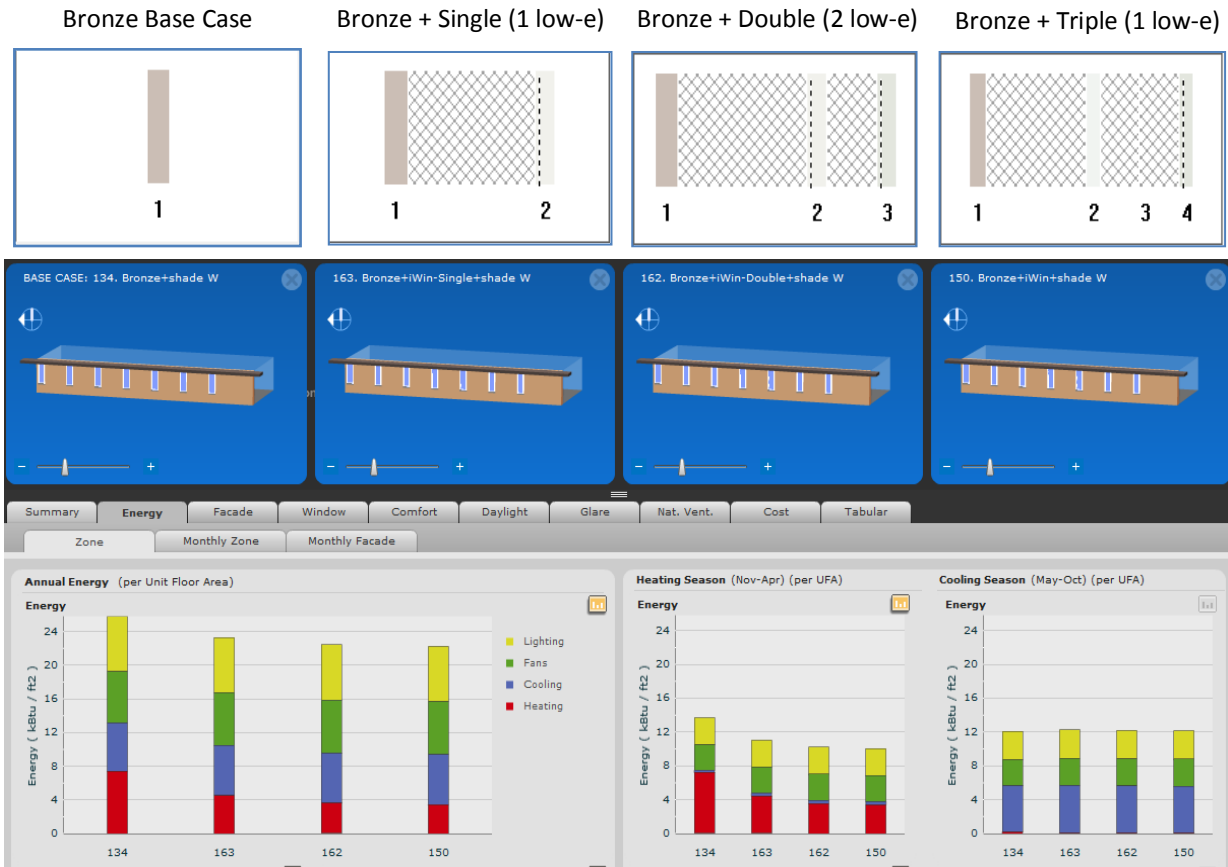
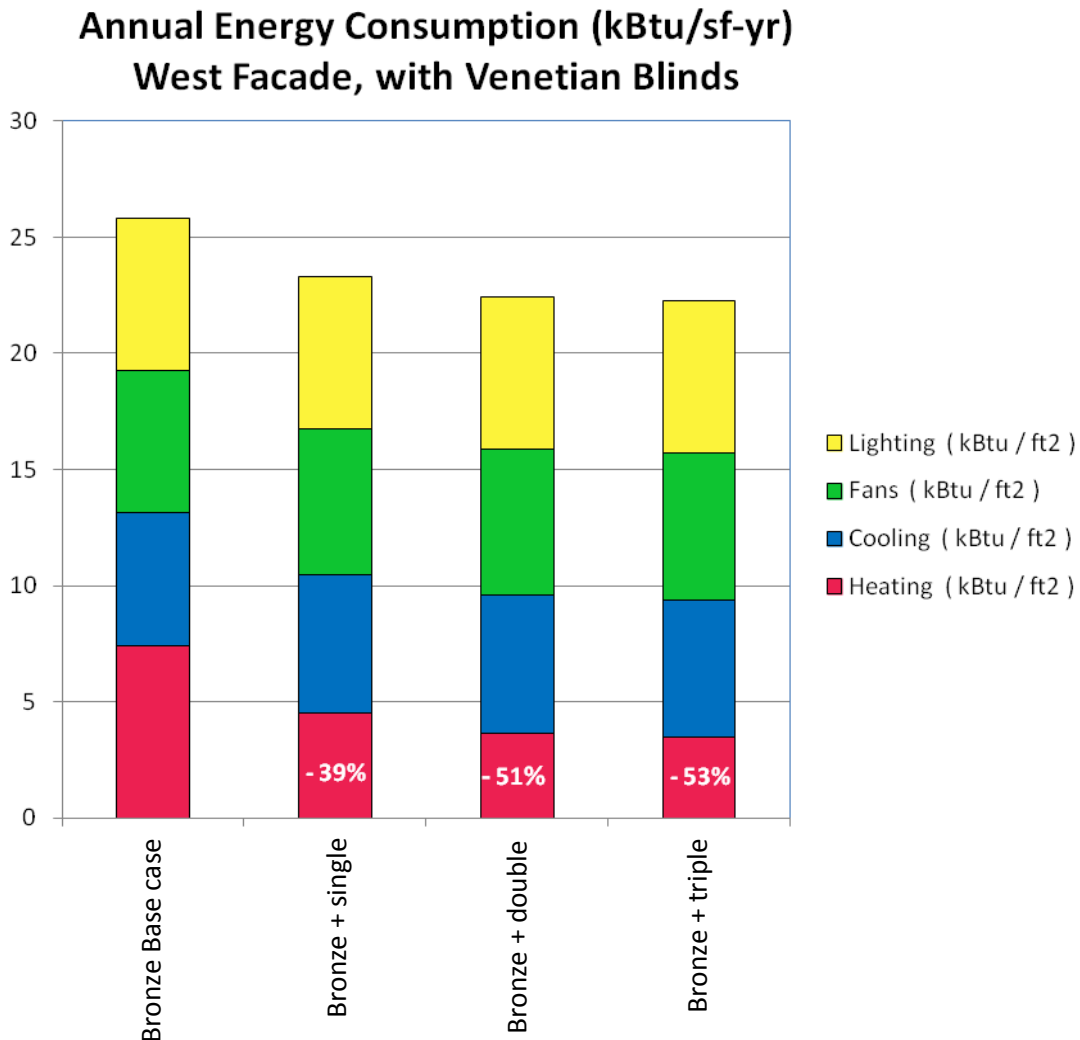


Figure 14. COMFEN annual energy model results comparing three retrofit configurations of different insulating value to the base configuration



G. PAYBACK OPTIMIZATION

The potential cost payback for Hi-R panel retrofit products will vary substantially depending on the particular building, climate and other factors. The specific cost and payback information for the Provo, Utah, test case is presented below. When evaluating these payback numbers it should be recognized that the building in Provo had a high wall to window area ratio (10:1), while a more typical ratio across the GSA building portfolio might be about 5:1. The payback for buildings with lower wall to window ratios are expected to be faster than demonstrated with the 10:1 ratio, because the incremental cost for materials and installation associated with the larger window area will be lower than the initial cost of lower area installations, and the retrofit associated energy savings will be a stronger factor of total building energy demand.

The manufacturer provided the Hi-R window panel material for the retrofit as a gift to the research project, with the value of the materials reported to be approximately \$19.80/sqft. Installation cost for this location was \$12.60/sqft, using a local contractor. The total material and installation cost for this installation of 21 panels with approximately 231 square feet of glass area was approximately \$7,500.

Measured savings data was not available for the entire year. As a result, the data from Table 5 was used to calculate MBTU/HDD values for each month and the trend was symmetrically assigned and extrapolated to months with assumed similar weather. These values are multiplied by the HDD values from a TMY3 weather data file for Provo, Utah, resulting in typical before- and after-retrofit energy use and cost for the whole year. Monetary savings for July and August were assumed to be zero for no heating; although there is variability in the warmer months for gas consumption, and generally much lower values, the majority of the gas is due to hot water and not related to window energy flows. The price of natural gas was estimated to be \$8/MBTU, based on the range of prices observed in the bills from the study period (\$7.2 – 8.8/MBTU). Natural gas prices can be volatile and this factor should be considered when evaluating the payback. For example, natural gas prices have recently declined due to increased production in the United States; however, it is likely that prices will fluctuate higher again in the future as the demand and production changes. Using the assumptions above, the annual savings totaled roughly \$860. Thus, the simple payback on the \$7,500 installation investment would be less than 9 years under these circumstances. Note, this is a conservative estimate because it does not attempt to account for the heating savings associated with the window retrofit that was ultimately not apparent, in this case, as a result of the reduction of internal gains following an LED lighting retrofit (resulting in lower heat dissipation from lighting). Additionally, this estimate does not include cost savings based on greater efficiencies in use of the space near the windows.

Table 8. Annual savings projected from measured data using HDD based scaling (\$8/MBTU)

	HDD 18°C TMY3-Provo	Pre-retrofit MBTU/HDD	Post-retrofit MBTU/HDD	Pre-retrofit MBTU	Post-retrofit MBTU	Savings %	Savings \$
Jan	594	0.09	0.06	53.5	35.6	33%	\$143
Feb	493	0.09	0.06	44.4	29.6	33%	\$118
Mar	386	0.10	0.06	38.6	23.2	40%	\$124
Apr	269	0.07	0.05	18.8	13.5	29%	\$43
May	131	0.08	0.05	10.5	6.6	38%	\$31
Jun	42	0.25	0.08	10.5	3.4	68%	\$57
July	3	0.25	0.08	0.8	0.2	68%	
Aug	2	0.08	0.05	0.2	0.1	38%	
Sept	69	0.07	0.05	4.8	3.5	29%	\$11
Oct	251	0.10	0.06	25.1	15.1	40%	\$80
Nov	458	0.09	0.06	41.2	27.5	33%	\$110
Dec	609	0.09	0.06	54.8	36.5	33%	\$146
Total annual savings				303-195 = 108		36%	\$863

As mentioned in the previous section regarding comparative annual energy modeling of different window configurations, it is likely that one- or two-layer retrofit panels can provide most, or all, of the annual energy savings at a lower initial cost. Multiple window performance and cost points should be analyzed to determine the optimum payback to suit the application. As shown in figure 14, there is a diminishing return in energy savings with higher and higher performance window retrofits. In many cases, the significant fraction of the energy savings will be achieved with one or two additional layers over the base window and these retrofit configurations are significantly less costly to manufacture than three-layer panel systems. The paybacks are expected to be significantly more favorable for one- and two-layer window panel retrofits compared to the three layer Hi-R panel used in this study. It is also worth noting that the center-of-glass performance level of the three-layer product was nearly matched by the two-layer case that was modeled, because only one low-e was used in the three-layer case and two were used in the two-layer case.

H. OCCUPANT RESPONSE SURVEY

A web-based survey was distributed to the occupants of the office, at a single time, after they had experienced the pre-retrofit and post-retrofit conditions in both winter and summer. The survey was distributed to 12 regular staff of this small office. The response rate was high, with ten surveys returned and very few skipped questions. The summary data shown in Table 9 represents 9-10 responses for each question. The survey confirms the expectation that most occupants have windows within 15 feet of their workspace. Occupant reports of thermal comfort were significantly improved following the retrofit; there were no reports of being “frequently too cold” following the retrofit, while 40% reported being frequently too cold before the retrofit. However, a substantial response of feeling “occasionally too cold” persisted following the retrofit. This could be related to the modestly insulated wall temperature with considerable thermal mass, lagging the room air temperature, as well as drafts from the front door that is operated without the buffer from the interior set of vestibule doors, which are left open. In addition, an adjustment was made to lower the heating set point after the retrofit. It is possible that some of the discomfort reported was associated with this adjustment, as the building operators tried to find the new optimal set point for energy efficiency and comfort. Normal variation in metabolism, circulation, and activity across individuals may also lead to some amount of disagreement on thermal comfort. This variability is supported by the relatively small decrease in the use of personal spaces heaters before and after the retrofit (from 3 out of 10 to 2 out of 9). Glare was reported by 40% of the occupants before the retrofit, while no one experienced glare discomfort after the retrofit. While most respondents did not have a strong feeling about recommending the retrofit, there were no negative responses, including no negative comments about aesthetics.

Table 9. Occupant survey questions and answers

Question		Response	Percentage
1. How close to a window do you sit to perform the majority of your work?		Less than 15 feet	60%
		15-30 feet	30%
		Greater than 30 feet	10%
2. How often were you thermally uncomfortable in your work space before and after the window retrofit in Feb. 2012? (you may select more than one answer in each row)	Before retrofit	Frequently too cold	40%
		Occasionally too cold	30%
		Never too cold	30%
		Never too hot	10%
		Occasionally too hot	10%
		Frequently too hot	0%
	After retrofit	Frequently too cold	0%
		Occasionally too cold	56%
		Never too cold	33%
		Never too hot	33%
		Occasionally too hot	0%
		Frequently too hot	0%
3. Have you used a portable electric space heater in your work space to increase comfort before and after the window retrofit (Feb. 2012)?	Before retrofit	Yes	30%
		No	70%
	After retrofit	Yes	22%
		No	78%
4. How often did windows cause visual discomfort (glare) before and after the window retrofit (Feb. 2012)?	Before retrofit	Frequently too bright	10%
		Occasionally too bright	30%
		Never too bright	60%
	After retrofit	Frequently too bright	0%
		Occasionally too bright	0%

Question	Response	Percentage
	Never too bright	100%
5. What is your preferred position for the window blinds in your work space? (you may select more than one answer)	Up, clear window view	30%
	Down, slats tilted horizontal (open)	10%
	Down, slats tilted (partially open)	20%
	Down, slats vertical (closed)	0%
	No preference	10%
	Don't have a window or window blinds in my workspace	40%
6. How often do you adjust the position of the window blinds in your work space?	Frequently adjust blinds	0%
	Occasionally adjust blinds	30%
	Never adjust blinds	30%
	Don't have window or window blinds in my workspace	40%
7. What factors motivate your adjustment of the window blinds in your work space?	Adjusting light level (glare control)	20%
	Thermal management	10%
	Privacy	30%
	Don't have a window or window blinds in my workspace	40%
8. Based on your experience with the window retrofit in your building, would you recommend similar retrofits elsewhere?	Strongly recommend	0%
	Recommend	20%
	No opinion	80%
	Don't recommend	0%
9. How would you characterize the visual appearance of the window retrofit?	No noticeable difference in appearance	30%

Question	Response	Percentage
	Noticeable, but acceptable difference in appearance	70%
	Negative impact on appearance	0%

I. ASSOCIATED OBSERVATIONS

In the process of monitoring window performance over several months, non-window related observations were also made to assess general energy efficiency measures in the building. Weekend and holiday temperature setbacks occurred reliably, as expected, and most lights were routinely cycled off outside of business hours, including irregular holiday schedules. The supplementary baseboard heaters were observed to start heating in anticipation of occupancy at about 4-5 am. While they were likely necessary to increase comfort and stabilize the perimeter temperature when the windows were single layers of glass, it is likely that these heaters are not as necessary after the window panel retrofit. However, there was no apparent operational change to the baseboard heaters following the retrofit, despite dramatically improved window insulation levels. After the retrofit, the baseboard heaters were observed to cycle on during some of the cooler days of late April and May, but it may have been more energy efficient, and just as comfortable, to provide the necessary heat without the supplemental baseboards during these periods. With higher glass temperatures at the perimeter and a lower total heating load under cold conditions, the forced air heating system is likely sufficient to meet demand comfortably without incurring the additional cycle losses associated with running a supplementary perimeter system. To take advantage of further potential heating energy savings associated with the window retrofit, limiting the baseboard system to use in only the coldest winter months (when wall and glass window temperatures may still benefit from some perimeter heat) is recommended. In addition, the rear vestibule heater was observed to be running very warm (perhaps not thermostatically controlled), and the front double-door vestibule was not being operated correctly as a vestibule. Instead, the interior doors were kept fully open, subjecting the building to greater air infiltration during door operation.

V. Conclusions and Recommendations

Based on the physical measurements of this case study and the results of window component thermal modeling, as well as whole building annual energy modeling, further deployment of retrofit highly insulating (Hi-R) window panels is recommended. There is great potential to reduce heating and cooling loads significantly among the commercial buildings with poor performance windows at a modest cost and favorable payback.

On average, it is expected that Hi-R window retrofit panels can save about 11% of the entire building heating and cooling energy demands, but, as shown in this case study, individual buildings may see 30-40% heating energy savings in winter months, possibly more, in some cases.

The Provo, Utah, office building that was studied received three layer retrofit Hi-R window panels over existing single pane glass. All 21 windows in the 6,347 sq. ft. building were retrofitted, a total of 231 sq. ft. of glass with a 1:10 window-to-wall area ratio. The total building heating load reduction was 34-41% during the winter months. Annual heating energy savings was 108 MBTU, with an associated 6.4 ton CO₂ emission reduction.

In addition to the significant energy savings, the Hi-R window panels also raised the room side surface temperatures of the windows in the winter by more than 10C° when the exterior was below freezing. This higher indoor surface temperature greatly increases thermal comfort, by reducing cold drafts and diminishing radiant heat exchange between the windows and the building occupants. The heating set point was turned down a few degrees following the retrofit (while maintaining similar comfort) and the cooling set point was set higher. The increased comfort factor provided by the widow retrofit enabled more energy savings by allowing these changes to the thermostat set points.

Using the annual heating savings reported above, and the natural gas prices paid during the period of the study, the simple payback on the \$7,500 installation investment for this project is less than 9 years. Note, this is a conservative estimate because it does not attempt to account for the heating savings associated with the window retrofit that was ultimately not apparent, in this case, because of the reduction of internal gains following an LED lighting retrofit (resulting in lower heat dissipation from lighting). Also, there are lower cost window retrofit panels that have nearly the same thermal performance and energy savings, so the potential payback of a similar measure could be faster.

Unlike many other energy efficient strategies/appliances, selecting optimal window properties is highly dependent on the context of the particular application, including climate, building type, orientation of windows, and shading,; these variables make the use of selecting window properties based on whole building annual energy simulation tools or context-specific guides very important.

The established window components thermal modeling methods (NFRC100), using software tools like WINDOW and THERM, are a good way to evaluate the performance of retrofit panel assemblies. Thermally and optically, the retrofit assembly is equivalent to factory sealed glazing units of similar construction, and the performance can be reliably modeled to determine the U-factor, solar heat gain coefficient (SHGC), and visible transmission (VT) for various retrofit products in combination with a particular base window.

The contact surface temperature measurements conducted as part of this study confirm agreement with the modeling tools, adding to the confidence that retrofit products can, for most purposes, be successfully modeled in the same manner as standard replacement windows. These component properties can then be used in a whole building annual energy simulation for the particular building application and climate to rapidly understand the energy impacts of various levels of window performance options.

While the center-of-glass performance of the three-layer Hi-R panel retrofit used in this study in combination with the original single layer of glass had an impressive combined U-factor of 0.14 BTU/hr-ft²-F (R-7.1), the whole window performance of the assembly (including frame effects) was 0.27 BTU/hr-ft²-F (R-3.7). This demonstrates that very good glazing performance can still be significantly diminished by a more modest frame performance. In this case, a four-layer glazing system with a highly conductive framing system has a similar whole window performance to that of a modern two-layer low-e window in a highly insulating frame. The result is still a window with less than 1/3 the heat flow of the original single-pane glass window that had a U-factor of 0.98 BTU/hr-ft²-F (R-1); however, this choice may not have been the most cost-effective route to get this level of performance.

Using the comparative annual energy modeling tool, COMFEN, to study the performance of different window configurations, it is clear, at least for this particular building and climate, that a one- or two-layer retrofit panel would have provided most, or all, of the annual energy savings of the three-layer panel. It is advised to explore multiple window performance and cost points to determine the optimum payback to suit the particular application under consideration. There can be a diminishing return in energy savings with higher and higher performance window retrofits. In many cases, the significant fraction of the energy savings will be achieved with one or two additional layers over the base window and these retrofit configurations are significantly less costly to manufacture than three-layer panel systems. The paybacks are expected to be significantly more favorable for one- and two-layer window panel retrofits compared to the three-layer Hi-R panel used in this study. It is also worth noting that the center-of-glass performance level of the three-layer product was nearly matched by the two-layer case that was modeled, because only one low-e was used in the three-layer case and two were used in the two-layer case.

Very low (*i.e.*, below freezing) surface temperatures were observed on both the original glass and frame, but no indications of condensation or frost in the gap between the original single pane and retrofit product were observed through the winter months. The reason for this might have been very low indoor air relative humidity (RH). Caution should be exercised when applying this technology in buildings with higher indoor RH. Venting the cavity between the original glazing and retrofit to the outdoor by drilling a small hole at the bottom of outdoor frame surface was tested side-by-side with undrilled windows on two façade orientations. There was no thermal performance degradation associated with this measure; however, there was also no significant moisture/temperature difference (condensation potential) between these two cases, although the conditions were very dry overall, such that it might not have been appropriate conditions to test for the efficacy of biasing the gap venting toward the exterior. This intentional gap venting bias is likely more important for cases with a higher room RH condition or a less effective gasket between the Hi-R panel and the original window frame. It should also be noted that very low indoor RH (15-25% observed for most of the winter) is not an advised RH level for occupant comfort and health. It is also necessary to have a higher thermostat set point to maintain the same level of comfort when humidity levels are very low. ANSI/ASHRAE standard 62-2001 recommends maintaining room RH levels between 30% and 60%. With the

window retrofits already in place, it might be useful to add humidification in the Provo field office building to help evaluate the sensitivity of interior insulating window panel retrofit products under a broader range of climate/building applications, including higher room RH.

The improvement in retrofit frame temperature was possible in this case because there was a lower conductivity (*e.g.*, wood) junction between the two aluminum frames of the original and retrofit glass. Mounting a highly conductive retrofit frame directly to another would result in little to no frame performance improvement over the original condition. There are many existing window framing configurations and one retrofit panel design and frame approach is not likely to suit all cases. Depending on the glass/frame area ratios, it can be very important to consider the thermal performance of the post-retrofit framing assembly, as well as the retrofit center of glass performance.

Baseboard heaters were found to continue cycling on in late April and May, although not on warmer days. This supplemental heat may not be necessary following the retrofit, but, at a minimum, the baseboard heat could be shutdown during late spring, summer, and early autumn.

A post-retrofit user survey was distributed to building occupants to assess their thermal comfort and other perceptions regarding the retrofit Hi-R window panels. The responses were positive, with significant reductions in thermal discomfort and approval of the short and minimally disruptive installation time. Hi-R window panels represent a major thermal improvement to the building envelope, especially for buildings with single-pane glass in highly conductive metal frames. The low level of occupant disruption necessary to install Hi-R window retrofits is particularly attractive. There are not many building envelope insulation retrofits that can be completed with the same modest level of occupant impact as highly insulating window retrofit panels.

Hi-R window panel retrofits are recommended as a significant energy saving measure with acceptably short return on investment. However, due to the variability of initial window conditions, climate and other factors, some individual site evaluation needs to be given to each project for best results. One Hi-R window retrofit product and performance point is not expected to suit a broad cross-section of buildings and locations.

VI. Appendices

A. TECHNOLOGY SPECIFICATION

SERIOUS ENERGY

iWindow™



Revolutionary Glass Upgrade System for Low-Cost Energy Efficiency and Noise Control Improvements

Without replacing the existing glass or altering the exterior appearance of the building, iWindow enables rapid glazing retrofits of commercial buildings - at a small fraction of the cost compared to full window replacements. iWindow delivers unmatched thermal and acoustic performance that can dramatically improve occupant comfort.

iWindow Benefits

- iWindow panel can be **installed in 20 minutes** or less
- Internally-mounted upgrade system causes **no disruption** to occupants or tenants
- **No change** to the existing outer glass or curtain wall, preserving the exterior appearance of a building
- **Lower cost** to install compared to typical aluminum replacement systems
- **Increases Center-of-Glass thermal performance** of ¼" clear single glazing from R-value 1.0 up to R-value 7.1 (U-factor 1.0 to 0.14)
- **Significantly reduces noise** transmission up to 20db
- Improves inside glass surface temperatures, making it **more comfortable** to work and sit near windows and enabling temperature setpoint changes that can reduce HVAC costs
- SeriousGlass low and high solar heat gain glass packages available, enabling **custom-tuned solar control** according to a building's unique location and orientation
- **96 to 99.6% UV blockage** reduces fading and damage to interior furnishings

iWindow Applications

- Designed specifically for curtain wall, storefront and window wall commercial applications
- Ideal for historic and landmark projects as it allows preservation of a building's existing exterior appearance



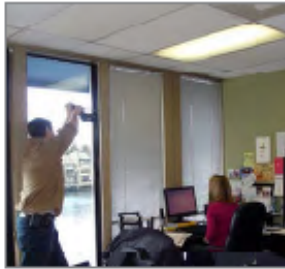
iWindow powered by SeriousGlass Low Solar Heat Gain (LSHG) reduces unwanted, uncomfortable solar heat on the south and west facades of an office building. iWindow units perfectly match interior aesthetics and do not alter exterior building appearance.

SERIOUS ENERGY

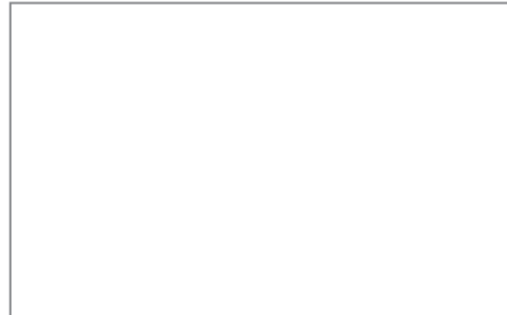
iWindow™



Installed in a typical single pane aluminum system, iWindow maintains interior and exterior appearances.



An iWindow can be installed in 20 minutes or less, with zero disruption or downtime for building occupants.



Technical Specifications

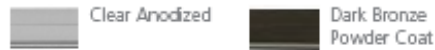
iWindow Features

- Low-emissivity glass coatings optimize solar gain control by climate and building orientation
- Easily secures to vertical supports of existing storefront, curtain wall or window wall to transfer the glass load to the vertical mullions
- Snap-on cover conceals fastener heads to preserve clean, unobtrusive frame sight lines

Minimum/Maximum Dimensions

	Width	Height
Minimum iWindow Size	12"	14"
Maximum iWindow Size	84"	84"
Max sqft = 36	-	-

Standard Colors

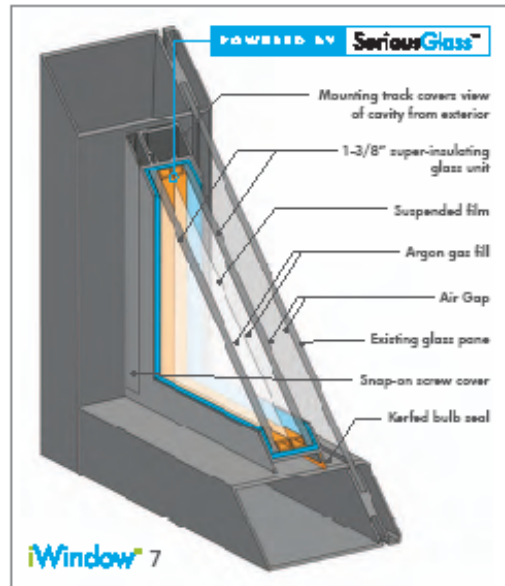


Custom colors are available upon request.

iWindow Performance Data

	iWindow 5		iWindow 7	
	High Solar Heat Gain (HSHG)	Low Solar Heat Gain (LSHG)	High Solar Heat Gain (HSHG)	Low Solar Heat Gain (LSHG)
Center of Glass (COG) Data: Includes 1/2" Clear Single Pane Existing Glass System				
R-value	5.6	5.9	6.3	7.1
U-factor	.18	.17	.16	.14
Solar Heat Gain Coefficient (SHGC)	.43	.36	.48	.34
Visible Light Transmittance (VT)	.64	.57	.64	.56
STC @ 1/2" Air Gap	38	38	39	39
STC @ 1" Air Gap	42	42	41	41
STC @ 2" Air Gap	45	45	44	44
Sash Thickness	1.5"	1.5"	1.8"	1.8"

R-value measures the insulative effectiveness of the window. The higher the R-value, the better the insulating performance. Solar Heat Gain Coefficient (SHGC) measures how well a window blocks heat from sunlight. The lower a window's SHGC, the less solar heat it transmits into the interior. Sound Transmission Class (STC) is a performance rating of airborne noise reduction in windows and walls. COG performance data calculated via Lawrence Berkeley National Laboratory's WINDOW v. 6.3 glass performance simulation software.



Call 877-797-1206 for a consultation.

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United States Energy Information Administration (2012), [Annual Energy Review 2011](http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf).
<http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf> Office of Energy Statistics, U.S. Department of Energy, Washington DC

WINDOW: Whole window performance rating software, Lawrence Berkeley National Laboratory
<http://windows.lbl.gov/software/window/window.html>

THERM: Two dimensional finite element heat transfer simulation software for modeling window frame performance, Lawrence Berkeley National Laboratory, <http://windows.lbl.gov/software/therm/therm.html>

COMFEN: User friendly software interface to EnergyPlus, an annual energy calculation engine, allowing comparative analysis of the energy impacts of particular windows choices for a particular building/orientation by means of a single zone, near window model, Lawrence Berkeley National Laboratory, <http://windows.lbl.gov/software/comfen/comfen.html>

C. GLOSSARY

Term	Definition
Low-emittance (Low-E) coating	Microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window or skylight glazing surface primarily to reduce the U-factor by suppressing radiative heat flow. A low-e coating can be highly transparent in the solar spectrum (visible light and short-wave infrared radiation) and reflective of long-wave infrared radiation. Low-e coatings are also often combined with solar heat gain control features that maintain high visible transmission, while reflecting most of the short-wave infrared in the solar spectrum.
U-factor (U-value)	A measure of the rate of non-solar heat loss or gain through a material or assembly. It is expressed in units of BTU/hr-ft ² -°F (US) or W/m ² -°K (metric). Values are normally given for NFRC/ASHRAE winter conditions of 0° F (-18° C) outdoor temperature, 70° F (21° C) indoor temperature, 15 mph wind, and no solar load. The U-factor may be expressed for the glass alone or the entire window, which includes the effect of the frame and the spacer materials. The lower the U-factor, the greater a window's resistance to heat flow and the better its insulating value.
Solar heat gain coefficient (SHGC)	The fraction of solar radiation admitted through a window or skylight, both directly transmitted, and absorbed and subsequently released inward. The solar heat gain coefficient has replaced the shading coefficient as the standard indicator of a window's shading ability. It is expressed as a number between 0 and 1. The lower a window's solar heat gain coefficient, the less solar heat it transmits, and the greater its shading ability. SHGC can be expressed in terms of the glass alone or can refer to the entire window assembly.
Insulating Glass (IG) Insulating Glass Unit (IGU)	A combination of two or more panes of glass with a hermetically sealed air space between the panes of glass, separated by a spacer. This space may or may not be filled with an inert gas, such as argon.
Heating degree day (HDD)	A measure of the number of degrees and time duration an outdoor ambient temperature condition is below the desired indoor temperature, specified relative to an (indoor) base temperature (often 60 to 65°F or 15.6 to 18.3°C). Higher heating degree day numbers represent a greater demand for heating energy to maintain a building at controlled room temperature.
Quad	One-quadrillion (10 ¹⁵) BTUs, a very large unit of energy commonly used to express national annual energy consumption. US annual energy consumption is roughly 100 quads.