Prepared for the General Services Administration
by the National Renewable Energy Laboratory

OCTOBER 2021

Demonstration and Evaluation of Lightweight High Performance Quad-Pane Windows

Kosol Kiatreungwattana (NREL)

Lin Simpson (NREL)

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.

Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the National Renewable Energy Laboratory, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the U.S. Department of Energy's National Renewable Energy Laboratory. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the National Renewable Energy Laboratory.

The work described in this report was funded by the U.S. General Services Administration and the Federal Energy Management Program of the U.S. Department of Energy under Contract No. IAG-11-01815.

Acknowledgements

U.S. General Services Administration (GSA) Region 8: Tyler Cooper, Douglas Baughman
GSA GPG Program: Michael Lowell and Kevin Powell
Alpen High Performance Products: Brad Begin, Craig Maierhofer, Robert Clark, Dwayne Kowaliuk
National Renewable Energy Laboratory: Kosol Kiatreungwattana, Lin Simpson, Jesse Dean
Mountain Energy Partnership: Ed Hancock, Greg Barker and Paul Norton
Tenfold Information Design Services: Andrea Silvestri

For more information contact:

Michael Lowell
General Services Administration
Email: mike.lowell@gsa.gov

Executive Summary

This demonstration project assessed the thermal performance, life cycle costs, and deployment potential of two types of ultra-high performance quad-pane replacement windows as an upgrade for high performance double-pane replacement windows for new construction.

A. BACKGROUND AND OVERVIEW OF THE TECHNOLOGY

The U.S. Department of Energy's (DOE) National Renewable Energy Laboratory evaluated the quad-pane windows at the U.S. General Services Administration's (GSA) Denver Federal Center Building 41 in Denver, Colorado. For this study, ten high performance quad-pane windows (five quad-pane windows with suspended film and five quad-pane windows with thin glass) were installed at Building 41.

Several different evaluations assessed the viability of the quad-pane windows for GSA applications. Some of these assessments were performed with models, while others required onsite evaluations including time series measurements.

B. STUDY DESIGN AND OBJECTIVES

The primary objectives of the onsite measurement and verification study include:

Objective 1. Verify the high performance benefits of the quad-pane windows, compared to a high performance double-pane window baseline:

a. Thermal performance
b. Heating, ventilating, and air conditioning (HVAC) energy reduction
c. Thermal load (cooling and heating) reduction
d. Comfort improvement

Objective 2. Economic analysis (savings to investment ratio [SIR] and payback)

Objective 3. Evaluate ease of installation and operability

Objective 4. Assess the deployment potential for other GSA sites and identify screening criteria for future candidate buildings and climate zones.

Qualitative objectives are provided in Table ES-1 and quantitative performance objectives and results for the project are provided in Table ES-2.

Table ES-1: Qualitative Objectives

Qualitative Objectives	Metrics & Data	Success Criteria	Results
Thermal Comfort	Tenant satisfaction survey	Improvement in tenant satisfaction with thermal conditions	Five surveys received; 4/5 were positive and recommended the retrofit. 1/5 did not recommend. Thermal discomfort occurred; may be caused by HVAC rather than windows. Glare issues when compared to electro-chromic/thermo-chromic windows. Blinds were adjusted by occupants during the day.
Ease of Installation	Interview with installer Time required to install & configure Labor associated with install	<1 day to install	Quad-pane window installation took within one day – The installation effort and cost of a quad-pane window are the same as a double-pane window.

Table ES-2: Quantitative Objectives and Results

Quantitative Objectives	Metrics & Data	Success Criteria	Results
Energy Savings	HVAC energy consumption (modeled), kBtu	Energy savings compared to a high performance double-pane window baseline 10% for HVAC energy usage	HVAC energy savings compared to high performance double-pane window baseline Quad-pane with film • 25% savings Quad-pane with thin glass • 23% savings
Thermal Performance Indices	U-values, Btu/h·ft^2·°F Solar heat gain coefficient (SHGC), % Visible transmittance (VT), %	Field installed window within 20% of National Fenestration Rating Council (NFRC) rated values/manufacturer's claims	Quad-pane with film • U-value, 13% greater • SHGC, 5% greater • VT, matched Quad-pane with thin glass • U-value 29% greater Lower thermal performance spacers were used in provided demonstration windows. They contributed to lower thermal performance than anticipated. • SHGC 5% greater • VT 7% lower
HVAC Capacity Reduction	HVAC cooling capacity (modeled), kBtu/hr HVAC heating capacity (modeled), kBtu/hr	HVAC capacity[a] reduction compared to high performance double-pane baseline 10% for HVAC cooling and loads	Quad-pane with film • 8% for HVAC heating capacity • 18% for HVAC cooling capacity Quad-pane with thin glass • 7% for HVAC heating capacity • 18% for HVAC cooling capacity
Cost-Effectiveness	Simple payback, years SIR, no unit that compared to high-performance double-pane, incremental cost used	Quad-pane window <15 years payback >1 SIR	Quad-pane with film • 3.7-yr simple payback/5.4 SIR Quad-pane with thin glass • 2.4-yr simple payback/8.3 SIR
Condensation	Room-side glass surface temperature, °F Relative humidity, % CR rating, 0–100	CR rating greater than 50	Quad-pane with film • 65 CR Quad-pane with thin glass • 67 CR

Quantitative Objectives	Metrics & Data	Success Criteria	Results
Thermal Comfort	Space temperature, °F and relative humidity, % Room side glass surface temperature, °F Wall temperature, °F	Space temperature and relative humidity are within occupant thermal comfort defined by ASHRAE Standard 55-2013	Both quad-pane windows A small number of hours (5% to 10%) were outside the comfort boundary.

[a] HVAC capacity for potential HVAC sizing reduction.

C. PROJECT RESULTS AND FINDINGS

The quad-pane windows operated as intended and most evaluation criteria were met. The quad-pane windows provide significant energy savings and are cost effective due to their superior thermal performance. Results, findings, and conclusions are summarized below.

- Quad-pane windows as an upgrade to high-performance double-pane windows provide a cost-effective and efficient way to improve thermal performance and occupant comfort.
- Quad-pane windows using suspended film or ultra-thin glass can significantly reduce overall window weight and structural requirements.
- Quad-pane windows are suitable for new construction and retrofits/replacements for residential, commercial, industrial, and high performance buildings.
- Both quad-pane windows with film and quad-pane windows with thin glass have similar (nearly the same) thermal performance.
- Windows with the same U-value are manufactured with various levels of SHGC. SHGC should be appropriately selected for a climate zone. The lower the SHGC, the less solar heat it transmits and the greater its shading ability. A product with a high SHGC rating is more effective at collecting solar heat during the winter. A product with a low SHGC rating is more effective at reducing cooling loads during the summer by blocking heat gain from the sun.
- The calculated CR for the quad-pane window is 65–67, indicating superior condensation resistance.
- The thermal comfort criteria are met as the results show that the majority of the indoor conditions were within the comfort boundary. However, the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) analysis shows that the space in Building 41 was slightly cool and predicts that up to 25% of the occupants could experience some local thermal discomfort. It is possible that thermal discomfort was already present and caused by other factors such as HVAC operation rather than the windows.
- Measured temperatures at the center of the glass of the quad-pane window during the coldest period were significantly warmer. Smaller differences between window surface and room air temperatures reduce the radiant asymmetry of vertical surfaces, improving occupant comfort.
- To evaluate deployment potential, the energy savings and economic analyses were conducted for ten ASHRAE climate zones. The energy cost was estimated for three levels of GSA utility rates—low, middle,

and high. Based on criteria of a payback of less than 15 years and a SIR greater than 1, both quad-pane windows are cost effective as an upgrade to the high performance double-pane window for all climate zones and all GSA utility rates.

- The quad-pane with thin glass has a lower cost than the quad-pane with film. Therefore, the economics of the quad-pane with thin glass are slightly better.
- The analysis results populated in Table ES-1 and ES-2 can be used to perform future screening for the technology and high-level energy savings estimates for individual climate zones. However, for a future retrofit project, a detailed study including energy modeling analysis of the window options for the specific building is recommended due to the fact that each building is unique. Some key findings are presented below.
    - HVAC energy reduction (heating, cooling, fan) for the quad-pane window could range from 19% to 33%, depending on the climate zone.
    - Energy and cost savings for the quad-pane windows could be 5.1–8.5 kBtu/ft^2/yr or \$0.07–\$0.31/ft^2/yr depending on the climate zone and utility rates.
    - Based on the incremental cost of upgrading to high performance double-pane windows, quad-pane windows could offer a payback period of 0.8–5.7 years and a SIR of 3.5–24.4 depending on climate zone and utility rates.
- The significant thermal improvement and the small incremental costs of quad-pane windows compared to high-performance double-pane windows make the quad-pane window an good option for window upgrades.

Table of Contents

List of Tables

List of Figures

I. Introduction

A. PROBLEM STATEMENT

A window is an opening in a wall, door, or roof that admits light and air into the building and also enables outside viewing. Windows may also enhance the aesthetic appearance of the building. However, windows typically have significantly inferior thermal properties when compared to walls and roofs, and present a significant energy load to buildings.

B. OPPORTUNITY

High performance, energy-efficient window and glazing systems can significantly reduce energy consumption. They have lower heat loss, less air leakage, and warmer window surfaces that improve occupant comfort and minimize condensation. By enabling people to comfortably sit closer to the windows, high performance windows could also increase occupant density. Additionally, they may allow the building to specify smaller, less costly heating and cooling systems.

Double-pane windows have been the industry standard for the last several decades. They are a vast improvement over single-pane windows, but the potential for even greater energy savings with highly insulting windows still remains largely untapped. The U.S. Department of Energy (2010) estimates that increasing the R-value from 3 (an ENERGY STAR® rated window) to 5 reduces heat loss through windows by 40%. Until now, windows with R-values of 5 or greater have been made with triple or quad panes of standard glass, making them thicker, heavier, and substantially more expensive than traditional units. Recent price reductions for the thin glass used in smart phones and flat-screen televisions as well as for krypton gas used in halogen lights have made it possible to build lighter high efficiency windows at a lower cost. In fact, a manufacturer stated that the manufacturing cost increment between the quad-pane and triple-pane window is insignificant. The quad-pane windows utilize fiberglass frames to help reduce thermal conductance through the frames.

This demonstration project assessed the thermal performance, life cycle costs, and deployment potential of two types of ultra-high performance quad-pane replacement windows.

C. TECHNOLOGY DESCRIPTION

Quad-pane windows are typically composed of four glass panes, with insulating gases in the cavities between the panes. However, this makes them relatively heavy and too thick for some applications. Two types of quad-pane windows were used for this study: (1) quad-pane window with two suspended films between two standard pieces of window glass to effectively form a quad window out of a double glass pane window, and (2) quad-pane with ultra-thin glass between the two outer standard glass panes to make up the quad pane. Both quad-pane windows have R-6 to R-7 insulating values with varying levels of solar heat gain coefficient (SHGC). Using suspended film or ultra-thin glass can significantly reduce overall window weight and structural requirements. The quad-pane windows are suitable for fixed, nonopenable, and operable windows. They are suitable for new construction as well as retrofits and replacements for residential, commercial, industrial, and high performance buildings. The windows' features include:

- Super-insulated energy-efficient pultruded fiberglass frames
- High-performance spacers and high-performance inert gas fill (i.e., krypton)
- Structural capability for expansive sizes and dramatic window walls

- Ultra-slim, modern profiles for contemporary and commercial aesthetics
- Versatility—styles include fixed and operable windows for ventilation
- Excellent sound attenuation
- Modular installation method which provides a cost-effective alternative to site-assembled storefront window systems.

Figure 1. Quad-pane window (Credit: Kosol Kiatreungwattana)

D. RESEARCH OPPORTUNITY

In general, windows account for approximately 39% of the annual U.S. energy used to heat commercial buildings as presented in Table 1. This fraction can be even higher in more northern latitudes and in older buildings that have single-pane glass and/or highly conductive, non-thermally broken metal frames. Highly insulating windows could significantly reduce the annual U.S. energy use attributable to windows, but replacement can be costly; even more so in older buildings where lead paint and/or asbestos must be remediated as part of a window replacement. However, in addition to the energy savings from highly insulating windows, these older buildings may benefit from improved comfort of occupants close to the windows, thereby increasing occupancy density, and being able to use smaller, less costly heating and cooling systems when they need to be replaced.

Table 1: U.S. Annual Commercial Building Heating, Ventilating, and Air Conditioning and Window-Related Energy Use, Reported in Quadrillion BTUs of Primary (Source) Energy

	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%

Source: Apte and Arasteh (2006)

The U.S. General Services Administration (GSA) aggressively pursues cost-effective energy efficiency opportunities for its more than 9,600 facilities. Thus, a variety of highly insulating fenestration products have been evaluated and recommended in the past. However, GSA facilities still have substantial numbers of poorly performing or underperforming windows, and the newest technologies still need to be evaluated. Presently, there are a variety of commercially available retrofit and replacement windows that may provide sufficient thermal insulation and reduce air infiltration. ENERGY STAR rated windows have an overall R-value of 3 (R-3). However, even a small increase to R-5 could reduce heat loss through the window by 30%–40%. Unfortunately, many facilities are not able to accommodate the size and/or weight increases associated with these more energy-efficient windows. Furthermore, the added expense of the extra glass and associated assemblies may be cost-prohibitive.

II. Evaluation Plan

A. EVALUATION DESIGN

STUDY DESIGN AND OBJECTIVES

As discussed below, several different evaluations assessed the viability of the quad-pane windows for GSA applications. Some of these assessments were performed with models, while others required onsite evaluations including time series measurements. The primary objectives of the onsite measurement and verification (M&V) study are:

Objective 1. Verify the high performance benefits of the quad-pane windows:

a) Thermal performance

b) Heating, ventilating, and air conditioning (HVAC) energy reduction

c) Thermal load (cooling and heating) reduction

d) Comfort improvement

Objective 2. Economic analysis (savings to investment ratio [SIR] and payback)

Objective 3. Evaluate ease of installation and operability

Objective 4. Assess the deployment potential for other GSA sites and identify screening criteria for future candidate buildings and climate zones.

OBJECTIVE 1: VERIFY THE HIGH PERFORMANCE BENEFITS OF QUAD-PANE WINDOWS

The most important M&V objective is to verify the energy savings. The HVAC energy consumption was evaluated using a simulation modeling approach. Lawrence Berkeley National Laboratory's WINDOW,[1] a computer program, is used for calculating total window thermal performance indices including U-value, SHGC, and visible transmittance (VT). WINDOW can be used to analyze window products with any combination of glazing layers, gas layers, frames, spacers, and dividers under any environmental conditions. It provides a versatile heat transfer analysis method consistent with the rating procedure developed by the National Fenestration Rating Council (NFRC) that is consistent with the International Organization for Standardization (ISO) 15099 standard. In addition, Lawrence Berkeley National Laboratory's THERM[2] is used with the WINDOW program to model two-dimensional heat transfer of the window including frame and edge effects. Monitoring data were used for calibrating WINDOW and THERM simulation models. Glass surface temperatures predicted by the THERM computer models were compared to measured surface temperatures using the measured environmental conditions as inputs to the model. The thermal performance characteristics of a high performance double-pane window (baseline) and high performance quad-pane windows were modeled in the EnergyPlus™[3] simulation modeling tool. EnergyPlus, developed by the U.S. Department of Energy (DOE), is a whole building energy simulation program that is widely used by engineers, architects, and researchers. EnergyPlus requires a detailed description of the building envelope (for thermal and optical properties), internal loads, operating schedules, lighting, HVAC system requirements, and utility rate schedules. The tool is capable of evaluating energy use and energy cost savings that can be achieved by applying energy conservation measures such as improved envelope components, active and passive heating and cooling strategies, lighting system improvements, and HVAC system improvements.

OBJECTIVE 2: ECONOMIC ANALYSIS (PAYBACK)

Cost effectiveness was evaluated based on energy cost savings, retrofit and installation costs, and operation and maintenance costs compared to the incumbent technology. Overall cost effectiveness was compared to the market claim as a part of this demonstration. The success criterion to qualify the product as cost effective was a payback period of less than 15 years and a savings-to-investment ratio (SIR) greater than 1. Savings were comprised of estimated energy cost savings and potential savings from HVAC system sizing reduction. Savings from HVAC system capacity reduction were estimated from the heating and cooling capacity reduction multiplied by cost per unit of HVAC heating and cooling capacity. The unit costs of HVAC heating and cooling capacity were derived from data presented within the U.S. Energy Information Administration's (EIA) *Updated Buildings Sector Appliance and Equipment Costs and Efficiencies* (EIA 2018). Costs of the technologies used in the analysis came from actual installed costs at the site. For the quad-pane window analysis, the incremental cost was used for comparison to high-performance double-pane windows.

---

[1] WINDOW, https://windows.lbl.gov/software/window
[2] THERM, https://windows.lbl.gov/software/therm
[3] EnergyPlus, https://energyplus.net/

OBJECTIVE 3: EVALUATE EASE OF INSTALLATION AND OPERABILITY

Ease of installation was gauged according to whether windows were installed in less than a day and commissioned in less than an hour. Operability was evaluated by interviewing operations and maintenance (O&M) staff and facility operators on site. The criterion for success was that the installation of the quad-pane window should be the same as the baseline double-pane window. It should not introduce a steep learning curve to install the windows and should not impact the regular O&M effort.

OBJECTIVE 4: ASSESS THE DEPLOYMENT POTENTIAL FOR OTHER GSA SITES AND IDENTIFY SCREENING CRITERIA FOR FUTURE CANDIDATE BUILDINGS AND CLIMATE ZONES

One of the main goals of this study was to evaluate suitability of the high performance quad-pane windows for deployment in GSA buildings across different climate zones. The key metric for determining suitability for deployment was that the simple payback period should be less than 15 years. To evaluate the deployment potential, the DOE Commercial Reference Building model of a large office was used for the analysis as it represents the majority of the GSA building stock. Analyses were conducted for ten ASHRAE climate zones in which the majority of GSA buildings are located. The energy costs were estimated for three levels of GSA utility rates (low, mid, and high).

Quantitative and qualitative performance objectives for the project are provided in Table 2 and Table 3, respectively.

Table 2: Quantitative Objectives

Quantitative Objectives	Metrics & Data	Success Criteria
Energy Savings	HVAC energy consumption (modeled), kBtu	Energy savings compared to a high performance double-pane window baseline: 10% for HVAC energy usage
Thermal Performance Indices	WINDOW (modeled) U-values, Btu/h·ft^2·F SHGC, % VT, %	Field installed window within 20% of NFRC-rated values/manufacturers claims
HVAC Peak Loads Reduction	HVAC cooling loads/capacity (modeled), kBtu/hr HVAC heating loads/capacity (modeled), kBtu/hr	HVAC load[a] reduction compared to a high performance double-pane window baseline 10% for HVAC cooling and heating loads
Cost-Effectiveness	Simple payback period, year SIR, unitless	<15-year payback >1 SIR

Quantitative Objectives	Metrics & Data	Success Criteria
Thermal Comfort	Space temperature, °F and relative humidity, % Room-side glass surface temperature, °F Wall temperature, °F	Space temperature and relative humidity are within range of occupant thermal comfort defined by ASHRAE Standard 55-2013
Condensation	Room-side glass surface temperature, °F Relative humidity, % Calculated Condensation Resistance (CR) rating, 0–100	CR rating greater than 50

[a] HVAC load or capacity for potential HVAC sizing reduction.

Table 3: Qualitative Objectives

Qualitative Objectives	Metrics & Data	Success Criteria
Ease of Installation	Interview with installer Time required to install and configure Labor associated with install	<1 day to install
Thermal Comfort	Tenant satisfaction survey	Improvement in tenant satisfaction with thermal conditions

B. INSTRUMENTATION PLAN

DESCRIPTION OF DEMONSTRATION SITE

GSA selected Building 41 at the Denver Federal Center in Colorado as a demonstration site for testing the high performance quad-pane windows. The building represents a typical GSA office building which constitutes the majority of the GSA building stock. Figure 2 shows the exterior and interior of Building 41.

Building 41 is a 150,000 square foot, two-story office building originally constructed in 1941 as part of an ammunitions plant. The building has been upgraded to office and warehouse space over the years. Today, the two-story, red brick building offers a mix of office, conference, warehousing and food service space. For this study, ten high performance quad-pane windows (five quad-pane with suspended film and five quad-pane with thin glass) were installed to replace existing thermochromic windows along the south end of the perimeter zone and electrochromic windows along the middle north end of the perimeter zone of the west side of the building.

The thermochromic and electrochromic windows had been installed for a previously completed research project. The southwest windows are exposed to direct sunlight from mid-day to evening. Each window has a manually operated interior white woven roller shade. Some shades were adjusted by occupants during operating hours. To eliminate thermal impacts to window heat transfer by the shade, the shades were set in a fully raised position during off hours and weekends. Only those periods during which the shades were raised and other criteria met were used for making comparisons between the measured and modeled data.

Figure 2: Building 41 - exterior and interior (Credit: Kosol Kiatreungwattana)

CLIMATE CHARACTERISTICS

Denver is a heating-dominated climate. Figure 3 and Figure 4 show binned outdoor temperatures and the binned outdoor relative humidity from the Typical Meteorological Year (TMY) 3 weather data for Denver International Airport. The outdoor temperature is less than 80°F for more than 80% of the total hours annually.

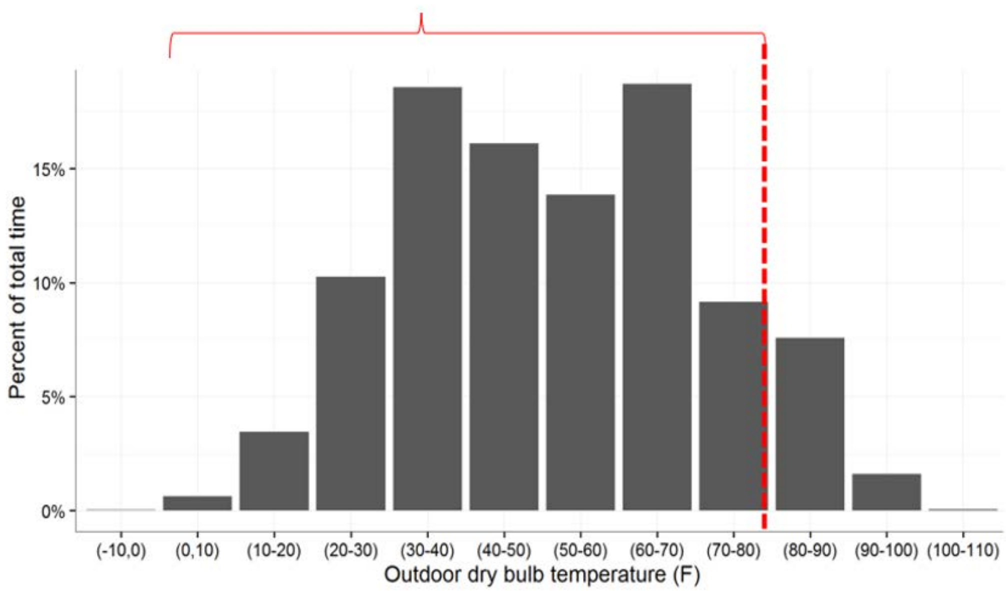

Figure 3: Binned outdoor temperature

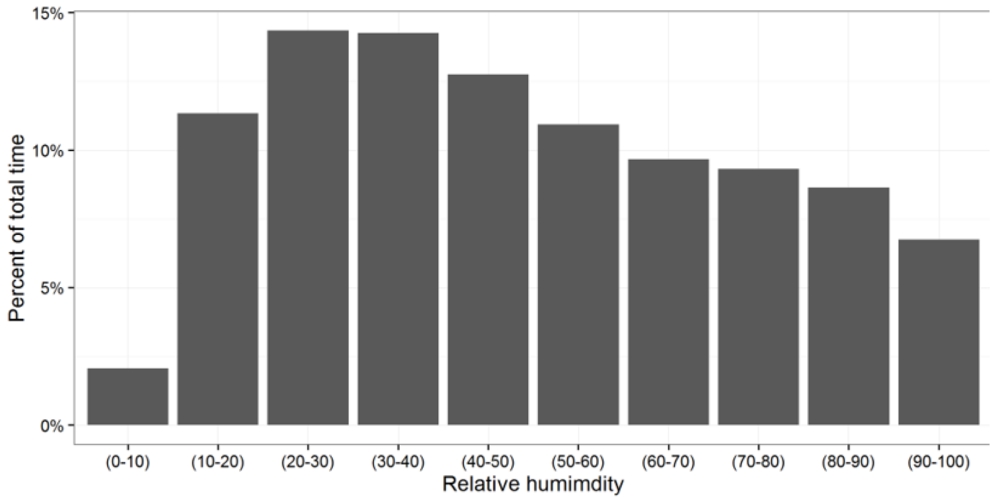

Figure 4: Binned outdoor relative humidity

MONITORING AND INSTRUMENTATION

The National Renewable Energy Laboratory (NREL) team installed a data acquisition system consisting of data loggers, temperature sensors, and wireless temperature and humidity sensors at the quad-pane windows. Space conditions were monitored for thermal comfort analysis. All monitoring points and instrumentation are described in Table 4. Monitoring data was collected remotely at NREL's office in Golden, Colorado. Information was sent via a modem connection to the data loggers. Figure 5 shows an example of sensor locations on a window.

Table 4: Monitoring Points and Instrumentation

Monitoring Point	Logging Equipment Description	Location	Notes
Window	Thermocouples	Two glazings (outer and inner) Center of glass, inside and outside surfaces (2 thermocouples total) 1. Two inches from glass edge, inside and outside surfaces (2 thermocouples total) 2. One inch from glass edge, inside and outside surfaces (2 thermocouples total) 3. Frame, inside and outside surfaces (2 thermocouples total) 4. Wall between windows	Up to 50 thermocouples total for Building 41 Eight thermocouples per window
Space conditions	Temperature sensors Humidity sensors	Work-plane height Room temperature Room relative humidity	Three temperature and humidity sensors for Building 41
Ambient conditions	Weather station	Temperature Humidity Wind speed	Temperature and humidity were measured on-site. Wind speed data from the weather station at the NREL Solar Radiation Research Laboratory (SRRL) was used. The NREL SRRL is approximately five miles from the Denver Federal Center.
Comfort	Comfort survey	Employees selected by GSA	Up to ten surveys for Building 41
Surface temperature	Thermal imaging camera	Window, frame, and wall	Conduct multiple thermal imaging studies in summer and winter to support window thermal performance indices calculation

The schedule for monitoring and evaluating the technologies is summarized in Table 5.

- The installation of quad-pane windows was completed on Dec. 26, 2019. The monitoring equipment was installed on Jan. 17, 2020.
- The monitoring data were collected from Jan. 17, 2020 to June 30, 2020.

Table 5: Monitoring and Instrumentation Schedules

Task	Note
Installation of replacement quad-pane windows at Building 41	Window replacement at Building 41 was completed on Dec. 26, 2019.
Installation of M&V equipment for quad-pane windows at Building 41	M&V equipment for quad-pane windows was installed on Jan. 17, 2020.

Figure 5: Example of sensor locations on a window (Credit: Kosol Kiatreungwattana)

III. Demonstration Results

A. MONITORING ACTIVITIES

Measured temperature responses were taken of high performance quad-pane window components at Building 41 for comparison to those predicted by the detailed computer models used in THERM and WINDOW. Driving functions, which were used as inputs to the models, and the responses of certain points in the window systems were measured. It should be noted that we did not attempt to measure the solar-gain-related behavior of the windows—only the conduction and convection behavior was measured. It was assumed that the transmittance and spectral properties of the glazing materials were already well characterized by laboratory tests. We were also not attempting to measure or model the thermal capacity behavior of the window components as the THERM and WINDOW programs assume steady-state conditions. With these parameters in mind, the following measurements were made:

1. Driving functions
   a. Outdoor dry-bulb temperature
   b. Indoor dry-bulb temperature approximately 30 cm from the window

2. Responses
   a. Window frame temperatures, inside and outside
   b. Glazing temperatures 2.5 cm (1 inch) from the frame, inside and outside
   c. Glazing temperatures at the center of the glazing, inside and outside.

All temperature measurements were taken using 30-gauge thermocouples affixed to the surfaces using Kapton tape. Temperatures were measured continuously and stored as 1-minute, 15-minute, 60-minute, and daily averages. All data were stored on the data loggers themselves, a personal computer, and on a cloud-based server. Our approach was to search for 15-minute-averaged points within the data that met the following criteria to ensure that the data represented near-steady-state conditions in which the temperatures are nearly constant and the wind is minimal for a period of time.

1. Time is after sunset and before sunrise to eliminate impacts of direct solar gain to the window
2. Wind speed has been near-zero for 30 minutes to eliminate the impacts of convection heat transfer to the window
3. Standard deviation of wind speed over the last 30 minutes is at a minimum
4. Standard deviation of outdoor dry-bulb temperature over the last hour is at a minimum
5. Standard deviation of indoor dry-bulb temperature near the window over the last hour is at a minimum
6. Standard deviation of outdoor center-of-glass temperature over the last hour is at a minimum
7. Standard deviation of indoor center-of-glass temperature over the last hour is at a minimum.

Sets of data that met the steady-state criteria were used for THERM and WINDOW modeling and calibration. Figure 6 shows an example of a data set. Filtered data (black dot) that met the steady-state criteria were used to support THERM and WINDOW modeling.

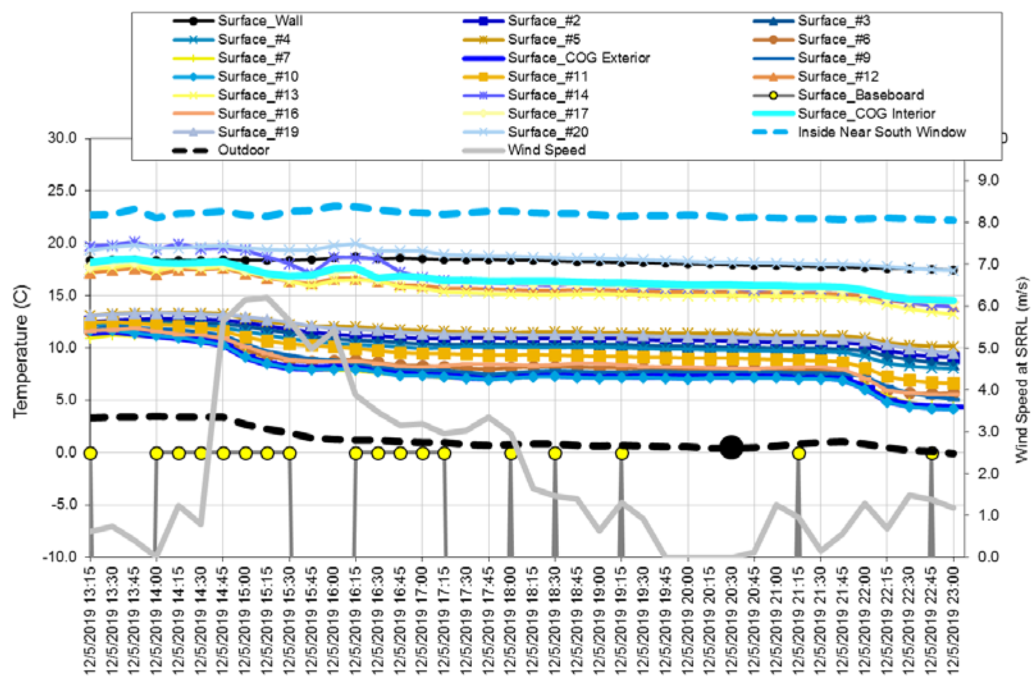

Figure 6: Example of measured data

In addition to the above measurements, several infrared (IR) photos of the temperature gradient near the edge of the glass were taken on a few occasions in the early morning before the sun hit the glass. These photos were analyzed to show a more detailed set of temperatures along the steep gradient than can be inferred from the few point measurements that were made continuously.

MONITORING ISSUES AND FINDINGS

Issues and findings related to monitoring included the following.

1. **Wind speed**: Calculating actual forced-convection heat transfer coefficients based on wind speed is notoriously difficult, but calculating natural convection based on surface and air temperatures under zero wind speed is much more reliable. Wind data was taken from the SRRL. The near-zero wind speed for a period of time was used to assume steady-state conditions. It was assumed that if the wind speed at SRRL was zero, it was likely to be zero at the Denver Federal Center.
2. **Infrared energy exchange**: Radiant temperature with which the window system exchanges heat via infrared radiation was not measured. There are two radiant environments, one outdoors and one indoors. The indoor environment can reasonably be assumed to be equal to the indoor dry-bulb temperature, as nearly all the view factor of the inside of the windows is to interior walls. The outdoor environment temperature is not as easily determined. The window has significant view factors to the adjacent buildings, to the ground, and to the sky. Sky temperature is available from SRRL, but the temperatures of the adjacent buildings and ground were unknown. The building and ground temperatures were estimated for boundary conditions in the THERM model.
3. **Window coverings**: All of the windows studied have operable window coverings that the occupants of the offices use regularly to reduce glare in the office space. When the window covering is down, even part-way, the heat transfer mechanisms affecting the window are changed significantly. Therefore, only data during periods when the window covering was disabled were compared to the THERM and WINDOW models. The building manager ensured the blinds were fully opened at the end of each day and weekend in Building 41.

THERM AND WINDOW MODELING

THERM and WINDOW models were created for the quad-pane windows. Measured glass and frame surface temperatures were used for calibration and comparison with predicted surface temperatures. Table 6 presents the WINDOW-calculated window system performance indices.

THERM and WINDOW models were created for the cases presented below:

1. Quad-pane window with suspended films
2. Quad-pane window with thin glass.

THERM and WINDOW Model Results and Findings

THERM and WINDOW model results and findings include the following:

- Calibrated THERM models accurately predict measured surface temperatures of the glass and frame of the windows
- Both quad-pane windows have low U-values as expected
- Quad-pane with thin glass has slightly higher U-value compared to quad-pane with suspended films because the thin glass does not have low-e coatings.

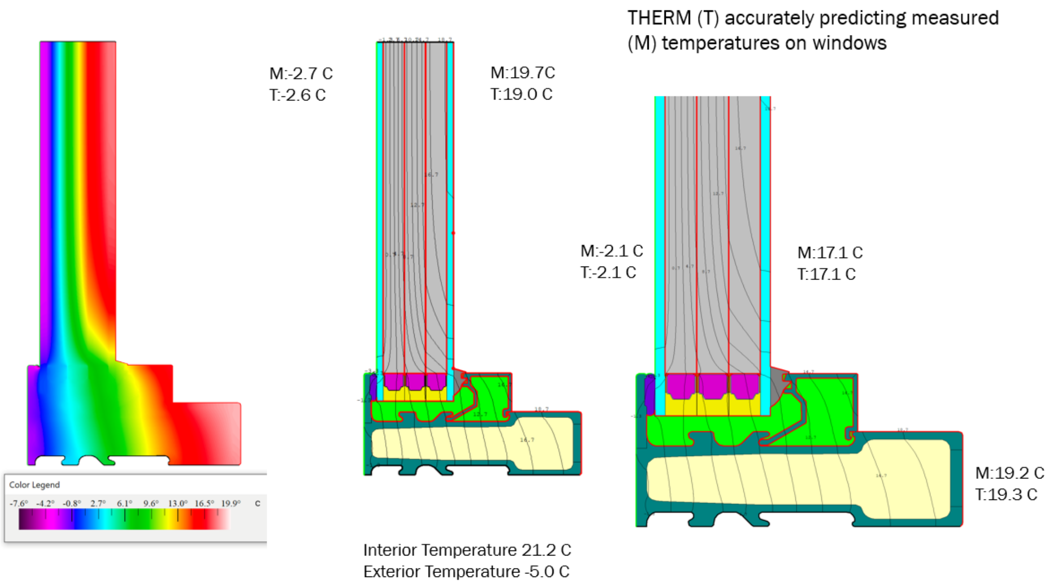

Figure 7: Calibrated THERM model for quad-pane window with suspended films (Source: THERM)

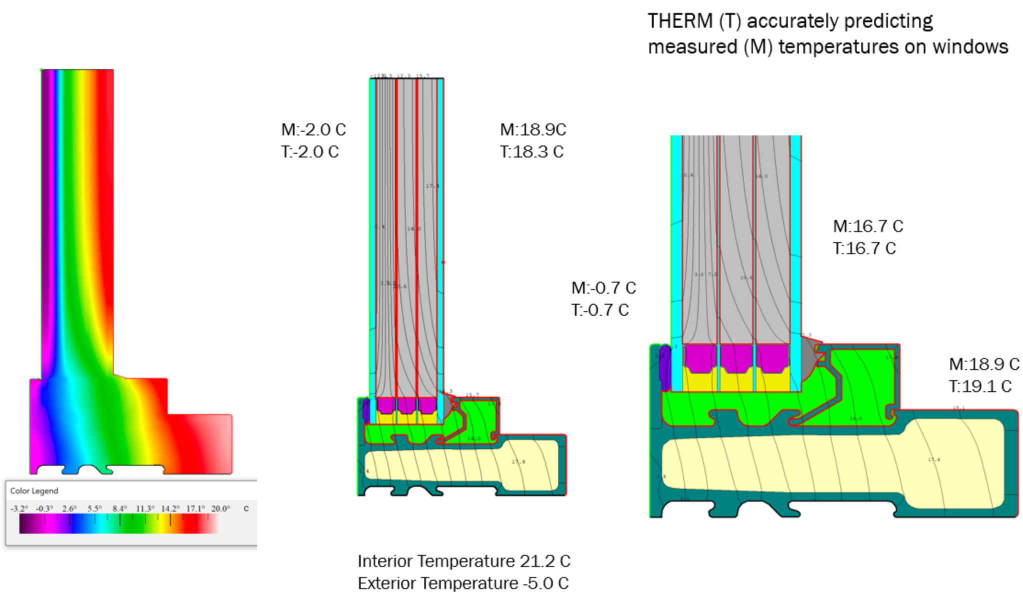

Figure 8: Calibrated THERM model for quad-pane window with thin glass (Source: THERM)

Table 6: Window Performance Indices Calculated Using WINDOW

	U-Value		Solar Heat Gain Coefficient	Visible Transmittance	Condensation Rating
	(W/m²·K)	Btu/(h·ft²·F)			
Quad-pane with suspended films	0.832	0.147	0.20	0.44	65
Quad-pane with thin glass	0.953	0.168	0.20	0.47	67

ENERGYPLUS MODELING

DOE's Commercial Reference Building Models for a large-sized office building, Denver TMY3 weather data, and GSA medium utility rates were used for the whole building simulation analysis to support the evaluation of the technologies at the Denver Federal Center. For the analysis, a high performance double-pane window was used as a baseline with an assumption that the high performance double-pane window is minimally compliant for new construction of a GSA building. Table 7 presents the window performance indices that were used for the EnergyPlus modeling analysis.

Table 7: Window Performance Indices for EnergyPlus Modeling

	U-Value		Solar Heat Gain Coefficient[a] (low/high)	Visible Transmittance (low/high)
	(W/m²·K)	Btu/(h.ft²F)		
High-performance double window baseline	1.82	0.32	0.67	n/a
Quad with film	0.74	0.13	0.19/0.38	0.44/0.53
Quad with thin glass	0.74	0.13	0.20/0.46	0.46/0.56

[a]SHGC should be appropriately selected for a climate zone. The lower the SHGC, the less solar heat it transmits and the greater its shading ability. A product with a high SHGC rating is more effective at collecting solar heat during the winter. A product with a low SHGC rating is more effective at reducing cooling loads during the summer by blocking heat gain from the sun.

A graphical representation of the building energy model developed in EnergyPlus is shown in Figure 9. Details and characteristics of the large-sized office building model are described and can be found in Appendix B. Figure 10 and Figure 11 graphically display the predicted monthly electricity and natural gas use. Figure 12 presents the EnergyPlus output for the baseline energy model by end use. As shown, lighting is the largest electrical energy consumer followed by equipment, fan, and cooling.

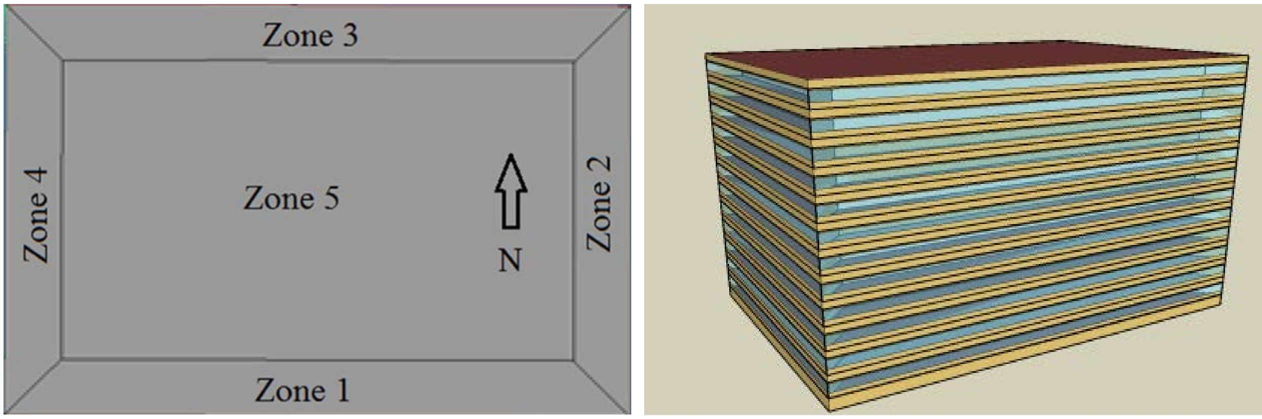

Figure 9: Large Office EnergyPlus model representation (Source: EnergyPlus)

Table 8: EnergyPlus Results for Large Office Baseline

Building Metric	Large Office
Total building area	498,588 ft^2
Weather file	Climate Zone 5B, Denver, Colorado
Total site energy	32,943,782 kBtu/yr
Site energy use intensity	66.07 kBtu/ft^2
Total energy cost	$937,905/yr
Normalized energy cost	$1.88/$ft^2$/yr

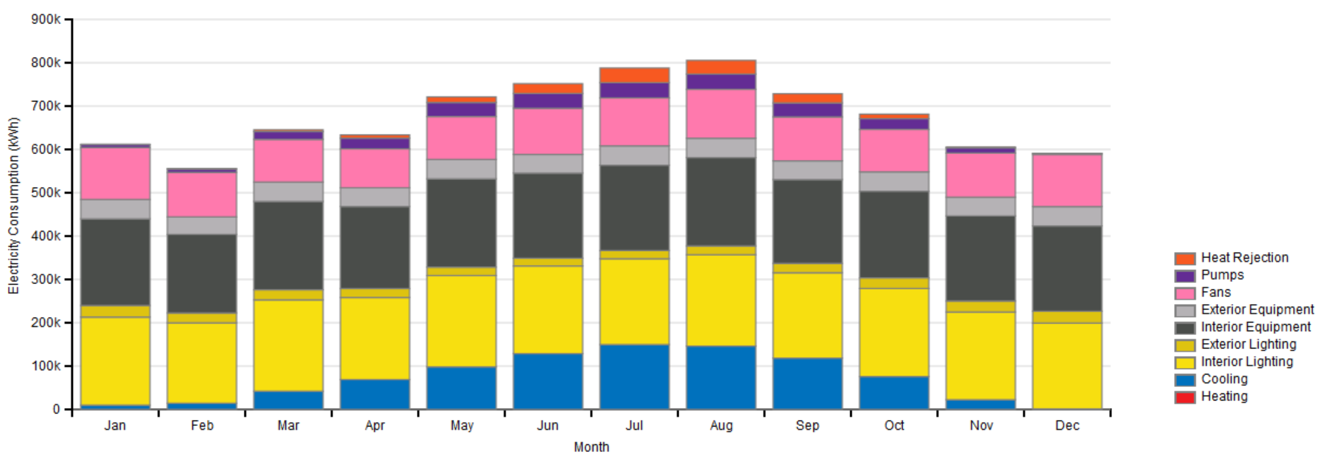

Figure 10: Baseline predicted monthly electricity use (Denver)

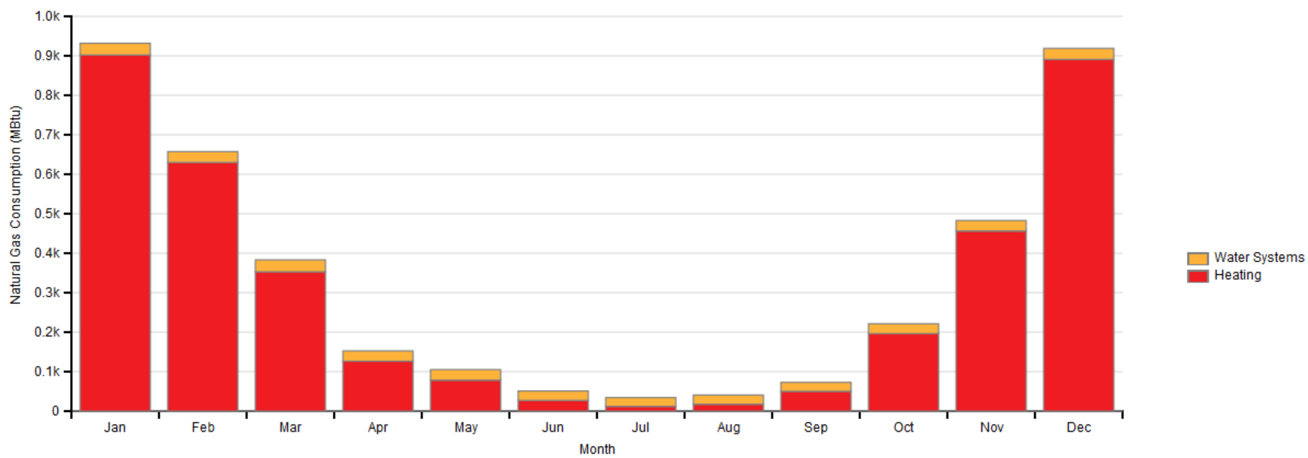

Figure 11: Baseline predicted monthly natural gas use (Denver)

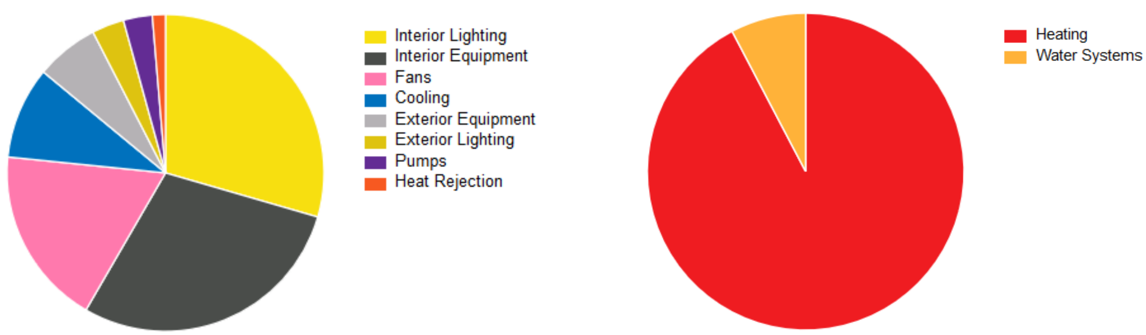

Figure 12: Baseline predicted energy use by end use (Denver)

B. QUANTITATIVE RESULTS

HEATING, VENTILATING, AND AIR CONDITIONING ENERGY SAVINGS

Quantitative results relative to the objectives set out at the start of the evaluation are discussed below. Energy savings were estimated from the EnergyPlus simulation models. The majority of energy savings are from heating and cooling energy reduction. The success criterion was a minimum 10% reduction in heating and cooling energy for the quad-pane windows.

This success criterion was met. Cooling energy reduction is expected to be 14% to 17% and heating energy reduction is expected to be 32% to 33%. The quad-pane windows provide great energy savings due to the fact that they have superior thermal performance. Details of the HVAC energy saving criteria and results can be found in Table 9 and Table 10.

Table 9: Quantitative Objectives and Results – Energy Savings

Quantitative Objectives	Metrics & Data	Success Criteria	Results
Energy Savings	HVAC energy consumption (modeled), kBtu	Energy savings compared to a high performance double-pane window baseline 10% for HVAC energy usage	HVAC energy savings compared to the high performance double-pane window baseline Quad-pane with film • 25% savings Quad-pane with thin glass • 23% savings

Table 10: Estimated Heating, Ventilating, and Air Conditioning Energy Savings

Metric	High Performance Double-Pane Baseline	Quad with Film	Quad with Thin Glass
Cooling Energy (MBtu)	2,432	2,017	2,093
Heating Energy (MBtu)	5,614	3,742	3,807
Fan Energy (MBtu)	4,430	3,588	3,720
Total HVAC Energy (MBtu)	12,476	9,347	9,620
Reduction in Cooling Energy (%)	N/A	17%	14%
Reduction in Heating Energy (%)	N/A	33%	32%
Reduction in Fan Energy (%)	N/A	19%	16%
Reduction in Total HVAC Energy (%)	N/A	25%	23%

THERMAL PERFORMANCE INDICES

Various thermal performance indices were used as criteria to compare the calculated values from the WINDOW program to manufacturers' claims. The thermal performance indices of U-value, SHGC, and VT are widely used as ratings values, similar to the gas mileage rating of an automobile or the energy rating of a refrigerator. The success criterion was that each of the calculated values should be within 20% of the manufacturer's claimed value. All performance indices are within the claimed values, except for the validated U-value of the quad-pane window with thin glass that is 29% greater than the claimed value. The manufacturer found that for the installed window, black Hi-Q steel spacers, which have lower thermal performance, were used as a substitute for Tri-Seal Super Spacers which were included in the specification. However, the modeled and claimed U-values are still very small, compounding the very small change from this manufacturing oversight and resulting in a not-pass for this criteria. Details of the thermal performance indices criteria and results are shown in Table 11 and Table 12.

Table 11: Quantitative Objectives and Results – Thermal Performance Indices

Quantitative Objectives	Metrics & Data	Success Criteria	Results
Thermal Performance Indices	U-values, Btu/h·ft^2·F SHGC, % VT, %	Field installed window within 20% of NFRC-rated values/manufacturer's claims	Quad-pane with film • U-value 13% greater • SHGC 5% greater • VT, matched Quad-pane with thin glass • U-value 29% greater • Lower-thermal-performance spacers were used in provided demonstration windows. They contribute to lower thermal performance than anticipated. • SHGC 5% greater • VT 7% lower

Table 12: Calculated Thermal Performance Indices

Metric	Claimed	Quad With Film Validated	Quad With Thin Glass Validated
U-value (Btu/(h·ft^2·°F)	0.13	0.15	0.17
SHGC	0.19	0.20	0.20
VT	44%	44%	47%

HVAC CAPACITY REDUCTION

HVAC capacity reduction was estimated from the EnergyPlus simulation models. This analysis investigated the heating and cooling capacity reduction potential as an additional benefit beyond energy savings from quad-pane windows. The success criteria were heating and cooling capacity reductions for quad-pane windows of at least 10%.

HVAC capacity reduction cost savings were estimated based on the EnergyPlus model and costs per capacity derived from data published by EIA (2018). Cost details can be found in Table 13. HVAC capacity reduction cost savings were estimated and annualized over 20 years as an assumed life expectancy of an HVAC system. The

HVAC capacity reduction and savings were estimated to demonstrate that a facility would be able to use smaller, less costly heating and cooling systems when they need to be replaced.

For the quad-pane windows, cooling capacity reduction potential is 18% and heating capacity reduction potential is 7% to 8%. Details of the HVAC capacity reduction criteria and results can be found in Table 14 and Table 15.

Table 13: HVAC Capacity Cost

System Type	System Function	Cost per capacity ($/kBtu/h)
Gas-fired boiler	Heating	40.56[a]
Water-cooled chiller	Cooling	40.6[b]

[a] EIA, *Updated Buildings Sector Appliance and Equipment Costs and Efficiencies*, 98 (commercial gas boiler)
[b] EIA, *Updated Buildings Sector Appliance and Equipment Costs and Efficiencies*, 102 (average cost per ton, water-cooled centrifugal [400–600 ton])

Table 14: Quantitative Objectives and Results – HVAC Capacity Reduction

Quantitative Objectives	Metrics & Data	Success Criteria	Results
HVAC Capacity Reduction	HVAC cooling capacity (modeled), kBtu/hr HVAC heating capacity (modeled), kBtu/hr	HVAC capacity[a] reduction compared to double-pane baseline 10% for HVAC cooling and loads	Quad-pane with film • 8% for HVAC heating capacity • 18% for HVAC cooling capacity Quad-pane with thin glass • 7% for HVAC heating capacity • 18% for HVAC cooling capacity

[a] HVAC capacity for potential HVAC sizing reduction.

Table 15: Estimated HVAC Capacity Reduction

Performance Metric	High Performance Double-Pane Baseline	Quad With Film	Quad With Thin Glass
Heating Capacity (kBtu/hr)	11,321	10,443	10,549
Cooling Capacity (kBtu/hr)	12,048	9,933	9,908
Reduction in Heating Capacity (%)	N/A	8%	7%
Reduction in Cooling Capacity (%)	N/A	18%	18%
Estimated total HVAC capacity savings ($)	N/A	$121,481	$118,200
Annualized HVAC capacity savings over 20 years ($/yr)	n/a	6,074	5,910

COST EFFECTIVENESS

Economic evaluations of the window technology were conducted for simple payback[4] and SIR.[5] Savings were estimated from energy savings only. Energy cost savings were estimated using the EnergyPlus model with a mid-level GSA utility rate. A window life expectancy of 20 years was assumed for the SIR analysis.

The costs of high performance double-pane and quad-pane windows were provided by the manufacturer. Incremental cost of quad-pane window to high-performance double-pane window was used for the analysis as the quad-pane windows are assumed to be an upgrade to a high performance double-pane window. Cost details are presented in Table 16. Details of GSA utility rates can be found in Table 17.

Table 16: Window Costs

Material	Material Cost ($/ft^2)
High performance double-pane window	$32.38
Quad-pane with film	$36.87
Quad-pane with thin glass	$34.87

[4] Simple payback refers to the time required to recoup the funds expended in an investment.

[5] SIR is a ratio of the present value savings to the present value costs of an energy conservation measure.

Table 17: GSA Utility Rates

Utility Rate*	Electricity ($/kWh)	Natural gas ($/MMBtu)
Low	0.078	5.516
Medium	0.113	7.434
High	0.180	10.506

* Rates were provided by GSA

Success criteria for quad-pane windows were a payback of less than 15 years and a SIR greater than 1.

The success criteria were met. Simple payback for the quad-pane windows is between 2.4 to 3.7 years and SIR is 5.4 to 8.3. Details of the cost effectiveness criteria and results can be found in Table 18 and Table 19.

Table 18: Quantitative Objectives and Results – Cost Effectiveness

Quantitative Objectives	Metrics & Data	Success Criteria	Results
Cost-Effectiveness	Simple payback, years SIR, no unit	**Quad-pane window** <15 years payback >1 SIR	**Simple payback/SIR** Quad-pane with film • 3.7 yr/5.4 SIR Quad-pane with thin glass • 2.4 yr/8.3 SIR

Table 19: Cost Effectiveness – Simple Payback and Savings-to-Investment Ratio

Performance Metric	Quad With Film	Quad With Thin Glass
Incremental Cost ($)[a]	223,984	124,214
Energy Savings ($/yr)	60,061	51,815
Simple Payback (yr)	3.7	2.4
SIR	5.4	8.3

[a] Incremental cost when compared to high-performance double-pane window was used for the analysis.

CONDENSATION

CR measures how well a window resists the formation of condensation on the inside surface. CR is scored from 1 to 100. The rating value is based on interior surface temperatures at 30%, 50%, and 70% indoor relative humidity for a given outside dry-bulb temperature of 0°F under 15 mph wind conditions. The higher the number, the better a product is able to resist condensation. CR is meant to compare products and their potential for condensation formation. However, CR is an optional rating on the NFRC label. In general, it is recommended to select a window with an NFRC CR rating greater than 50.[6] For this study, CR was estimated using the WINDOW model at 50% indoor relative humidity, outside dry-bulb temperature of 0°F and 15 mph wind speed.

The success criterion for the CR rating was that it must be greater than 50. Both quad-pane windows met the criteria with CR at 65 and 67. Details of the condensation criteria and results can be found in Table 20 and Table 21.

Table 20: Quantitative Objectives and Results – Condensation

Quantitative Objectives	Metrics & Data	Success Criteria	Results
Condensation	Room-side glass surface temperature, °F Relative humidity, % Calculated CR rating, 0–100	CR rating greater than 50	**CR rating** Quad-pane with film • 65 CR Quad-pane with thin glass • 67 CR

Table 21: Window Performance Ratings Calculated Using the WINDOW Model

Material	U-value		Solar Heat Gain Coefficient	Visible Transmittance	Condensation Rating
	(W/m²·K)	Btu/(h·ft2·F)			
Quad-pane with film	0.832	0.147	0.20	0.44	65
Quad-pane with thin glass	0.953	0.168	0.20	0.47	67

THERMAL COMFORT

Thermal comfort is the feeling of satisfaction with the thermal environment and is assessed by subjective evaluation. ASHRAE Standard 55 specifies conditions for acceptable thermal environments and is intended for use in design, operation, and commissioning of buildings and other occupied spaces. Thermal comfort analysis was conducted using the University of California at Berkeley Center for the Built Environment (CBE) Thermal Comfort Tool.[7] The monitored indoor temperature and humidity ratio during occupied and unoccupied periods for the month of January (representing the winter peak month) and July (representing the summer peak month) were averaged. Other inputs, shown in Table 22, including air velocity, metabolic rate, and clothing level were assumed and used with the indoor temperatures and humidity ratios for those hours in winter and summer. Details and description of inputs can be found on the CBE Thermal Comfort Tool website.

---

[6] http://www.mnshi.umn.edu/kb/scale/condensationresistance.html
[7] CBE Thermal Comfort Tool, https://comfort.cbe.berkeley.edu/

Table 22: Inputs to the CBE Thermal Comfort Tool

	Winter	Summer
Air velocity [fpm]	20	29.5
Metabolic rate [met]	1	1.1
Clothing level [clo]	1	0.5

The CBE Thermal Comfort Tool calculates the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD), the most widely used thermal comfort indices (Figure 13).

PMV is an index that aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale. Thermal equilibrium is obtained when an occupant's internal heat production is the same as its heat loss. The heat balance of an individual can be influenced by levels of physical activity and clothing insulation, as well as the parameters of the thermal environment. For example, thermal sensation is generally perceived as better when occupants of a space have control over indoor temperature (i.e., natural ventilation through opening or closing windows), as it helps to alleviate high-occupancy thermal expectations on a mechanical ventilation system. Within the PMV scale, +3 indicates "too hot," while -3 indicates "too cold."

Once the PMV is calculated, the PPD, an index that establishes a quantitative prediction of the percentage of thermally dissatisfied occupants (i.e., those who are too warm or too cold), can be determined. PPD essentially gives the percentage of people predicted to experience local discomfort. The main factors causing local discomfort are unwanted cooling or heating of an occupant's body. Common contributing factors are drafts, abnormally high vertical temperature differences between the ankles and head, and/or floor temperature.[8]

[8] What is PMV and PPD? https://www.simscale.com/blog/2019/09/what-is-pmv-ppd/

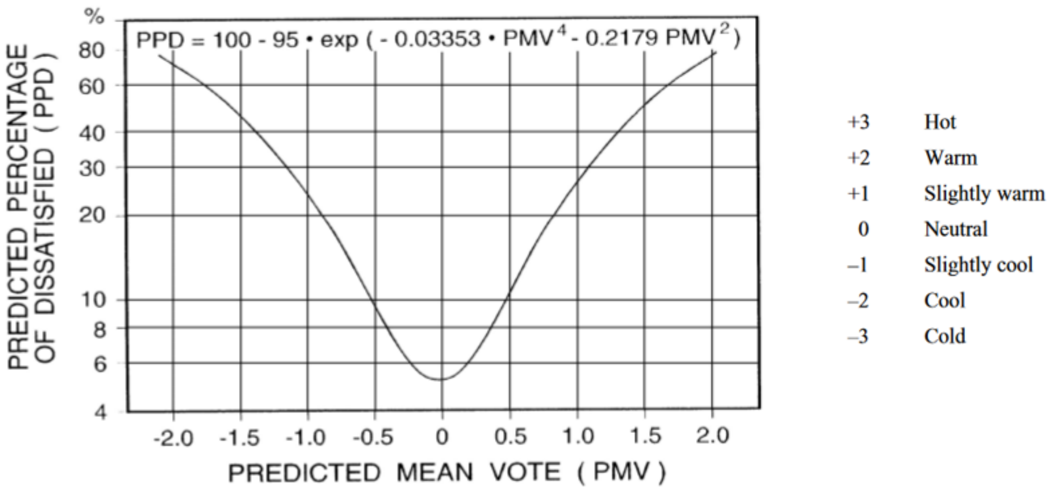

Figure 13: PMV and PPD scale (Source: ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy)

Figure 14 shows the plots of monitored indoor conditions from Building 41 during occupied and unoccupied periods in winter and summer within the comfort boundary on a psychrometric chart per ASHRAE Standard 55. It should be noted that none of the measured indoor conditions were expected to have been completely affected by the presence of the window systems being evaluated. However, the indoor temperatures and humidity levels are also expected to have been produced by the HVAC system and could have been the same with or without the new windows. Therefore, the thermal comfort analysis results may not present the effects caused by the windows alone, but include the other factors such as physical activity and clothing insulation, as well as the parameters of the thermal environment caused by HVAC operation.

The thermal comfort criteria are met as the results show that the majority of the conditions were within the comfort boundary. Details of the thermal comfort criteria and results can be found in Table 23. The results show that there were a small number of hours (5% to 10%) that were outside the comfort boundary. However, the PMV and PPD analysis presented in Figure 15 shows that the space in Building 41 was slightly cool and predicts that up to 25% of the occupants could experience some local thermal discomfort.

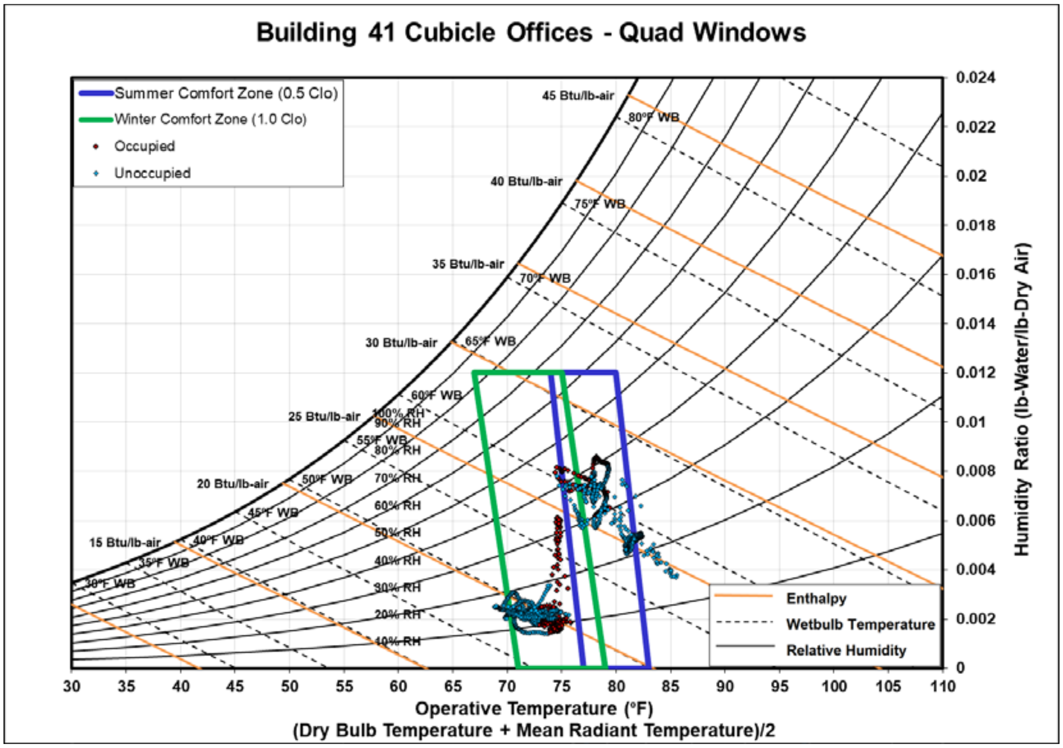

Figure 14: Building 41 – Indoor conditions and comfort boundary

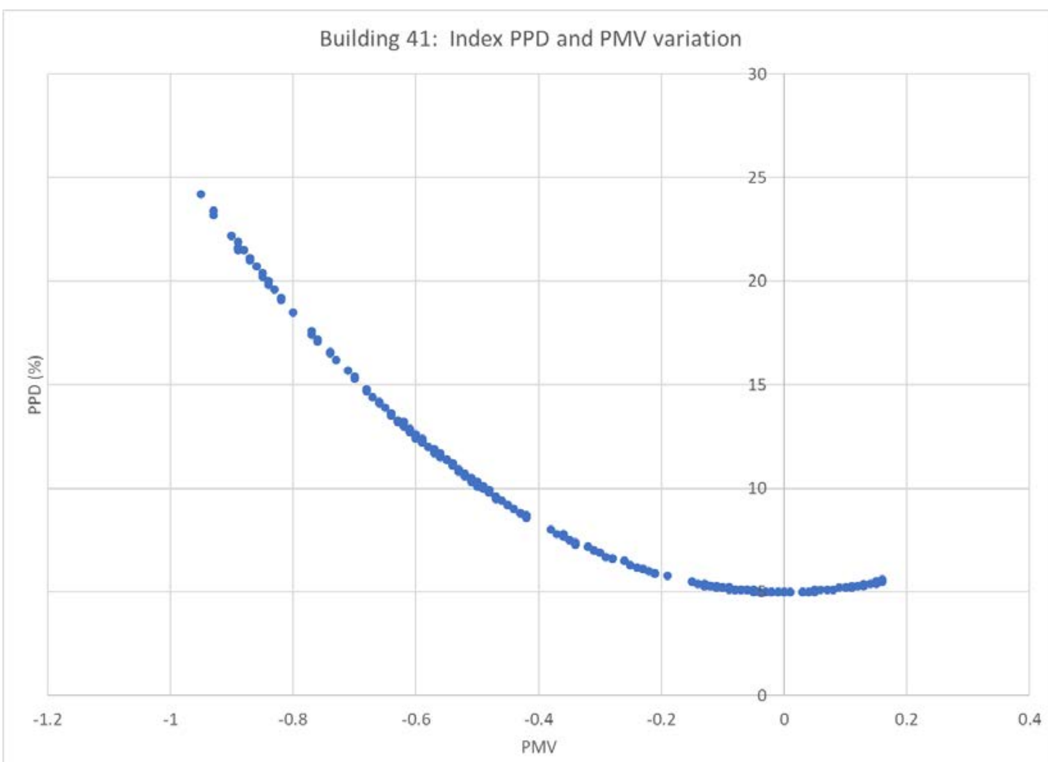

Figure 15: Building 41 – PMV and PMV analysis

Table 23: Quantitative Objectives and Results – Thermal Comfort

Quantitative Objectives	Metrics & Data	Success Criteria	Results
Thermal Comfort	Space temperature, °F and relative humidity, % Room side glass surface temperature, °F Wall temperature, °F	Space temperature and relative humidity are within occupant thermal comfort defined by ASHRAE Standard 55-2013	Quad-pane window A small number of hours (5% to 10%) were outside the comfort boundary

Temperature differences between the window surface and indoor air can also induce convective heat transfer through air movement, particularly during cold conditions. Drafts caused by the air movement can also contribute to occupant discomfort. Figure 16 demonstrates convective and radiative heat transfer effects on thermal comfort.

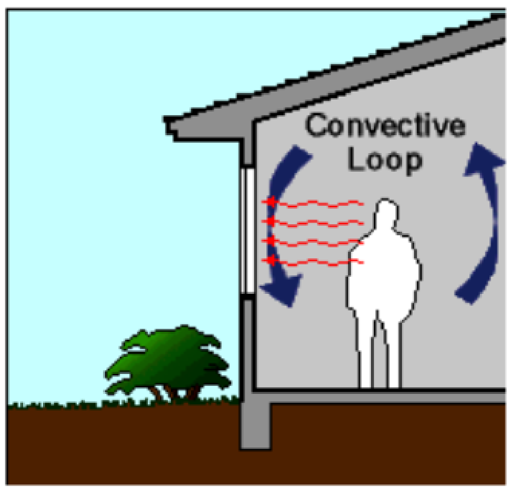

Figure 16: Convective and radiative heat transfer effects on thermal comfort (Source: Huizenga 1999)

In addition, measured temperatures at the center of the glass during the coldest period (Figure 17) show significant improvement over the quad-pane windows. The average temperatures (Table 24) at the center of the glass of quad-pane with film and quad-pane with thin glass are 66.1°F and 65°F. Large temperature differences increase radiant asymmetry that contributes to occupant discomfort. ASHRAE 55 Guidelines state that for vertical surfaces, radiant asymmetry should be kept to less than 18°F (Huizenga 1999). The vertical surface radiant asymmetry of the quad-pane with film and quad-pane with thin glass are approximately 3°F and 4°F, respectively, within the ASHRAE guidelines.

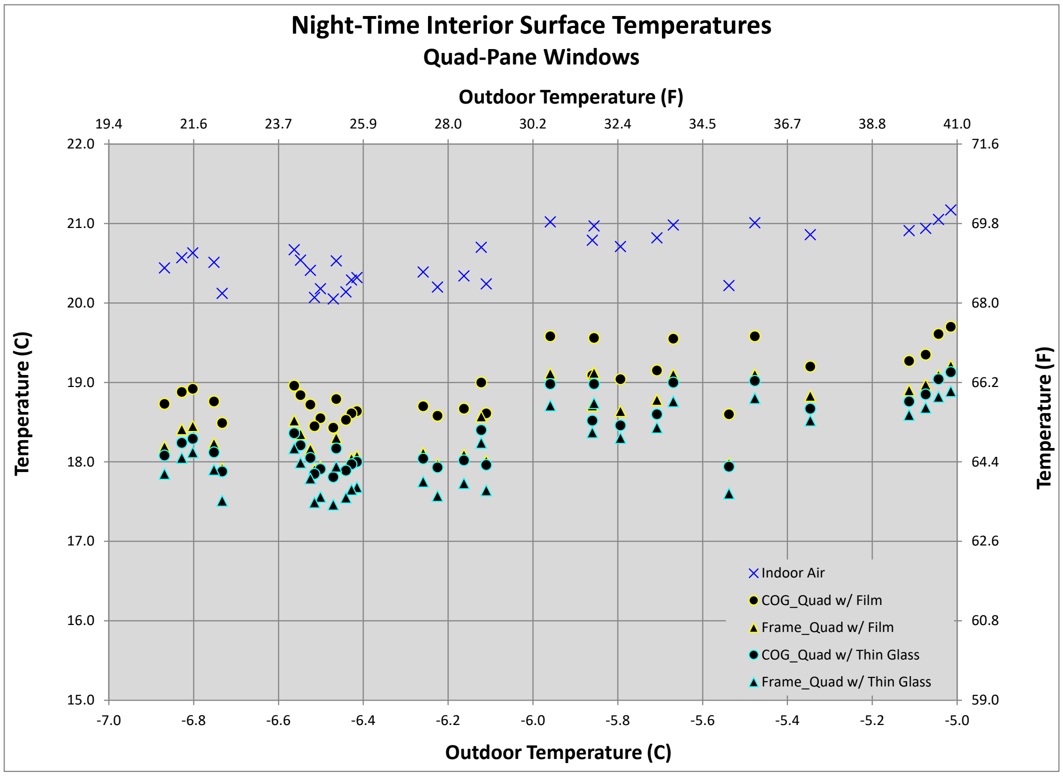

Figure 17: Frame, center of glass surface temperatures of quad-pane window during cold period

Table 24: Average Surface Temperatures During Cold Period

	Center of Glass		Frame	
	ºC	ºF	ºC	ºF
Quad-Pane With Film	18.9	66.1	18.4	65.2
Quad-Pane With Thin Glass	18.3	65.0	18.1	64.6

Mean Outdoor Temperature: -6.1˚C (21°F)
Mean Indoor Temperature: 20.6°C (69°F)

C. QUALITATIVE RESULTS

OCCUPANT SURVEYS

In addition to reduced energy consumption, the improved thermal performance of the high performance quad-pane windows results in warmer room-side glass surface temperatures under cold winter conditions, thereby improving thermal comfort for the occupants and increasing usable office space near windows. A survey was developed and distributed to occupants of the spaces in Building 41 to acquire feedback regarding the thermal comfort of post-installation conditions. Details of the occupant survey form can be found in Appendix D. Details of the qualitative thermal comfort criteria and results can be found in Table 23.

Occupant Survey Results and Findings

- Most survey respondents were positive and recommended the retrofit in the future.
- Thermal discomfort possibly already existed and may be caused by HVAC operation rather than by the windows.
- There is a glare issue when compared to electrochromic/thermochromic windows. However, window blinds were adjusted several times during the day to manually reduce the glare.
- A survey participant did not recommend the quad-pane window for the retrofit. The participant did not provide a reason. It could be due to the fact that the quad-pane replaced the existing electrochromic/thermochromic windows which have automatic tinting capability.

Table 25: Qualitative Objectives and Results – Thermal Comfort

Qualitative Objectives	Metrics & Data	Success Criteria	Results
Thermal Comfort	Tenant satisfaction survey	Improvement in tenant satisfaction with thermal conditions	**Building 41 for quad-pane window** Five surveys came back; 4/5 were positive and recommended the retrofit. 1/5 did not recommend. Thermal discomfort existed and may be caused by HVAC, not windows. Glare issue when compared to electrochromic/thermo-chromic windows. Blinds were adjusted during the day.

EASE OF INSTALLATION

This criterion looks at the ease of the installation of the technology. Replacement and installation of a quad-pane window is the same as for a typical window. A single quad-pane window was installed in less than a day. Details of the qualitative ease of installation criteria and results can be found in Table 26.

Table 26: Qualitative Objectives and Results – Ease of Installation

Qualitative Objective	Metrics & Data	Success Criteria	Results
Ease of Installation	Interview with installer Time required to install & configure Labor associated with install	<1 day to install	Quad-pane window installation is typical and it took within one day

DEPLOYABILITY

One of the main goals of this study was to evaluate the suitability for deployment of the quad-pane windows in GSA buildings across different climate zones. The key metric for determining suitability for deployment is a simple payback or SIR. The payback should be less than 15 years and the SIR should be greater than 1. To evaluate the deployment potential, the economic analysis was applied to ASHRAE climate zones 1A to 6A, where most GSA facilities are located. Energy cost savings were estimated for all levels of GSA utility rates (low, medium and high) as shown in Table 17. Table 27 shows that buildings with 50,000 to 500,000 square feet account for 57% of the portfolio.

Table 27: GSA Portfolio by Facility Size

Gross Area (sf)		Percent of Inventory
From	To	
1	10,000	9%
10,001	25,000	9%
25,001	50,000	10%
50,001	100,000	17%
100,001	500,000	40%
500,001	1,000,000	10%
1,000,001	1,000,001+	5%

For the analysis, a high performance double-pane window was used as a baseline with an assumption that the high performance double-pane window is minimally compliant for a GSA new construction for large office. Performance specifications of the windows used in the analysis are presented in Table 28.

Table 28: Window Performance Specification Used in Analysis

	U-value Btu/(h·ft2·F)	SHGC (low/high)	VT	CR
High Performance Double-Pane	0.32	0.67	n/a	n/a
Quad-Pane With Film	0.147	0.19/0.38	0.44/0.53	65
Quad-Pane With Thin Glass	0.168	0.20/0.46	0.47/0.56	67

For the same U-value of a quad-pane window, two SHGC levels (low, high) are offered by the manufacturer. Low and high SHGC for quad-pane with film are 0.19 and 0.38, and low and high SHGC for quad-pane with thin glass are 0.20 and 0.46, respectively. Windows with a high SHGC rating are more effective at collecting solar heat during the winter. Windows with a low SHGC rating are more effective at reducing cooling loads during the summer by blocking heat gain from the sun. For the analysis, an appropriate shading coefficient level was selected for a climate zone as presented in Table 29. Both low and high SHGC were used for the simulation for climate zones 3C and 4A as they are defined as mixed. The energy cost was estimated for three levels of GSA utility rates (low, mid, and high). Incremental costs for installing a high performance double-pane window were used in the analysis.

Table 29: Selected SHGC Levels for Climate Zones

Climate Zone	SHGC Level
1A Miami, Florida	low
2A Houston, Texas	low
2B Phoenix, Arizona	low
3A Atlanta, Georgia	low
3B Las Vegas, Nevada	low
3C San Francisco, California	low/high
4A Baltimore, Maryland	low/high
5A Chicago, Illinois	high
5B Boulder, Colorado	high
6A Minneapolis, Minnesota	high

Table 30 to Table 32 present estimated heating, cooling and fan energy savings of the quad-pane windows. Table 33 to Table 40 show the estimated total building energy and cost savings of the quad-pane windows at various utility rate levels. Table 41 presents estimated payback and savings-to-investment analysis results of the quad-pane windows for the various climate zones and utility rates. The highlighted values in the tables are the cases that meet the criteria for the payback period (less than 15 years) or SIR (greater than 1). The results show that both quad-pane with film and quad-pane with thin glass windows have similar (almost the same) thermal performance. The quad-pane with thin glass has a lower cost than the quad-pane with film. Therefore, the economics of the quad-pane with thin glass are slightly better.

Both quad-pane windows with film and thin glass are cost effective as an upgrade from high performance double-pane windows for all climate zones and all GSA utility rates. Significant thermal improvement and small incremental costs of updating quad-pane windows to high performance double-pane windows make them an optimal choice for window upgrade.

At current pricing, the quad-pane with thin glass configuration is more cost effective, but the suspended film version offers more versatility in low-e coatings, provides better ultraviolet light protection, and is a better option when tempered glass is a requirement. The film version is also lighter, about one-half lb. per square foot lighter when compared to thin glass.

The economic analysis and savings estimate results could be used for future screening of the technology. However, for a future retrofit project, a detailed study including energy modeling analysis of the window options for the specific building is recommended due to the fact that each building is unique. The results and findings of both quad-pane windows are summarized below.

Estimated Heating Energy

- Heating energy reduction between 24% and 99%
- Normalized heating energy savings of 0.6–5.0 kBtu/sf/yr

Estimated Cooling Energy

- Cooling energy reduction between 12% and 27%
- Normalized cooling energy savings of 0.5–2.5 kBtu/sf/yr

Estimated Fan Energy

- Fan energy reduction between 15% and 28%
- Normalized fan energy savings of 1.2–2.1 kBtu/sf/yr

Estimated Total HVAC Energy

- HVAC energy reduction between 19% and 34%
- Normalized fan energy savings of 5.0–8.5 kBtu/sf/yr

Estimated Total Building Energy

- Total building energy reduction between 7% and 12%
- Normalized fan energy savings of 5.0–8.5 kBtu/sf/yr

Estimated Total Building Energy Cost and Economics

- Normalized building energy savings:
    - $0.07–$0.13/sf/yr for low utility rate
    - $0.10–$0.19/sf/yr for medium utility rate
    - $0.15–$0.30/sf/yr for high utility rate
- Payback period:
    - 1.9–5.7 yr for low utility rate
    - 1.3–4.0 yr for medium utility rate
    - 0.8–2.6 yr for high utility rate
- SIR:

- 3.5–10.8 for low utility rate
- 5.0–15.5 for medium utility rate
- 7.7–24.3 for high utility rate

Table 30: Estimated Heating Energy, Normalized Heating Energy, and Heating Energy Savings

Climate Zone	Heating Energy (kBtu)			Normalized Heating Energy (kBtu/sf)			Heating Energy Savings (%)	
	High Performance Double-Pane Baseline	Quad With Film	Quad With Thin Glass	High Performance Double-Pane Baseline	Quad With Film	Quad With Thin Glass	Quad With Film	Quad With Thin Glass
1A Miami, Florida	318,192	199	284	0.64	0.00	0.00	99.9%	99.9%
2A Houston, Texas	866,087	324,836	326,485	1.74	0.65	0.65	62.5%	62.3%
2B Phoenix, Arizona	1,116,623	523,432	552,625	2.24	1.05	1.11	53.1%	50.5%
3A Atlanta, Georgia	2,922,234	1,942,456	1,939,234	5.86	3.90	3.89	33.5%	33.6%
3B Las Vegas, Nevada	1,699,256	935,296	931,524	3.41	1.88	1.87	45.0%	45.2%
3C San Francisco, California	1,297,173	328,987	325,964	2.60	0.66	0.65	74.6%	74.9%
4A Baltimore, Maryland	5,171,252	3,553,414	3,548,352	10.37	7.13	7.12	31.3%	31.4%
5A Chicago, Illinois	7,451,966	5,214,444	5,258,622	14.95	10.46	10.55	30.0%	29.4%
5B Boulder, Colorado	5,613,798	3,741,641	3,807,173	11.26	7.50	7.64	33.3%	32.2%
6A Minneapolis, Minnesota	10,376,199	7,889,469	7,904,861	20.81	15.82	15.85	24.0%	23.8%

Table 31: Estimated Cooling Energy, Normalized Cooling Energy, and Cooling Energy Savings

Climate Zone	Cooling Energy (kBtu)			Normalized Cooling Energy (kBtu/sf)			Cooling Energy Savings (%)	
	High Performance Double-Pane Baseline	Quad With Film	Quad With Thin Glass	High Performance Double-Pane Baseline	Quad With Film	Quad With Thin Glass	Quad With Film	Quad With Thin Glass
1A Miami, Florida	7,766,669	6,599,461	6,628,294	15.58	13.24	13.29	15.0%	14.7%
2A Houston, Texas	7,964,289	6,768,874	6,787,337	15.97	13.58	13.61	15.0%	14.8%
2B Phoenix, Arizona	5,444,262	4,367,465	4,367,058	10.92	8.76	8.76	19.8%	19.8%
3A Atlanta, Georgia	5,645,071	4,472,104	4,493,544	11.32	8.97	9.01	20.8%	20.4%
3B Las Vegas, Nevada	4,256,609	3,335,406	3,352,600	8.54	6.69	6.72	21.6%	21.2%
3C San Francisco, California	4,057,150	3,042,180	3,063,620	8.14	6.10	6.14	25.0%	24.5%
4A Baltimore, Maryland	4,684,908	3,424,823	3,451,343	9.40	6.87	6.92	26.9%	26.3%
5A Chicago, Illinois	2,273,785	1,924,382	1,995,326	4.56	3.86	4.00	15.4%	12.2%
5B Boulder, Colorado	2,431,558	2,016,718	2,093,150	4.88	4.04	4.20	17.1%	13.9%
6A Minneapolis, Minnesota	2,364,150	2,026,158	2,088,638	4.74	4.06	4.19	14.3%	11.7%

Table 32: Estimated Fan Energy, Normalized Fan Energy, and Fan Energy Savings

Climate Zone	Fan Energy (kBtu)			Normalized Fan Energy (kBtu/sf)			Fan Energy Savings (%)	
	High Performance Double-Pane Baseline	Quad With Film	Quad With Thin Glass	High Performance Double-Pane Baseline	Quad With Film	Quad With Thin Glass	Quad With Film	Quad With Thin Glass
1A Miami, Florida	3,544,182	2,725,467	2,741,324	7.11	5.47	5.50	23.1%	22.7%
2A Houston, Texas	3,506,980	2,696,843	2,710,520	7.03	5.41	5.44	23.1%	22.7%
2B Phoenix, Arizona	4,154,491	3,154,354	3,155,624	8.33	6.33	6.33	24.1%	24.0%
3A Atlanta, Georgia	3,508,032	2,670,570	2,684,929	7.04	5.36	5.39	23.9%	23.5%
3B Las Vegas, Nevada	4,070,059	3,014,570	3,032,171	8.16	6.05	6.08	25.9%	25.5%
3C San Francisco, California	3,223,318	2,318,645	2,333,886	6.46	4.65	4.68	28.1%	27.6%
4A Baltimore, Maryland	3,410,701	2,568,338	2,582,555	6.84	5.15	5.18	24.7%	24.3%
5A Chicago, Illinois	3,565,764	2,869,441	2,959,824	7.15	5.76	5.94	19.5%	17.0%
5B Boulder, Colorado	4,430,164	3,587,715	3,719,974	8.89	7.20	7.46	19.0%	16.0%
6A Minneapolis, Minnesota	3,895,216	3,210,977	3,312,962	7.81	6.44	6.64	17.6%	14.9%

Table 33: Estimated Total Building Energy

Climate Zone	High Performance Double-Pane Baseline			Quad With Film			Quad With Thin Glass		
	Electricity (kBtu)	Natural Gas (kBtu)	Total (kBtu)	Electricity (kBtu)	Natural Gas (kBtu)	Total (kBtu)	Electricity (kBtu)	Natural Gas (kBtu)	Total (kBtu)
1A Miami, Florida	33,382,138	547,668	33,929,806	31,131,451	229,656	31,361,107	31,183,875	229,741	31,413,616
2A Houston, Texas	33,620,230	1,117,893	34,738,123	31,282,562	576,661	31,859,223	31,318,750	578,301	31,897,051
2B Phoenix, Arizona	31,073,208	1,369,890	32,443,098	28,705,172	776,727	29,481,899	28,706,139	805,919	29,512,058
3A Atlanta, Georgia	30,798,948	3,212,209	34,011,157	28,356,139	2,232,432	30,588,571	28,398,999	2,229,209	30,628,208
3B Las Vegas, Nevada	29,327,064	1,979,582	31,306,646	27,081,789	1,215,642	28,297,431	27,121,721	1,211,869	28,333,590
3C San Francisco, California	28,246,836	1,591,593	29,838,429	25,963,952	623,427	26,587,379	26,008,566	620,403	26,628,969
4A Baltimore, Maryland	29,499,718	5,491,302	34,991,020	26,900,756	3,873,473	30,774,229	26,952,365	3,868,411	30,820,776
5A Chicago, Illinois	25,991,041	7,797,483	33,788,524	24,809,653	5,559,952	30,369,605	25,006,373	5,604,130	30,610,503
5B Boulder, Colorado	26,991,595	5,952,187	32,943,782	25,597,887	4,080,040	29,677,927	25,832,253	4,145,572	29,977,825
6A Minneapolis, Minnesota	26,474,778	10,740,550	37,215,328	25,322,015	8,253,819	33,575,834	25,510,242	8,269,202	33,779,444

Table 34: Estimated Normalized Building Energy, and Building Energy Savings

Climate Zone	High Performance Double-Pane Baseline			Quad With Film				Quad With Thin Glass			
	Electricity (kBtu/sf)	Natural Gas (kBtu/sf)	Total (kBtu/sf)	Electricity (kBtu/sf)	Natural Gas (kBtu/sf)	Total (kBtu/sf)	Savings (kBtu/sf)	Electricity (kBtu/sf)	Natural Gas (kBtu/sf)	Total (kBtu/sf)	Savings (kBtu/sf)
1A Miami, Florida	66.95	1.10	68.05	62.44	0.46	62.90	5.15	62.54	0.46	63.01	5.05
2A Houston, Texas	67.43	2.24	69.67	62.74	1.16	63.90	5.77	62.81	1.16	63.97	5.70
2B Phoenix, Arizona	62.32	2.75	65.07	57.57	1.56	59.13	5.94	57.57	1.62	59.19	5.88
3A Atlanta, Georgia	61.77	6.44	68.21	56.87	4.48	61.35	6.86	56.96	4.47	61.43	6.79
3B Las Vegas, Nevada	58.82	3.97	62.79	54.32	2.44	56.76	6.04	54.40	2.43	56.83	5.96
3C San Francisco, California	56.65	3.19	59.85	52.07	1.25	53.33	6.52	52.16	1.24	53.41	6.44
4A Baltimore, Maryland	59.17	11.01	70.18	53.95	7.77	61.72	8.46	54.06	7.76	61.82	8.36
5A Chicago, Illinois	52.13	15.64	67.77	49.76	11.15	60.91	6.86	50.15	11.24	61.39	6.37
5B Boulder, Colorado	54.14	11.94	66.07	51.34	8.18	59.52	6.55	51.81	8.31	60.13	5.95
6A Minneapolis, Minnesota	53.10	21.54	74.64	50.79	16.55	67.34	7.30	51.16	16.59	67.75	6.89

Table 35: Estimated Total Building Energy Cost – Low Utility Rate

Climate Zone	High Performance Double-Pane			Quad With Film				Quad With Thin Glass			
	Electricity ($)	Natural Gas ($)	Total ($)	Electricity ($)	Natural Gas ($)	Total ($)	Savings ($)	Electricity ($)	Natural Gas ($)	Total ($)	Savings ($)
1A Miami, Florida	762,909	3,021	765,929	711,472	1,267	712,739	53,191	712,670	1,267	713,937	51,992
2A Houston, Texas	768,350	6,166	774,516	714,925	3,181	718,106	56,410	715,752	3,190	718,942	55,574
2B Phoenix, Arizona	710,141	7,556	717,697	656,022	4,284	660,307	57,390	656,044	4,445	660,490	57,207
3A Atlanta, Georgia	703,873	17,719	721,591	648,045	12,314	660,359	61,232	649,025	12,296	661,321	60,270
3B Las Vegas, Nevada	670,235	10,919	681,154	618,922	6,705	625,627	55,527	619,834	6,685	626,519	54,635
3C San Francisco, California	645,547	8,779	654,327	593,375	3,439	596,814	57,513	594,394	3,422	597,817	56,510
4A Baltimore, Maryland	674,180	30,290	704,471	614,784	21,366	636,150	68,320	615,964	21,338	637,302	67,169
5A Chicago, Illinois	593,994	43,011	637,005	566,995	30,669	597,663	39,341	571,491	30,912	602,403	34,602
5B Boulder, Colorado	616,860	32,832	649,693	585,009	22,506	607,514	42,178	590,365	22,867	613,232	36,461
6A Minneapolis, Minnesota	605,049	59,245	664,294	578,704	45,528	624,232	40,062	583,006	45,613	628,619	35,675

Table 36: Estimated Normalized Total Building Energy Cost – Low Utility Rate

Climate Zone	High Performance Double-Pane			Quad With Film				Quad With Thin Glass			
	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Savings ($/sf)	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Savings ($/sf)
1A Miami, Florida	1.53	0.01	1.54	1.43	0.00	1.43	0.11	1.43	0.00	1.43	0.10
2A Houston, Texas	1.54	0.01	1.55	1.43	0.01	1.44	0.11	1.44	0.01	1.44	0.11
2B Phoenix, Arizona	1.42	0.02	1.44	1.32	0.01	1.32	0.12	1.32	0.01	1.32	0.11
3A Atlanta, Georgia	1.41	0.04	1.45	1.30	0.02	1.32	0.12	1.30	0.02	1.33	0.12
3B Las Vegas, Nevada	1.34	0.02	1.37	1.24	0.01	1.25	0.11	1.24	0.01	1.26	0.11
3C San Francisco, California	1.29	0.02	1.31	1.19	0.01	1.20	0.12	1.19	0.01	1.20	0.11
4A Baltimore, Maryland	1.35	0.06	1.41	1.23	0.04	1.28	0.14	1.24	0.04	1.28	0.13
5A Chicago, Illinois	1.19	0.09	1.28	1.14	0.06	1.20	0.08	1.15	0.06	1.21	0.07
5B Boulder, Colorado	1.24	0.07	1.30	1.17	0.05	1.22	0.08	1.18	0.05	1.23	0.07
6A Minneapolis, Minnesota	1.21	0.12	1.33	1.16	0.09	1.25	0.08	1.17	0.09	1.26	0.07

Table 37: Estimated Total Building Energy Cost – Medium Utility Rate

Climate Zone	High Performance Double-Pane			Quad With Film				Quad With Thin Glass			
	Electricity ($)	Natural Gas ($)	Total ($)	Electricity ($)	Natural Gas ($)	Total ($)	Savings ($)	Electricity ($)	Natural Gas ($)	Total ($)	Savings ($)
1A Miami, Florida	1,105,239	4,071	1,109,311	1,030,722	1,707	1,032,429	76,881	1,032,458	1,708	1,034,166	75,145
2A Houston, Texas	1,113,122	8,310	1,121,433	1,035,725	4,287	1,040,012	81,421	1,036,923	4,299	1,041,222	80,210
2B Phoenix, Arizona	1,028,794	10,184	1,038,977	950,391	5,774	956,165	82,812	950,423	5,991	956,414	82,563
3A Atlanta, Georgia	1,019,713	23,880	1,043,593	938,835	16,596	955,431	88,162	940,254	16,572	956,826	86,767
3B Las Vegas, Nevada	970,981	14,716	985,697	896,643	9,037	905,680	80,017	897,965	9,009	906,974	78,723
3C San Francisco, California	935,216	11,832	947,048	859,633	4,635	864,267	82,781	861,110	4,612	865,722	81,326
4A Baltimore, Maryland	976,697	40,822	1,017,520	890,649	28,795	919,445	98,075	892,358	28,758	921,116	96,404
5A Chicago, Illinois	860,530	57,966	918,496	821,415	41,333	862,748	55,748	827,929	41,661	869,590	48,906
5B Boulder, Colorado	893,657	44,249	937,905	847,513	30,331	877,844	60,061	855,272	30,818	886,091	51,815
6A Minneapolis, Minnesota	876,546	79,845	956,391	838,379	61,359	899,738	56,653	844,611	61,473	906,084	50,307

Table 38: Estimated Normalized Total Building Energy Cost – Medium Utility Rate

Climate Zone	High Performance Double-Pane			Quad With Film				Quad With Thin Glass			
	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Savings ($/sf)	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Savings ($/sf)
1A Miami, Florida	2.22	0.01	2.22	2.07	0.00	2.07	0.15	2.07	0.00	2.07	0.15
2A Houston, Texas	2.23	0.02	2.25	2.08	0.01	2.09	0.16	2.08	0.01	2.09	0.16
2B Phoenix, Arizona	2.06	0.02	2.08	1.91	0.01	1.92	0.17	1.91	0.01	1.92	0.17
3A Atlanta, Georgia	2.05	0.05	2.09	1.88	0.03	1.92	0.18	1.89	0.03	1.92	0.17
3B Las Vegas, Nevada	1.95	0.03	1.98	1.80	0.02	1.82	0.16	1.80	0.02	1.82	0.16
3C San Francisco, California	1.88	0.02	1.90	1.72	0.01	1.73	0.17	1.73	0.01	1.74	0.16
4A Baltimore, Maryland	1.96	0.08	2.04	1.79	0.06	1.84	0.20	1.79	0.06	1.85	0.19
5A Chicago, Illinois	1.73	0.12	1.84	1.65	0.08	1.73	0.11	1.66	0.08	1.74	0.10
5B Boulder, Colorado	1.79	0.09	1.88	1.70	0.06	1.76	0.12	1.72	0.06	1.78	0.10
6A Minneapolis, Minnesota	1.76	0.16	1.92	1.68	0.12	1.80	0.11	1.69	0.12	1.82	0.10

Table 39: Estimated Total Building Energy Cost – High Utility Rate

Climate Zone	High Performance Double-Pane			Quad With Film				Quad With Thin Glass			
	Electricity ($)	Natural Gas ($)	Total ($)	Electricity ($)	Natural Gas ($)	Total ($)	Savings ($)	Electricity ($)	Natural Gas ($)	Total ($)	Savings ($)
1A Miami, Florida	1,760,558	5,754	1,766,312	1,641,858	2,413	1,644,271	122,041	1,644,623	2,414	1,647,036	119,275
2A Houston, Texas	1,773,115	11,745	1,784,860	1,649,827	6,058	1,655,886	128,974	1,651,736	6,076	1,657,812	127,048
2B Phoenix, Arizona	1,638,786	14,392	1,653,178	1,513,897	8,160	1,522,057	131,121	1,513,948	8,467	1,522,415	130,763
3A Atlanta, Georgia	1,624,322	33,747	1,658,069	1,495,489	23,454	1,518,943	139,126	1,497,750	23,420	1,521,170	136,900
3B Las Vegas, Nevada	1,546,695	20,797	1,567,493	1,428,281	12,772	1,441,052	126,441	1,430,387	12,732	1,443,119	124,374
3C San Francisco, California	1,489,725	16,721	1,506,446	1,369,327	6,550	1,375,876	130,570	1,371,679	6,518	1,378,197	128,249
4A Baltimore, Maryland	1,555,801	57,692	1,613,493	1,418,733	40,695	1,459,428	154,065	1,421,455	40,642	1,462,096	151,396
5A Chicago, Illinois	1,370,755	81,920	1,452,676	1,308,449	58,413	1,366,862	85,813	1,318,824	58,877	1,377,701	74,974
5B Boulder, Colorado	1,423,524	62,534	1,486,058	1,350,020	42,865	1,392,885	93,172	1,362,381	43,553	1,405,934	80,123
6A Minneapolis, Minnesota	1,396,267	112,840	1,509,107	1,335,471	86,715	1,422,186	86,922	1,345,398	86,876	1,432,274	76,833

Table 40: Estimated Normalized Total Building Energy Cost – High Utility Rate

Climate Zone	High Performance Double-pane			Quad with Film				Quad with Thin Glass			
	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Savings ($/sf)	Electricity ($/sf)	Natural Gas ($/sf)	Total ($/sf)	Savings ($/sf)
1A Miami, Florida	3.53	0.01	3.54	3.29	0.00	3.30	0.24	3.30	0.00	3.30	0.24
2A Houston, Texas	3.56	0.02	3.58	3.31	0.01	3.32	0.26	3.31	0.01	3.33	0.25
2B Phoenix, Arizona	3.29	0.03	3.32	3.04	0.02	3.05	0.26	3.04	0.02	3.05	0.26
3A Atlanta, Georgia	3.26	0.07	3.33	3.00	0.05	3.05	0.28	3.00	0.05	3.05	0.27
3B Las Vegas, Nevada	3.10	0.04	3.14	2.86	0.03	2.89	0.25	2.87	0.03	2.89	0.25
3C San Francisco, California	2.99	0.03	3.02	2.75	0.01	2.76	0.26	2.75	0.01	2.76	0.26
4A Baltimore, Maryland	3.12	0.12	3.24	2.85	0.08	2.93	0.31	2.85	0.08	2.93	0.30
5A Chicago, Illinois	2.75	0.16	2.91	2.62	0.12	2.74	0.17	2.65	0.12	2.76	0.15
5B Boulder, Colorado	2.86	0.13	2.98	2.71	0.09	2.79	0.19	2.73	0.09	2.82	0.16
6A Minneapolis, Minnesota	2.80	0.23	3.03	2.68	0.17	2.85	0.17	2.70	0.17	2.87	0.15

Table 41: Estimated Simple Payback and Savings-to-Investment Ratio

Climate Zone	Low Utility Rate				Medium Utility Rate				High Utility Rate			
	Quad With Film		Quad With Thin Glass		Quad With Film		Quad With Thin Glass		Quad With Film		Quad With Thin Glass	
	Payback (yr)	SIR	Payback (yr)	SIR	Payback (yr)	SIR	Payback (yr)	SIR	Payback (yr)	SIR	Payback (yr)	SIR
1A Miami, Florida	4.2	4.7	2.4	8.4	2.9	6.9	1.7	12.1	1.8	10.9	1.0	19.2
2A Houston, Texas	4.0	5.0	2.2	8.9	2.8	7.3	1.5	12.9	1.7	11.5	1.0	20.5
2B Phoenix, Arizona	3.9	5.1	2.2	9.2	2.7	7.4	1.5	13.3	1.7	11.7	0.9	21.1
3A Atlanta, Georgia	3.7	5.5	2.1	9.7	2.5	7.9	1.4	14.0	1.6	12.4	0.9	22.0
3B Las Vegas, Nevada	4.0	5.0	2.3	8.8	2.8	7.1	1.6	12.7	1.8	11.3	1.0	20.0
3C San Francisco, California	3.9	5.1	2.2	9.1	2.7	7.4	1.5	13.1	1.7	11.7	1.0	20.6
4A Baltimore, Maryland	3.3	6.1	1.8	10.8	2.3	8.8	1.3	15.5	1.5	13.8	0.8	24.4
5A Chicago, Illinois	5.7	3.5	3.6	5.6	4.0	5.0	2.5	7.9	2.6	7.7	1.7	12.1
5B Boulder, Colorado	5.3	3.8	3.4	5.9	3.7	5.4	2.4	8.3	2.4	8.3	1.6	12.9
6A Minneapolis, Minnesota	5.6	3.6	3.5	5.7	4.0	5.1	2.5	8.1	2.6	7.8	1.6	12.4

IV. Summary Findings and Conclusions

This demonstration utilized several different evaluation criteria to assess the viability of quad-pane windows for GSA applications. Some of these assessments were performed with models, while others required onsite evaluations including time series measurements.

The quad-pane windows operated as intended and most evaluation criteria were met. Quad-pane windows can provide energy savings and can be more cost effective compared to high performance double-pane windows due to their superior thermal performance. Results, findings, and conclusions are outlined below.

- Quad-pane windows provide a cost effective and efficient way to improve thermal performance and occupant comfort.
- Quad-pane windows using suspended film or ultra-thin glass can significantly reduce overall window weight and structural requirements.
- Quad-pane windows are suitable for new construction and retrofits/replacements for residential, commercial, industrial, and high performance buildings.
- Both quad-pane with film and quad-pane with thin glass windows have similar (almost the same) thermal performance.
- Windows with the same U-value are manufactured with various levels of SHGC. SHGC should be appropriately selected for a climate zone. The lower the SHGC, the less solar heat it transmits and the greater its shading ability. A product with a high SHGC rating is more effective at collecting solar heat during the winter. A product with a low SHGC rating is more effective at reducing cooling loads during the summer by blocking heat gain from the sun.
- The calculated CR rating for the quad-pane window is 65–67, indicating superior condensation resistance.
- The thermal comfort criteria are met as the results show that the majority of the indoor conditions were within the comfort boundary. However, the PMV and PPD analysis shows that the space in Building 41 was slightly cool and predicts that up to 25% of the occupants could experience some local thermal discomfort, being slightly cool. However, thermal discomfort may have already existed, caused by other factors such as HVAC operation rather than the windows.
- Measured temperatures at the center of the glass of the quad-pane window during the coldest period were significantly warmer. Smaller temperature differences between window surface temperatures and room air temperature reduce vertical surfaces' radiant asymmetry to improve occupant comfort.
- To evaluate the deployment potential, energy savings and economic analyses were conducted for ten ASHRAE climate zones. The energy cost was estimated for three levels of GSA utility rates (low, mid, and high). The criteria are that the payback is less than 15 years and the SIR is greater than 1 for both types of quad-pane window. Using this criteria, both quad-pane windows are cost effective as an upgrade from high performance double-pane window for all climate zones and all GSA utility rates.
- The quad-pane with thin glass has a slightly lower cost than the quad-pane with film. Therefore, the economics of the quad-pane with thin glass are slightly better. The quad-pane with film offers greater versatility in low-e coatings, provides better ultraviolet light protection, and is a better option when

tempered glass is a requirement. It is also about one-half lb. per square foot lighter when compared to thin glass.

- The results were populated in a table for each building type and can be used for screening the technology and generating high-level energy savings estimates in the future. However, for a future retrofit project, a detailed study including energy modeling analysis of the window options for the specific building is recommended due to the fact that each building is unique.
- Significant thermal improvement and small incremental costs of the quad-pane window compared to the high performance double-pane window make them an optimal choice for window upgrade.

References

1. Apte J. 2006. “Real Prospect for Energy Efficiency in the United States.”

2. Curcija C., Goudey H., and Mitchell R. 2017. “Low-e Applied Film Window Retrofit for Insulation and Solar Control.”

3. Curcija C., Goudey H., Mitchell R., and Dickerhoff E. 2013. “Highly Insulating Window Panel Attachment Retrofit.”

4. Deru M., Field K. Studer D., Benne K., Griffin B., and Torcellini P. “U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.”

5. Fernandes L., Lee E., and Thanachareonkit, A. 2015. “Electrochromic Window Demonstration at the Donna Land Port of Entry.”

6. General Services Administration. 2013. “Hi-R Low-e Window Retrofit System.”

7. General Services Administration. 2014. “Electrochromic and Thermochromic Windows.”

8. General Services Administration. 2016. “Denver Federal Center Long-term Space Strategic Plan.”

9. Huizenga C. 1999. *Window Performance for Human Thermal Comfort*. Berkeley, CA: Lawrence Berkeley National Laboratory. https://gaia.lbl.gov/btech/papers/44032.pdf.

10. Lee E., Fernandes L., Goudey H., Johnsson C., Curcija C., Pang X., DiBartolomeo D., and Hoffmann S. 2014. “A Pilot Demonstration of Electrochromic and Thermochromic Windows in the Denver Federal Center, Building 41, Denver, Colorado.”

11. Lee E., Fernandes L., Touzani S., Thanachareonkit A., Pang X., and Dickerhoff D. 2016. “Electrochromic Window Demonstration at the 911 Federal Building, 911 Northeast 11th Avenue, Portland, Oregon.”

12. U.S. Department of Energy. 2010. “Highly-Insulating (R-5) Windows and Low-e Storm Windows Volume Purchase Program.” Washington, DC: U.S. Department of Energy. https://www.energystar.gov/sites/default/files/AAMA%20Attachment%20B%20-%20DOE%20BTO%20R-5%20Windows%20and%20Low-e%20Storm%20Windows%20Fact%20Sheet.pdf.

13. U.S. Energy Information Administration. 2018. “Updated Buildings Sector Appliance and Equipment Costs and Efficiencies.”

WEBSITES

1. Alpen High Performance Products, https://thinkalpen.com/

2. Center for The Built Environment Thermal Comfort Tool, https://comfort.cbe.berkeley.edu/

3. DOE EnergyPlus, https://energyplus.net/

4. Lawrence Berkeley Laboratory THERM, https://windows.lbl.gov/software/therm

5. Lawrence Berkeley Laboratory WINDOW, https://windows.lbl.gov/software/window

6. OpenStudio, https://www.openstudio.net/

7. Minnesota Sustainable Housing Initiative, http://www.mnshi.umn.edu/kb/scale/condensationresistance.html

8. What is PMV and PPD? https://www.simscale.com/blog/2019/09/what-is-pmv-ppd/

Appendix A - Details of Quad-Pane Windows

1. Quad-pane window with suspended coated film

Frame: Alpen “400 Series,” low profile, long strand pultruded fiberglass with foam insulation

Glass: Solar Control 9 (3/16” Cardinal 366 – Heat Mirror 88 – Heat Mirror 88 – 3/16” Clear)

Spacer: Stainless Steel

Gas: Krypton

2. Quad-pane window with ThinGlass

Frame: Alpen “400 Series,” low profile, long strand pultruded fiberglass with foam insulation

Glass: 3/16” Cardinal 366 – ThinGlass – ThinGlass – 3/16” Cardinal 180

Spacer: TriSeal Superspacer

Gas: Krypton

Appendix B - Example of NFRC Data for Quad-Pane Window

	Description		NFRC Full-Frame / Total Unit Performance				Air Infiltration @ 1.57psf	Center-of-Glass (COG) Performance			
	Glass Package	Makeup	U-factor	R-value	SHGC	VT		U-factor	R-value	SHGC	VT
9-Series TGQ	SolarControl-9 TGQ	Quad Pane with Thin Glass, Krypton Gas Fill	0.12	8.33	0.20	0.46	0.001 cfm/sqft	0.10	10.0	0.23	0.53
	HighGain-9 TGQ	Quad Pane with Thin Glass, Krypton Gas Fill	0.13	7.69	0.46	0.56		0.10	10.0	0.53	0.65

ZR-9	Description		NFRC Full-Frame / Total Unit Performance					Air Infiltration @ 1.57psf	Center-of-Glass (COG) Performance*			
	Glass Package	Use	U-factor	R-value	SHGC	VT	CR		U-factor	R-value	SHGC	VT
Fixed Low Profile *Suspended Film*	Balanced-9	Low U-factor High Visible Light	0.11	8.3	0.27	0.44	60	<0.01 cfm/ft^2	0.07	13.5	0.31	0.50
	SolarControl-9	Lowest Solar Heat Gain Coefficient	0.12	7.7	0.20	0.45	61		0.08	12.7	0.21	0.51
	HighGain-9	Maximum Passive Gain and Daylight	0.12	7.7	0.41	0.55	62		0.08	12.3	0.46	0.63
Fixed Low Profile *Thin Glass*	Balanced-9 TGQ	Low U-factor High Visible Light	0.12	8.3	0.30	0.48	76	<0.01 cfm/ft^2	0.09	11.1	0.33	0.53
	SolarControl-9 TGQ	Lowest Solar Heat Gain Coefficient	0.12	8.3	0.20	0.47	77		0.10	10.0	0.23	0.53
	HighGain-9 TGQ	Maximum Passive Gain and Daylight	0.12	8.3	0.47	0.58	80		0.10	10.0	0.53	0.65
Fixed High Profile *Suspended Film*	Balanced-9	Low U-factor High Visible Light	0.11	9.1	0.25	0.39	63	<0.01 cfm/ft^2	0.07	13.5	0.31	0.50
	SolarControl-9	Lowest Solar Heat Gain Coefficient	0.12	8.3	0.18	0.40	64		0.08	12.7	0.22	0.51
	HighGain-9	Maximum Passive Gain and Daylight	0.12	7.7	0.37	0.49	65		0.08	12.3	0.46	0.63
Fixed High Profile *Thin Glass*	Balanced-9 TGQ	Low U-factor High Visible Light	0.12	8.3	0.27	0.43	75	<0.01 cfm/ft^2	0.09	11.1	0.33	0.53
	SolarControl-9 TGQ	Lowest Solar Heat Gain Coefficient	0.12	8.3	0.18	0.42	78		0.10	10.0	0.23	0.53
	HighGain-9 TGQ	Maximum Passive Gain and Daylight	0.12	8.3	0.42	0.52	79		0.10	10.0	0.53	0.65
Casement *Suspended Film*	Balanced-9	Low U-factor High Visible Light	0.15	6.3	0.22	0.33	74	0.02 cfm/ft^2	0.07	13.5	0.31	0.50
	SolarControl-9	Lowest Solar Heat Gain Coefficient	0.15	6.3	0.16	0.35	74		0.08	12.7	0.22	0.51
	HighGain-9	Maximum Passive Gain and Daylight	0.16	6.3	0.32	0.42	73		0.08	12.3	0.46	0.63
Casement *Thin Glass*	Balanced-9 TGQ	Low U-factor High Visible Light	0.15	6.7	0.23	0.37	79	0.02 cfm/ft2	0.09	11.1	0.33	0.53
	SolarControl-9 TGQ	Lowest Solar Heat Gain Coefficient	0.15	6.7	0.16	0.36	79		0.10	10.0	0.23	0.53
	HighGain-9 TGQ	Maximum Passive Gain and Daylight	0.15	6.7	0.37	0.45	81		0.10	10.0	0.53	0.65

Appendix C - Infrared Thermography Field Measurements

The main purpose of taking IR images of quad-pane windows as part of the study was to quantify the thermal gradient near the edge of the glass. For overall monitoring, most thermocouples were attached to the glass and frame, but only one or two thermocouples were attached near the edge of glass for each monitored window. These point measurements are useful for comparison to thermal models. The IR images can provide pixel-by-pixel temperature measurements in a location where the temperature changes significantly in a small distance.

Figure 18 shows an IR image (left) of the two windows that were instrumented with thermocouples and the visual photo (right) of the same location. They were taken from the outside before sunrise on a cold morning. Figure 19 shows an IR image and visual photo also taken of one of the same windows from the inside. The window frame appeared as a colder surface than the glass. In addition, reflections of people in the room near the window can be seen on the IR image. Most glass is specularly reflective in infrared; therefore, it is not as simple as one might imagine to measure glass temperature with an IR camera.

A strip of blue masking tape was adhered to the glass and frame as shown in Figure 20. It provides a surface that is not reflective and does not change the temperature of the glass very much. Figure 20 shows that surface temperature varied almost 10°F over a small distance from the glass to the frame edge.

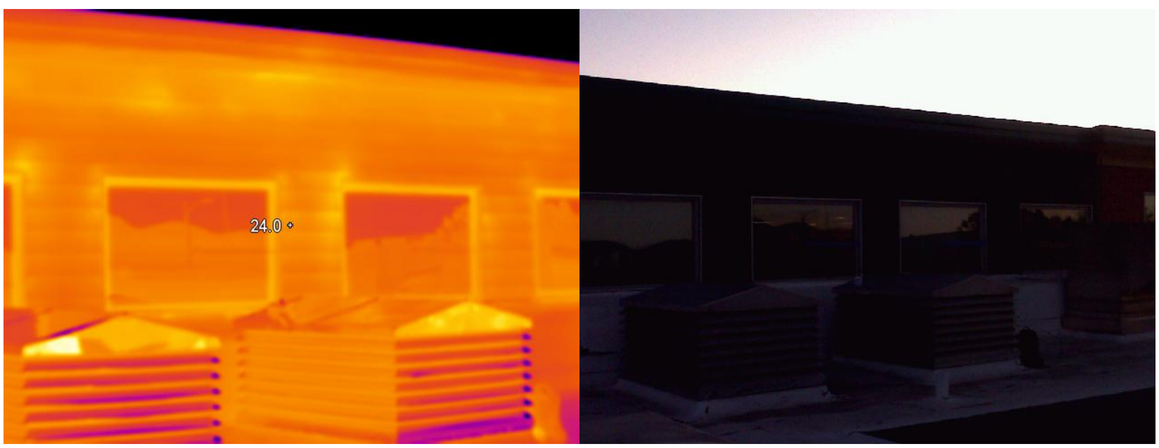

Figure 18: IR image (left) of the two quad-pane windows outside and the visual photo (right) of the same location (Credit: Ed Hancock)

Figure 19: IR image (left) of the two quad-pane windows inside and the visual photo (right) of the same location (Credit: Ed Hancock)

Figure 20: Thermocouples for temperature measurement on glass and frame (Credit: Ed Hancock)

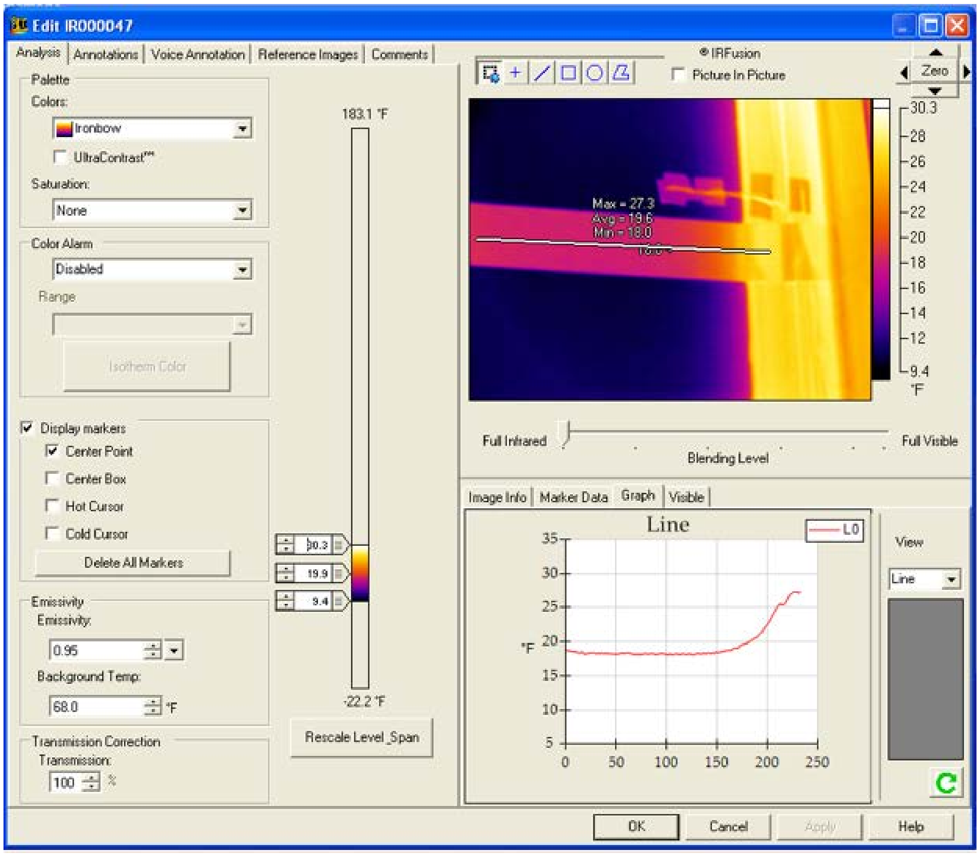

Figure 21: Surface temperature from the glass to the frame edge

Appendix D - EnergyPlus Modeling and Economic Analysis Assumptions

Table 42 summarizes the building characteristics of a DOE Commercial Reference Building model for a large office built from 1980–2004 in Climate Zone 5B. Three levels of GSA utility rates were used for economic and deployment potential analysis for the technology.

Table 42: Summary of EnergyPlus Model for Large Office

Large Office, 1980–2004 Construction		
	Weather Data	Climate Zone 5B
	Building Type	Large office
	Total Number of Buildings Modeled	1
	Building Areas	498,588 ft^2
	Above-Grade Floors	12
Building Footprint	Building Orientation	Plan North
	Zoning Pattern	Perimeter and core zones
	Perimeter Zone Depth	30 ft
	Floor to Floor Height	14 ft
	Floor to Ceiling Height	10 ft
	Roof Pitch	0°, flat roof
Roof	Construction	Typical insulation entirely above deck roof
	Roof	
	Insulation	R-18.83
Walls	Construction	Typical insulated steel framed exterior wall
	Exterior Insulation	Effective R-6.29
Exterior Doors	Door Type	Typical insulated metal door
Exterior Windows	Window Type	Double-pane window (baseline)
Window to Wall Ratio	Gross Window-Wall Ratio	38.05%
Building Operation	Schedule	7 a.m. to 5 p.m., Mon–Fri; closed on the weekends
Power Density	Lighting	1.50 W/ft^2
	Plug Loads	1.0 W/ft^2
HVAC Systems	System Type	VAV system with hot water reheat
	Cooling System	Chilled water, chillers

Large Office, 1980–2004 Construction		
	Chiller efficiency	0.7 kW/ton
	Heating System	Natural gas boiler
	Reheat Boiler efficiency	Hot water reheat 80%

Appendix E - Comfort Survey

GSA High Performance Windows Study – Comfort Survey

Instructions: Please check what applies and/or add clarifications. Your name will not be mentioned in the results. The research team may follow up for additional information. If you have any questions, please contact Kosol.Kiatreungwattana@nrel.gov.

Name:
Email:
Phone:

1. Where are you located?
    ☐ Building 41
    ☐ Building 53

2. How close to a window do you sit to perform the majority of your work?
    ☐ Less than 15 feet
    ☐ 15–30 feet
    ☐ Greater than 30 feet

3. How often are you thermally uncomfortable? Please select all that apply.
    Before retrofit
    ☐ Frequently too cold (4+ times per week)
    ☐ Occasionally too cold (1–2 times per week)
    ☐ Usually comfortable
    ☐ Occasionally too hot (1–2 times per week)
    ☐ Frequently too hot (4+ times per week)

    After retrofit
    ☐ Frequently too cold (4+ times per week)
    ☐ Occasionally too cold (1–2 times per week)
    ☐ Usually comfortable
    ☐ Occasionally too hot (1–2 times per week)
    ☐ Frequently too hot (4+ times per week)

4. Have you used a portable electric space heater in your work space to increase comfort?

Before retrofit	After retrofit
☐ Yes	☐ Yes
☐ No	☐ No

5. Have you used a fan in your work space to increase comfort?

Before retrofit	After retrofit
☐ Yes	☐ Yes
☐ No	☐ No

6. How many hours do you spend at your desk per day?
    ☐ 1 to 3 hours

☐ 3 to 5 hours
☐ 5 to 8 hours
☐ 8 or more hours

7. What is your preferred position of the window in relation to your desk?
   ☐ Behind me
   ☐ To one of my sides
   ☐ In front of me, behind the computer screen

8. How often did windows cause visual discomfort such as glare?

Before retrofit	After retrofit
☐ Frequently too bright	☐ Frequently too bright
☐ Occasionally too bright	☐ Occasionally too bright
☐ Never too bright	☐ Never too bright

9. What is your preferred position for the window blinds in your work space? Please select all that apply.

Before retrofit	After retrofit
☐ Up, clear window view	☐ Up, clear window view
☐ Partially down	☐ Partially down
☐ Fully down	☐ Fully down
☐ No preference	☐ No preference
☐ No window/blind in my workspace	☐ No window/blind in my workspace

10. How often do you adjust the position of the window blinds in your work space?

Before retrofit	After retrofit
☐ Frequently adjust blinds	☐ Frequently adjust blinds
☐ Occasionally adjust blinds	☐ Occasionally adjust blinds
☐ Never adjust blinds	☐ Never adjust blinds
☐ No window/blind in my workspace	☐ No window/blind in my workspace

11. What factors motivate your adjustment of the window blinds in your work space?
    ☐ Adjusting light level (glare control)
    ☐ Thermal management
    ☐ Privacy
    ☐ No window/blind in my workspace
12. Have you noticed the windows as being a cause of thermal discomfort before?
    Before retrofit
    ☐ Yes, please describe:
    ☐ No

    After retrofit
    ☐ Yes, please describe:
    ☐ No

13. What garments do you typically wear in the office in the winter?
    - ☐ Jacket
    - ☐ Light sweater or long-sleeved top
    - ☐ Short-sleeved top

14. What is your gender?
    - ☐ Male
    - ☐ Female

15. If you were to guess your metabolic rate while working, it would resemble which of the following for the majority of the time?
    - ☐ Seated, quiet
    - ☐ Standing relaxed
    - ☐ Walking slowly
    - ☐ Typing
    - ☐ Lifting/packing

16. How would you characterize the visual appearance of the window retrofit?
    - ☐ No noticeable difference in appearance
    - ☐ Noticeable, but acceptable difference in appearance
    - ☐ Negative impact on appearance

17. Based on your experience with the window retrofit in your building, would you recommend similar retrofits elsewhere?
    - ☐ Strongly recommend
    - ☐ Recommend
    - ☐ No opinion
    - ☐ Do not recommend