An Analysis of the Thermal Performance of Repaired and Replacement Windows

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Data and analysis of in-situ thermal monitoring reveal that the repair of aging steel windows offers the opportunity to retain historic building fabric and secure a level of energy performance that can match or exceed that of modern aluminum-framed replacement windows.

Fig. 1. Southwest elevation, Lafayette Building, Vermont Avenue and H Street NW, Washington, D.C. The building's neoclassical exterior has regularly placed, double-hung steel windows. All images by authors.

Introduction

As federal buildings that were constructed to support the expanding role of the U.S. government and the war effort during the late 1930s and 1940s reach the end of their useful lives, their caretakers are embarking on rehabilitation and modernization projects to meet modern and often greatly expanded performance standards. The original window systems often lack the construction detailing and other characteristics needed to provide a level of performance acceptable for modern office space, such as humidification and energy performance. Many of these window systems have suffered years of neglect and deferred maintenance and owe their longevity largely to the durability of original materials, the robustness of the original construction, and layers upon layers of paint.

A common and as-yet unresolved issue is the final fate of these windows. More often than not, building-renovation projects call for the replacement of original windows with modern replicas rather than the rehabilitation of the existing windows, often under the guise of improving energy performance or occupant safety (blast resistance), with little thought given to the embodied energy in the existing windows or the whole-life energy commitment of the new product. This consideration becomes even more crucial when considering the demands of achieving LEED ratings in a renovation project.

One structure currently being considered for such renovation is the Lafayette Building, a federal office building located in downtown Washington, D.C. (Fig. 1). Originally housing the Export-Import Bank of the United States and more recently the Department of Veteran Affairs, the Lafayette Building has had a long and storied history of federal use and is being proposed for a significant modernization project. Built in 1940 and designed by the Chicago architectural firm of Holabird and Root, it is a National Historic Landmark.

The building has nearly 1,200 windows along the primary facades and a single interior light court. The windows are constructed of steel shapes and were installed in a double-hung configuration (Fig. 2). The windows are approximately 54 inches wide and 72 inches high and have single glazing without intermediate muntins. Many of the windows exhibit paint flaking and some surface rusting, while others have more significant rusting, particularly at the base of the jambs (Fig. 3). The windows are currently operable and have counterweights in concealed weight pockets. This paper discusses a brief study comparing two options for treating the windows during the planned repair program.

Performance Requirements and Design Options

The Lafayette Building is scheduled to undergo a comprehensive renovation, including upgrades to the mechanical and electrical systems, reprogramming and renovation of interior spaces, and renovations to all exterior facades, including upgrading the windows for blast resistance in accordance with requirements of the General Services Administration (GSA), the building owner. In order to assist the building owner in selecting the most appropriate treatments for the windows, an overall design program for the windows was developed. It identified the performance requirements for the windows, including the following:

- provide blast resistance per GSA requirements.

Fig. 2. View of an unrepaired steel-framed window on the east elevation of the Lafayette Building. Note the loss of paint coatings and corrosion of the built-up steel frame.

- preserve the original window sash and frames where possible, including original materials, configuration, dimensions, sight lines, and profiles, as well as the clarity and reflectivity of the original glazing. Any replacement windows must match existing window configuration, dimensions, sight-lines and profiles, as well as the clarity and reflectivity of the original glazing.
- improve energy performance and reduce air infiltration and water penetration at the windows.
- provide windows that are easily maintainable.
- provide a cost-efficient treatment.

These performance requirements were used to develop design options, evaluate the technical options, and then help select the most appropriate treatment. Based on the existing conditions and the design requirements, the following two options were identified:

Option 1. Repair the existing steel windows and provide a supplemental interior storm window that meets the blast requirements and also improves the thermal performance of the existing window. The window frame would not be removed from the window opening during repair. The sash would be removed, repaired, and reinstalled; all steel would be prepared to SSPC-SP3, the standard specification for power-tool cleaning of steel surfaces by the Society for Protective Coatings (SSPC), and given two coats of acrylic enamel paint. The exterior light of glass, a single pane of clear float glass, would be retained where possible. Blast resistance requires that the original sash be fixed shut. A blast-resistant aluminum-framed storm window would be installed on the interior face of the window, approximately 3 inches from the face of the glass in the lower operable sash. The storm window would include a single laminate sheet of glazing that includes low-E glass with a high solar heat-gain coefficient (SHGC) to provide improved passive solar heat gain.

Option 2. Replace the existing windows with new blast-resistant, thermally broken, aluminum-framed windows with 1-inch insulating glazing. The new windows would closely match the existing configuration, dimensions, profiles, and sight lines of the original windows. Original windows would be removed from the opening; interior finishes would be removed from the perimeter of the window; and modifications made to the perimeter substrate and trim to allow installation of mounting clips to secure the replacement windows to the masonry back-up. Interior finishes would then be repaired to conceal the anchorages. The replacement-window insulated-glass unit would include low-E glass that has a high SHGC glazing, which would minimize passive solar heat gain. The operable sash would be fixed shut to meet blast requirements. More historically accurate steel replacement windows were not considered for this option as they were cost prohibitive compared to restoring the existing windows as described in Option 1 and offered little thermal-performance improvement over the existing windows.

Window Mock-ups

To assist in evaluating the two options, in-situ mock-ups of both options were installed in the building, allowing for a review of aesthetic impacts, constructability, and cost, as well as testing and monitoring of the thermal performance.[1] These mock-ups were constructed using the same materials and treatments proposed for the actual construction in order to provide accurate results for comparison (Figs. 4 through 7). Mock-ups were installed in the east elevation of the building at the eleventh-floor level based upon input from the owner and design team. The location on the east elevation of the eleventh floor, a height roughly equal with the rooftops of surrounding building, allowed a relatively unobstructed solar exposure and conditions that vary between the diffuse solar radiation of north exposures and the intense solar radiation of south and west exposures.

Performance Monitoring

The monitoring study was undertaken in 2006 by Harboe Architects and Simpson Gumpertz & Heger, Inc. (SGH). The purpose of the study was to document and evaluate the performance of a repaired window and a proposed replacement window under similar exposures and to provide direction and feedback to the design team for incorporation into the rehabilitation program. The monitoring system allowed for the recording of surface and air temperatures, as well as relative humidity for multiple locations.

The two mock-up windows were monitored between March and July 2006. Though the duration was limited to just over three months by program and tenant constraints, sufficient data was gathered to compare the performance of the mock-ups over a significant range of exterior conditions. This recorded performance allowed for the extrapolation of performance outside of the range of measured interior and

Fig. 3. View of a steel window sill on the east elevation of the eleventh floor. Note the significant corrosion of the steel frame at the sill-to-jamb corner.

Fig. 4. Sill of the replacement window.

Fig. 5. Sill of the repaired window.

exterior conditions. Though relatively limited in scope and duration, this study provided valuable real-world performance information, which was used to help guide the design team in the evaluation of potential treatment options. Additional analysis using computer simulation and other analytical tools could be used to further develop performance characteristics, such as evaluating other exposures and other glazing options.

Setup and procedure. Surface temperatures, ambient conditions, and the heat gain and loss experienced through each window were measured in order to fully evaluate and compare the thermal performance of the two mock-ups. A sealed chamber was installed on the interior face of each specimen window. The chambers were insulated, and the interior surface of each chamber (facing the window) was covered with a reflective white coating to minimize unwanted solar heat gain within the chamber. An air inlet was installed at the top of the chamber, and an outlet with an electric fan was installed at the bottom to ventilate the chamber with a known quantity of air. The air inlet and outlet temperatures were measured using thermistors and recorded on a data logger. The change in temperature between the inlet and outlet was used to calculate the heat gain or loss through the window, as described below.

Both window mock-ups were instrumented with surface-temperature sensors (thermocouples) at critical frame and glass locations where maximum and minimum surface temperatures are expected to occur, such as at the center of the glass, the horizontal meeting rail, and perimeter frame locations. Relative-humidity and air-temperature sensors were also installed within the air cavity between the storm glazing and the exterior window to evaluate condensation potential within the storm cavity (Figs. 8 and 9). Ambient conditions were recorded on the building's exterior and interior, including the pressure differential between the interior and exterior conditions, using relative-humidity and temperature sensors and a digital pressure gauge. Data points for accessible locations were recorded on a laptop computer, while inaccessible data points (temperature and relative humidity within the storm of the rehabilitation window) were recorded on stand-alone data loggers.

Heat-flow calculations. Following data collection, raw temperature and humidity data were used to calculate the heat loss or gain through each window. Window heat-flow calculations were made by comparing the temperature of the air entering the insulated chamber to the temperature of the air leaving. The humidity ratio was calculated using interior temperature and relative humidity, allowing calculation of the change in enthalpy of the air as it entered and exited the chambers.[2] Formulas for air properties are found in the *ASHRAE Handbook: Fundamentals* 2005.

This analysis method produces representative heat flows for comparison; however, the method has some error because it does not account for the dynamics of constantly changing boundary conditions. Also, the data comparisons produced anomalies when one window heat flow indicates a thermal loss or gain while the other window indicates the opposite. The heat-flow analysis compares only the loss at one window to the simultaneous loss at the other window and the gain at one window to the simultaneous gain at the other window, while ignoring the time periods when the windows indicated opposing flows, which is limited to less than 10 percent of the data where flux approaches equilibrium between gains and losses. Overall, the effect of these two minor simplifications on the overall comparative thermal analysis was considered negligible.

Results

The analytical review of the thermal performance of the two mock-up windows was a complex process with many obvious variables, as well as several that were not so obvious. The main variables considered were heat gains and losses due to conduction through the window frame and solar heat gain (radiation) through the glass, as these were the most significant mechanisms for heat transfer through the window assembly. The mock-up apparatus was designed to determine heat gain and loss, as noted above. However, it was not capable of isolating conductive heat loss or gain from solar heat gain without additional processing of the data. In order to isolate conductive losses from solar gain, the data indicating heat loss was isolated from the data indicating solar gain (i.e., daytime conditions with solar exposure) where possible. As most conductive heat-gain opportunities during the monitoring were during the warmer, sunny hours of the day, conductive heat gain was unable to be isolated from solar heat gain. Therefore,

Fig. 6. Head of the replacement window.

Fig. 7. Head of the repaired window. Note the similar sight lines but missing articulations and accessories of the replacement window when viewed in conjunction with the repaired window.

conductive performance is best measured during nighttime conditions during colder temperatures (i.e., night conditions with no solar exposure and large thermal gradient across the mock-up). Total heat gain and loss through the windows were then calculated (Table 1).

Solar heat gain. As expected for the east-facing windows, solar heat gain is the largest source of heat gain for the window system and spikes for both window mock-ups in the late morning when the windows are most exposed to sunlight. Heat gain tapers off in the afternoon as direct solar exposure decreases due to indirect diffuse solar exposure. There was a significant difference in peak heat gains between the two mock-up windows (Fig. 10).

Calculations show that the daily peak solar heat gain for the repaired window was approximately 35 to 40 percent greater than for the replacement window during the coldest week of monitoring. In addition, the net heat gain also included reductions in heat gain due to conductive heat loss through the window unit, which was greater for the replacement window, as noted below. As expected, when comparing the measured performance during warmer weather, the difference between the peak heat gains of the two windows was smaller (Fig. 11).

Calculations reveal that the peak solar heat gain for the repaired window was only 10 to 25 percent greater than that of the replacement window during the warmest week. A comparison with the solar gains during the coldest week illustrates the improved conductive heat gain and loss performance of the repaired window mock-up with respect to the replacement window mock-up. Heat loss was calculated to be 4.0 kW for the replacement window and 1.5 kW for the repaired window during the warmest week. When daytime solar heating conditions (net heat gain for both windows) were considered, a heat gain of 150.6 kW for the replacement window and 169.3 kW for the repaired window was calculated during the coldest week. The net heat gain/loss for the week (excluding conditions where one window is experiencing heat gain or loss and the other window is experiencing the opposite) for each window was found to be 146.6 kW gain for the replacement window and 167.7 kW gain for the repaired window. The repaired window experienced approximately 15 percent more heat gain during the warm week.

Conductive and radiation heat loss and gain. Conductive heat loss or gain occurs through the frame of the window and was the primary mode of energy loss through the window-frame assembly. Radiation heat loss or gain occurs through the glazing assembly and was the primary mode of energy loss through the window. Conductive and radiation heat losses and gains are driven by temperature differential across the window and are easiest to measure during cold winter months, when the temperature differential across the window is greatest. However, conductive and radiation heat gains can occur during summer months when exterior temperatures are greater than the conditioned interior temperature. Since hot-weather conductive and radiation heat gains occur during the hottest part of the day when solar gain is peaking, it was not possible to separate solar and conductive gains through the window, and the data therefore were not separated in the analysis.

The coldest exterior temperatures were observed during the first week of monitoring. Temperatures were not as cold as typical peak winter conditions.[3] However, they provided adequate opportunity to measure window performance during cold weather. Heat-loss data was isolated from the heat-gain data, and the differences in the daily peak heat loss for each of the windows were compared for this cold week (Fig. 12).

As expected, heat-loss peaks occurred in the very early morning hours, before solar heat gain begins. The repaired window experienced 15 to 35 percent less heat loss through the window than the replacement window during the coldest week. Heat loss was calculated to be 121 kW for the replacement window and was 89.5 kW for the repaired window during the week. Considering daytime solar heating conditions (net heat gain for both windows) only, a heat

Table 1. Heat Gain and Loss Totals for the Two Mock-up Windows over a Testing Period of Approximately 12 Weeks

Specimen	Net Heat Loss (kW)	Net Heat Gain (kW)
Replacement Window	-419.1	994.6
Repaired Window	-296.9	1264.8

gain of 33.1 kW for the replacement window and 62.1 kW for the repaired window was calculated for the coldest week, a significantly smaller heat flux than with conductive losses alone. The net heat gain or loss for the week for each window (excluding conditions where the mock-ups are experiencing opposing heat flows) was found to be 87.9 kW loss for the replacement window and 27.4 kW loss for the repaired window. The repaired window experienced nearly 70 percent less heat loss during the cold week. It is important to understand that as the exterior temperature drops, the heat loss (and difference in heat loss) for the windows will increase and that this difference in performance would be expected to become more pronounced during typical peak wintertime conditions. Thus, the conductive gains during hot weather are inversely proportional to the losses.

Fig. 8. Interior view of the repaired window prior to installation of the interior chamber. Note the thermal and relative-humidity sensors are indicated with dots. Some sensors are installed on the repaired window, and others are installed on the storm sash, resulting in more sensor locations than on the replacement window.

Fig. 9. View of the replacement-window mock-up prior to the installation of the interior chamber. The temperature sensors are indicated with dots.

Discussion

The purpose of this study was to compare differences in thermal performance of the two window mock-up specimens under identical operating conditions. After analyzing the monitoring data, several trends became apparent, and they may impact the selection of the window-treatment option for the repair and replacement program. To better understand the results of the testing and monitoring, it is essential to have a general understanding of window performance. The pertinent performance factors and observations are discussed below.

Solar heat-gain performance. The most significant component of heat gain is solar heat gain through the window glazing. Several factors affect the solar heat-gain performance of windows, including the geometry and configuration of the window unit (such as the amount of clear window opening), its placement and orientation, the type of glazing and coatings used, and the amount of interior and exterior shading. Optimizing these characteristics to improve thermal performance can significantly improve building operating costs and occupant comfort.

Window configuration. The configuration and geometry of a window affects its solar heat-gain performance. For example, a window with a wide frame and numerous small lights separated by mullions and muntins has less glazing area available to capture solar energy. By contrast, a window in the same rough opening with a thin frame and one large light will have a greater proportion of glass-to-frame area and will allow more sunlight into the building interior. Both mock-up windows had similar construction, with large unobstructed glazing areas and narrow metal perimeter frames. Therefore, the difference in performance due to frame configuration and design was small.

Window orientation. Placement and orientation of the window with respect to compass direction is the root factor affecting solar gains. West- and south-facing windows experience the most significant gains, but some gain is possible in all directions from diffuse sky radiation. The majority of the windows at the Lafayette Building are on the east, west, and north elevations, with very few windows facing due south. Both mock-up windows faced east, and therefore the recorded data represents only one of the four possible orientations existing on the building, a limitation of the study scope and budget.

During the winter the low elevation of the sun at midday causes it to shine through south-facing windows, in addition to east-facing windows in the morning and west-facing windows in the afternoon. The resulting solar gains can help reduce heating costs during the winter. In the summer, when the sun is much higher at midday, the angle of incidence of the solar radiation is much sharper. Consequently, more solar radiation reflects off of south-facing windows than is transmitted to the interior. Overheating in summer therefore tends to occur more frequently at unshaded west-facing windows and, to a lesser extent, at east windows than at windows that face directly south. The desired amount of summer and winter solar heat gain is determined by the design of the mechanical system for the building. If the primary load on the building is heating during winter, then optimizing solar heat gain during winter months should dictate window-performance requirements.

Glazing coatings. The number and type of glazing layers and coatings will also affect the thermal performance of the

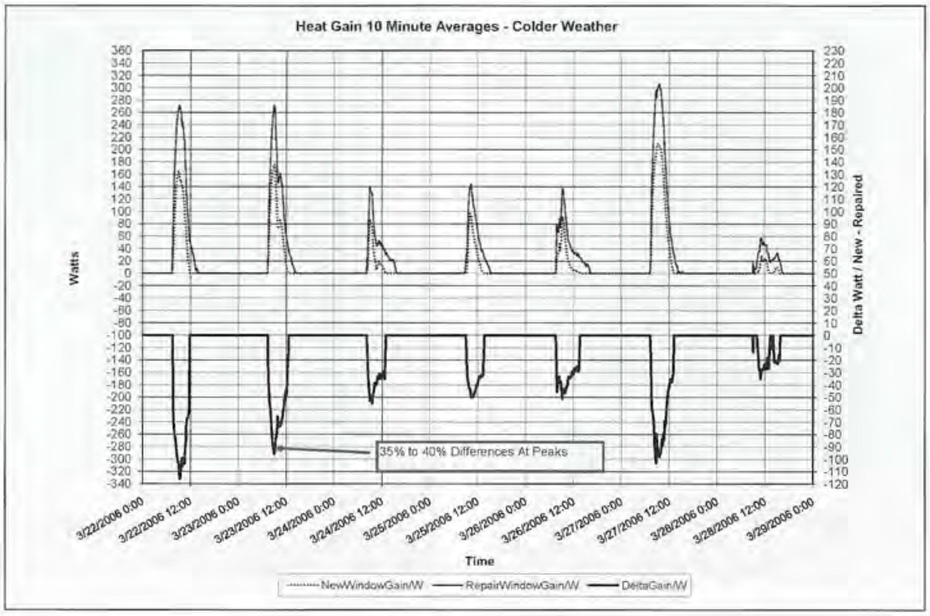

Fig. 10. Heat gain during the coldest week.

windows. For example, a double-glazed, insulated glass unit consisting of ordinary clear glass reduces solar gain by approximately 10 percent compared to a single-glazed window with the same glazing area. Since both mock-up windows included two layers of glazing, the glazing is not a differentiating factor. The addition of glazing coatings have a more significant impact. Low-emittance (low-E) coatings are microscopically thin metal or metallic-oxide layers or a film coating deposited on the surface of the glass (typically on a surface within the glazing cavity) to reduce the U-factor (the heat transfer through the glazing) by suppressing radiation heat flow.

The difference in solar heat gain between the repaired window and the replacement window is likely due to the location and type of glazing coating on the two window mock-ups, in addition to the configuration of the glass. The replacement window had a low-E coating with a relatively low solar heat-gain coefficient (SHGC) in the outer pane of glass. The low-E coating has a SHGC of 0.41, meaning that 41 percent of the solar heat gain is absorbed and transmitted through the glazing, while the rest is reflected back to the exterior. The repaired window has a low-E coating with a higher SHGC on the repaired window storm. This low-E coating has a SHGC of 0.83, meaning that 83 percent of the solar heat gain is absorbed and transmitted through the glazing. This difference in SHGC of the two glazing systems had a substantial effect on the solar heat gain measured in the two mock-ups. Adjusting the heat gains to offset the heating load during the winter or to minimize the cooling load in the summer can be achieved in either window treatment option, in part by the selection of the glazing coating.

If building-load calculations reveal that summer solar heat gain must be minimized, the solar heat-gain performance of the repaired window can be improved with some modification. The least invasive modification involves reducing the low-E coating on the storm window to reduce the solar heat gain. A second option for reducing solar gain through the repaired window would be to add a low-E coating on the inside surface of the exterior glass. The addition of a low-E coating would require replacement of the original glass with a pane of laminated low-E glass (the thermal stress placed upon the original float glass of the existing windows by adding a coating would likely result in glass fracture). Even though there is a diminished benefit to adding low-E coating to the interior storm window rather than to the exterior glass, this procedure does not require replacement of the exterior glass and avoids a change in appearance.

Changes in the position and type of low-E coating on the repaired window may also affect the condensation resistance of the glazing. Although not specifically discussed in this paper, it is important to note here that the most susceptible location for condensation is the interior face of the exterior glass in the repaired window. Adding a low-E coating with a lower SHGC to the interior storm would likely improve condensation resistance of the exterior glass, as would providing a new outer pane of glass with a low-E coating with a mid- to low SHGC.

Other factors. Covering the window openings with draperies and curtains or other shading devices will also reduce the amount of solar heat gain transmitted to the building interior. Keeping the window coverings open to admit as much solar gain as possible on sunny days during the winter will improve performance. This testing did not include interior window treatments, so their impact on thermal performance was not quantified; however, it seems likely that they would impact both mock-ups similarly.

Heat-loss performance. Several processes influence the rates of non-solar heat gain or loss through window components. These processes follow a basic law of thermodynamics: heat energy tends to move from warmer areas to colder areas. In Washington, D.C., the primary flow of heat is from interior spaces to the building exterior during fall, winter, and early spring. The differential temperature tends to be lower during summer months, when heat flow is from the hot exterior to the cooler, conditioned interior. The principal heat-transfer processes in windows are radiation, conduction, and convection. In addition, excessive air leakage can contribute to the overall heat loss.

During colder temperatures, heat is absorbed by the inside pane of a double-glazed window, moves to the cooler outside pane, and is released to the outdoors. Not only does this heat loss take place through the glazing by radiation; it also occurs across the spacer material of the insulating glass unit, which separates the two glazing layers at their edges (at

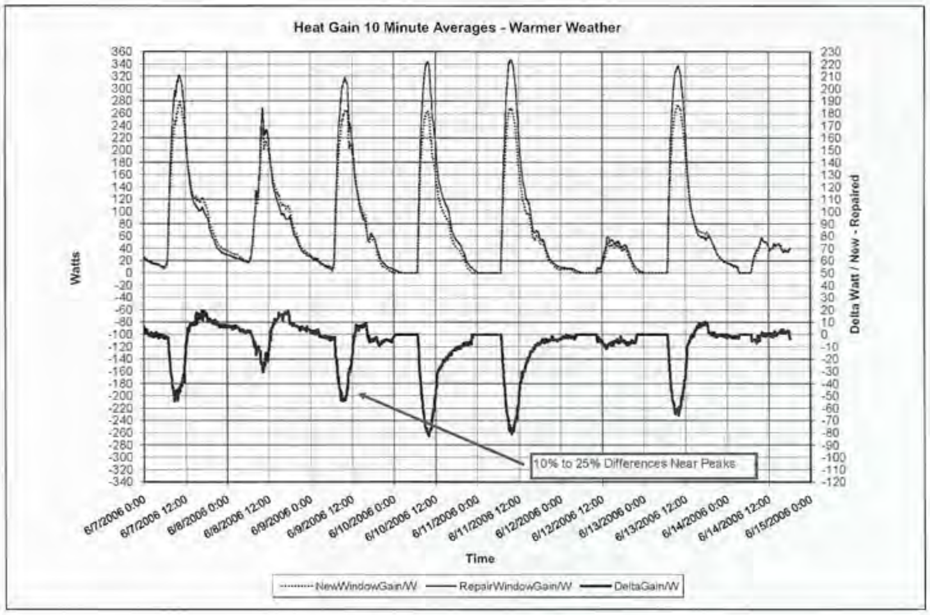

Fig. 11. Heat gain during the warmest week.

the replacement window only); through the frame of the window by conduction; through the movement of air in the space between the two glazing layers by convection (more pronounced in the larger air space of the repaired window); and between the moveable or operable frame components by air leakage. Convective losses are typically negligible with respect to other losses and were not addressed in this study.

Radiative losses and gains. Typically, radiation losses through the window glass represent about two thirds of the total heat loss in a standard window. Because ordinary glass readily emits heat to colder surfaces (i.e., has a high emissivity), radiation losses can be reduced by lowering the emissivity of the glass by installing low-E films. Placement of the low-E coating in the pane of glass experiencing the greatest temperature differential will have the greatest effect on radiation loss through the window. Review of data from this study indicates the greatest temperature differential is across the outer pane of glass in the repaired window during cold weather. Therefore, placement of the low-E coating in the exterior glass will have the greatest impact on radiative loss.

Conductive losses and gains. Conduction losses in windows occur primarily through the edges and frames of the units and are often expressed in terms of U-value, the overall measurement of conductive heat transfer through the window. The thermal-conductance characteristics or resistance to heat transfer, i.e. R-value of the aluminum frame of the replacement window and the steel frame of the repaired window, also has an effect. Steel is less conductive than aluminum and has a higher R-value, thereby reducing the overall U-value of the window. Data from this study indicate that the temperature drop across the frame was different for the two windows. The thermal break installed in the aluminum-framed replacement window helps to reduce the heat loss across the frame; however, the interior storm window of the repaired window better isolated the steel window frame of the repaired window from the building interior (e.g., no metal-to-metal contact at the sash meeting rail), thus reducing heat transfer.

Air leakage. Window air leakage is a significant contributor to energy costs during both heating and cooling seasons for most buildings. Air leakage also affects occupant comfort. Most of the air leakage through operable windows occurs between the window's sash and frame or at the meeting rails of a sliding sash, as on the replacement window. Bigger windows tend to leak less air per unit area than smaller ones. In poorly constructed fixed windows, air leakage also occurs between the insulated glass unit and the frame. Windows with the lowest leakage rates, regardless of type, tend to be fixed windows. Although the repaired window had a fixed sash, it originally was an operable window.

The condition of the perimeter construction also affects the air-infiltration resistance of the replacement window. Air leakage around the replacement window can be a significant problem if the windows are carelessly installed in the rough opening. Air infiltration at and through the perimeter (frame) of the window mock-ups was evident during air-infiltration testing, particularly around the replacement window. Air leakage is likely increased by construction activities to remove the original window and install the new replacement window. Air infiltration around the perimeter of the replacement window can be improved by installing spray foam in the cavity when the original window is removed. Foam will improve thermal performance of the window frame, as well as limit air infiltration. Similar improvements can be made at the repaired window by installing spray-foam insulation in weight pockets and the window perimeter.

Conclusions

This analysis shows significant differences in thermal behavior between the repaired-window and the replacement-window mock-ups. The repaired window experienced more solar heat gain during morning and early afternoon hours than the replacement window. In turn, the replacement window experienced more heat loss through the glass and frame during evening and early morning hours. Because solar heat gain can be manipulated (e.g., through the use of low-E coatings) but heat loss through the frame cannot, the repaired window provides superior heat-loss performance and significantly greater potential for optimizing glazing and heat-gain performance (particularly for the different building exposures) than the replacement window. Solar heat gains for both windows tended to more than offset the heat loss through the frame and glazing, a conclusion that

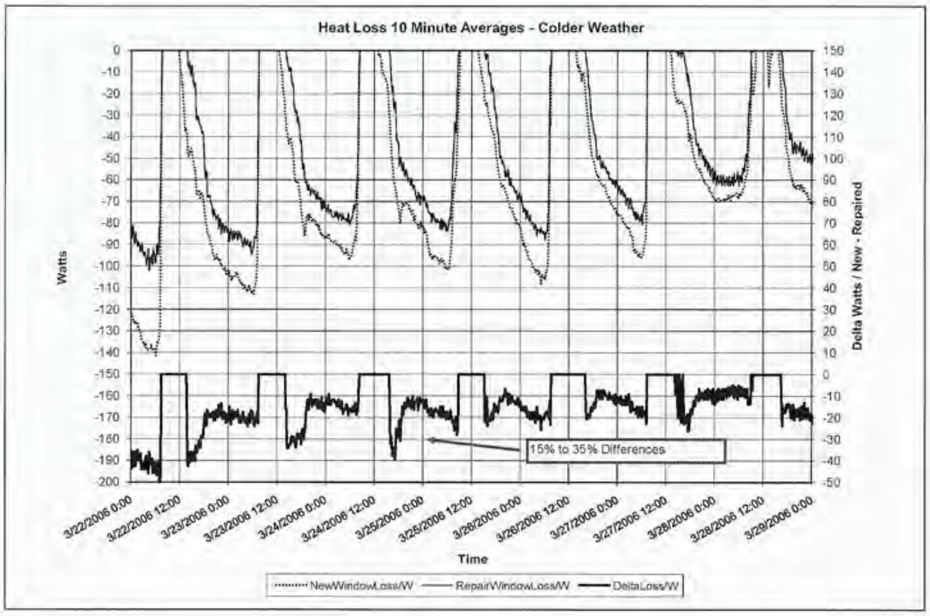

Fig. 12. Heat loss during the coldest week.

may not be applicable to north-facing windows and requires further analysis. As solar heat gains vary throughout the year, careful consideration of the comprehensive building heating and cooling loads and mechanical-system requirements are needed to optimize the gains and losses through the windows, maximizing gains when needed while minimizing losses throughout the day and the changing seasons. Additional assessment — including the evaluation of other exposures (e.g., north and south), glazing-coating options, and other factors — is required to fully develop the options and will likely impact overall design decisions. This analysis can be achieved with additional mock-ups, careful application of computer simulation, or a combination of both.

The overall result of this study does not diminish the fact that thermal performance is only a portion of the overall decision process. While the repaired window offers superior thermal performance, it will also conserve original building fabric and minimize material waste by maximizing efficient use of preexisting embodied energy. Careful evaluation of historical and architectural significance, as well as the physical condition of the windows, must also be considered, in addition to future maintenance and operation needs. For an in-depth discussion of these and other considerations, the reader should refer to the Secretary of the Interior's *Preservation Brief 13: The Repair and Thermal Upgrading of Historic Steel Windows,* by the U.S. Department of the Interior (available at http://www.nps.gov/history/hps/tps/briefs/brief13.htm). Any rehabilitation project considering similar window programs should include careful identification and evaluation of these often competing factors conducted in concert with technical analysis performed by competent professionals so that appropriate options can be evaluated and an optimal solution selected.

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Notes

1. Both window mock-ups were instrumented with temperature sensors and relative-humidity and air-temperature sensors installed within the air cavity between the storm glazing and the repaired window. Surface-temperature sensors were self-adhesive E-type thermocouples that were connected to Veriteq thermocouple loggers. Each Veriteq logger monitored the temperature of four thermocouples. Thermocouples were installed at the following locations on the interior face of the repaired window frame and the replacement window frame: windowsill frame (center), horizontal meeting rail (center), left jamb (upper left), center of glass (lower light). Thermocouples were also installed on the cavity face of the storm window at the following locations: windowsill frame (center), frame of window head (center), left jamb (upper left), and center of glass (corresponding with lower light). Two Dickson D-200 data loggers were installed within the cavity space between the repaired window and the storm. The D-200 data loggers recorded air temperature and relative humidity at the lower left and upper right corners of the cavity between the storm and the repaired window. To record ambient conditions on the building exterior and interior, two Vaisala HMP44 probes and an Omega data-logging pressure box were installed. The pressure box measured the difference in interior and exterior ambient pressure.

The window mock-ups were constructed on site to allow review of numerous features, including but not limited to appearance, constructability, cost, and impact to building tenants, as well as performance. In addition to thermal-performance monitoring, testing included air-infiltration testing in accordance with American Society for Testing of Materials (ASTM) E783: Standard Test Method for Field Measurement of Air Leakage through Installed Exterior Windows and Doors, as well as water-penetration testing in accordance with ASTM E1105: Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls, by Uniform or Cyclic Static Air Pressure Difference. Though not discussed in this paper, the repaired-window mock-up allowed roughly 50 percent less air-infiltration leakage than the replacement window, likely due to the operable sash of the repaired window being fixed and sealed shut with sealants and paint coatings, while the replacement window, though fixed shut, relied upon gasket seals. The repaired-window mock-up had comparable water-penetration resistance to the replacement window.

2. Since monitoring did not include barometric-pressure measurements, calculations include a constant barometric pressure of 101.325 kPa. This assumption carries through calculations for both windows and will cancel out as the

windows are compared. The humidity ratio in kg/kg is calculated using interior temperature and relative humidity. The entering- and leaving-air enthalpy is calculated in kJ/kg using the humidity ratio and respective air temperatures. The mass of the air flow is calculated using the specific volume of the discharge air in m^3/kg. The data-logger time interval is five minutes, and all kJ calculations are converted to watts by multiplying by 1,000 and dividing by 300 seconds. *American Society of Heating, Refrigerating and Air-Conditioning Engineers Handbook*, vol. 1, *Fundamentals* (Atlanta: ASHRAE, 2005).

3. The coldest temperatures recorded were approximately 32°F (0°C), observed over a span of several hours throughout the first week of data recording. The average peak wintertime temperatures are typically found by using the exterior heating design temperature for Washington, D.C., which can be found in Table D-1 of the ASHRAE Standard 90.1-2004. The exterior heating design temperature of 15°F (-9.5°C) corresponds to the 99.6 percent annual cumulative frequency of occurrence, which means that actual exterior temperatures exceed this design temperature for all but 0.4 percent of the year, or about 1.4 days, during a typical year.

Bibliography

American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy.* Atlanta: ASHRAE, 2004.

American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings.* Atlanta: ASHRAE, 2004.

Park, Sharon C. *Preservation Brief No. 13: The Repair and Thermal Upgrading of Historic Steel Windows.* Washington, D.C.: National Park Service, 1984.