Prepared for the General Services Administration
By Lawrence Berkeley National Laboratory - Windows and Envelope Materials Group

November 2014

Liquid-Applied Absorbing Solar Control Window Film Retrofit

Charlie Curcija, Principal Investigator
Howdy Goudey
Robin Mitchell
Leandro Manes
Stephen Selkowitz

GPG

Green Proving Ground Program

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 Lawrence Berkeley National 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 Lawrence Berkeley National 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 Lawrence Berkeley National Laboratory.

The work described in this report was funded by the U.S. General Services Administration (GSA) [and the Federal Energy Management Program of the U.S. Department of Energy] under interagency agreement number PX0013877, and task order number GS-P-00-12-CY-0046.

ACKNOWLEDGEMENTS

The demonstration facility was the GSA’s Goodfellow Federal Center, St. Louis, Missouri.

This project was supported by Kevin Powell and Michael Lowell of the GSA-Public Buildings Service (PBS)-Green Proving Ground National Program Team. In addition, the project was supported by GSA Region 6, Chris Cockrill and Perry Boeschen.

Special thanks and appreciation to the GSA staff, Larry O’Neill, Terry Townsend, and Tara Van Bibber of GSA’s St. Louis West Field Office, St. Louis Missouri, and the tenants in building 110, for their support of this project.

For more information contact:

Kevin Powell
Program Manager, Green Proving Ground
Office of the Commissioner, Public Buildings Service
U.S. General Services Administration
50 United Nations Plaza Room: 3667
San Francisco, CA 94102-4912
Email: kevin.powell@gsa.gov

Table of Contents

I. Executive Summary

BACKGROUND

Nationwide, on an annual basis, windows in commercial buildings are responsible for 0.96 quadrillion BTUs (quads) of heating energy and 0.52 quads of cooling energy (Apte 2006). This is equal to about 1.5% of the total energy consumption by the United States in 2011, and is equivalent to the energy consumed by more than 8 million U.S. households (US EIA 2012). There is substantial potential for reducing both the heating and cooling energy use in existing commercial buildings associated with windows by using a wide range of technologies and strategies. This study focuses on solar control window retrofit technology that primarily targets the energy savings potential of reducing the cooling load. A previous study estimated that there is a potential to save 0.32 quads (or 62%) of the window-related cooling energy if the entire U.S. commercial building stock were to be retrofitted with typical solar control, low-e double pane glass units (Apte 2006). Replacing the entire window captures the greatest savings, but can be very expensive. Retrofit applied films do not usually change the insulating value of a window; however, they directly reduce the solar gain through the window. A significant portion of potential cooling energy savings is available through reducing the solar heat gain properties of a window, which can be accomplished with a solar control film retrofit, applied directly to existing glass. Retrofit films have a much less complicated, and less expensive, installation than a complete window replacement. It is important to recognize that reducing solar gain through the window, while it saves cooling energy during portions of the year, can contribute to increased heating energy consumption in winter, such that the annual energy performance of the retrofit for the particular building and climate must be considered. Solar control films are often applied to improve thermal comfort of occupants near the window and to reduce glare from high transmission glazing. A larger potential for energy savings is expected for a solar control film retrofit when the building is in a warmer climate with mild winters and the building is cooling load dominated as a result of internal loads, window area, orientation, solar exposure, and other building and user specific factors.

The U.S. General Services Administration (GSA) is a leader among federal agencies in aggressively pursuing energy efficiency opportunities for its facilities and installing renewable energy systems to provide heating, cooling, and power to these facilities. GSA's Public Buildings Service (PBS) has jurisdiction, custody or control over more than 9,600 assets and is responsible for managing an inventory of diverse Federal buildings totaling more than 354 million square feet. GSA has an abiding interest in examining the technical performance and cost-effectiveness of different energy-efficient technologies in its existing building portfolio, as well as in those buildings currently proposed for construction. Given that the large majority of GSA's buildings include office spaces, identifying appropriate energy-efficient solutions has been a high priority for GSA, as well as for other Federal agencies. Recent legislation and executive orders mandate strong energy use reductions in Federal buildings in coming years. It is expected that GSA's large portfolio of buildings in warmer climates would benefit from energy savings potential associated with solar control film retrofits.

OVERVIEW OF THE TECHNOLOGY AND TEST SITE

This study evaluates a surface-applied solar control film. The family of surface-applied film products is often referred to simply as films or applied films. The particular window retrofit film technology examined in this study distinguishes itself from traditional applied films for windows, in that it is applied in place on the existing glass as a liquid, and hardens into a film that is adhered to the existing glass. The liquid contains a nano-particle suspension that provides moderately high light transmission but absorbs strongly in the near infrared part of the solar spectrum. The finished appearance is similar to competitive applied window film products based on plastic substrates. Most existing surface-applied solar control films consist of plastic substrate films that are adhered to the existing glass surface. Often these plastic film products have integrated factory applied coatings to achieve desired optical properties. Applied films can be designed to absorb and reflect visible light, and other portions of the solar spectrum, to various degrees, depending on the properties of the product.

For installation of the film in this study, the installer cleans and masks off the window frame before pumping the liquid onto the glass with an applicator nozzle. A thin uniform liquid sheet flows down the glass by gravity and cures in 30 minutes to form a durable window film with solar control optical properties. The application process involves minimal disruption to building occupants compared to a complete window glazing and frame replacement, and installation can take place after work hours, with minimal loss of business hour occupancy or productivity. The typical cost of materials and installation for this retrofit is specified by the manufacturer to be \$10/ft^2. There are opportunities for this price to come down with future domestic production that is not subject to import costs (projected to be as much as a 20-25% cost reduction). The manufacturer states that 20-40% heating and cooling energy savings can be expected when using this liquid applied film.

The liquid applied solar control film was installed on a selection of windows in a 135,500 ft^2, 3 story, GSA office building in St. Louis, MO. Out of approximately 4,700 ft^2 of double glazed window area in the building, a total of 25 windows were coated, comprising a combined glass surface area of about 500 ft^2 and a window-to-wall area ratio of 30-40% in the areas studied. The coated windows were distributed in five zones, mostly small enclosed offices, each with a floor area of approximately 150 ft^2. Each of the five zones with coated windows had a corresponding reference or control zone, a separate enclosed space with an equivalent untreated window area, floor area and solar exposure. These corresponding zones were monitored alongside the coated areas in order to provide an energy performance baseline for comparison. The windows in the reference zones (control windows) received no window film retrofit. The energy monitoring period for all zones extended from February to August 2013, allowing evaluation of the product during both heating and cooling seasons. The St. Louis climate was also selected to provide a mixture of heating and cooling load conditions, to evaluate the claims of both heating and cooling energy savings. A cooling dominated climate would have been selected if the study was looking exclusively cooling load reduction.

A solar control applied window film works by reducing the transmission of solar radiation through the window, either by increasing the solar reflection or absorption properties of the glazing system. The most effective coatings and films reflect solar energy back to the exterior environment. If the film absorbs energy, some of the absorbed energy may ultimately reach the occupied space and present additional cooling load to the building. The product examined in this study is a “spectrally selective” absorbing film, providing high transmission in the visible spectrum and high absorption in the solar infrared spectrum. Human eyes are not sensitive to solar infrared energy (also known as near infrared radiation, or NIR), so the film appears transparent. However, since roughly half the energy in the solar spectrum is infrared radiation, a spectrally selective film can reduce solar gain without reducing visible light transmission. The manufacturer of the product used in this study offers two formulations with differing optical properties. The version of the film used in this study (when installed on a single layer of clear glass) has a solar transmission of 0.36 and visible transmission of 0.64. This is the more absorbing version of the liquid applied window films offered by this manufacturer, and it includes more absorption in the visible spectrum than the higher transmission version.

There is a mature market of existing competitive applied film products for solar control through windows that is relevant to the film in this study. Applied film solar control retrofit products are typically based on thin flexible plastic substrates that are adhered to the interior surface of existing glass. Applied films are available with a wide array of optical properties, including absorbing and reflective optical properties. These products can have an appearance nearly identical to clear glass, or they can include visible tints and colors. Some of the films reduce visible and infrared light roughly equally, as in the case of a flat spectrum tint or a visible mirror-like film. Many competitive applied films are spectrally selective like the subject film. They block more solar radiation in the near infrared portion of the solar spectrum compared to the visible, maintaining a high visible light transmittance while providing solar control. Some of these films reduce transmission by absorbing the radiation like the liquid applied film, while others reduce transmission by reflecting more of the incident radiation back toward the outside environment. Installed costs of applied films are typically between \$6.40/ft^2 for simple tinted films to \$10/ft^2 for spectrally selective reflective films (the same cost currently reported for the subject film in this study). Although the liquid applied film application is significantly different from plastic substrate applied films, the installation is otherwise similar from the point of view of building occupants. Both procedures require cleaning the existing glass and both can be accomplished in a relatively short time after work hours, with minimal disruption to building occupants during business hours. A professional commercial installation of a traditional plastic applied film will typically carry a 6-15 year warranty and many installations will be functional beyond that time period. With proper installation it is difficult to distinguish the applied film from conventional tinted or reflective glass. Poor preparation and installation can lead to bubbles, and eventually peeling of the applied film. Fading and crazing of plastic applied films can be a long term durability issue, particularly if a low quality film is used. Because it is a relatively new product on the market, there is no data available regarding the long term durability of the liquid applied film used in this study; however, the manufacturer offers a 15 year warranty. The nature of the liquid applied installation and the direct, durable bond to the glass suggests it may be less likely to experience the bubbling and delamination failures that can occur with plastic applied films when improperly installed. However, just as with the plastic substrate applied films, improper installation of the liquid applied film may lead to visible flaws or premature failure. Both film installation techniques rely on attentive quality control by the installer for the best results. No visible failures were observed in the liquid applied film over the 10 month observation period of this study.

The overall solar control performance of a window is typically reported as a solar heat gain coefficient (SHGC). This metric includes the performance of all the layers in a glazing system and characterizes the total fraction of incident solar energy that is transferred through the glazing system. Incident solar energy can be 1) directly reflected away from the glazing system, 2) absorbed on one or more glazing layers, or 3) transmitted into the room. Solar energy that is absorbed in a glazing layer may eventually be dissipated outside the glazing unit by convection, conduction and long wave radiation, or it can enter the room by the same processes. The ratio of the absorbed energy flowing inside, versus that which flows outside, is determined by other aspects of the glazing assembly such as the surface emittance of glazing layers, the location of solar absorbing layers in the glazing assembly, gas fills, etc. It is important to recognize that the optical properties of a retrofit film layer are not a complete performance indicator for a particular installation. Ultimately, the SHGC performance of the window system, and therefore cooling load reduction potential, will be determined by both the film properties and its context in the overall glazing system in which it is used. For instance, an absorbing film retrofit product will have a lower solar control impact when mounted on the room side of a double glazing compared to the same film applied on single glazing because of the relative positions of the absorbing and insulating layers in the glazing system. These differences can be directly seen in the relative SHGC values calculated for the complete glazing systems.

The existing windows in the subject building are double glazed (with no low-e coating). The outer pane of glass has an existing bronze tint as a solar control measure, which is typical of many older commercial buildings. An absorbing film applied on the interior of a double glazing is not expected to enable strong reduction of the SHGC because a larger fraction of the energy absorbed in the film will propagate to the interior, as it is trapped behind the insulating layer of the double glazing. The same absorbing applied film, applied instead to the outer surface of the outer glazing, will have a larger impact on cooling savings. For this reason, the study included an exploration of both interior and exterior applied films to demonstrate the impact on energy use associated with the location of an absorbing film on a dual pane window. It should be noted that although the film used in this study was installed on the exterior side of some of the window test zones in the subject building, the formula of the film was not intended for exterior use. However, the manufacturer reports that a similar product is under development for exterior use. Exterior applied films are subject to more challenging durability factors of solar radiation, rain, and physical abrasion, as well as being more difficult to prepare and apply on multi-story buildings. There are commercially available plastic substrate applied films for exterior applications, enabling stronger solar gain control with an absorbing product on existing double glazing.

The insulating value of a window (heat transfer related to indoor/outdoor environmental temperature difference) is typically reported as a heat transfer coefficient or U-factor, in BTU/hr-ft^2-F, where a smaller number indicates a better insulator. The U-factor of a base window is unchanged by application of most retrofit applied films, unless the film has a significantly lower surface emittance than typical glass (0.84). The film used in this project has a slightly higher emittance than glass, resulting in higher thermal radiation heat transfer, so there is actually a very small reduction in the insulating value of retrofitted windows although this would not present a measurable change in the test building. While most traditional applied films also do not have a strong impact on the insulation properties of a window, there are now two new classes of applied films with insulating benefits. There are some applied films with a moderate emittance (~0.5) and a few with a very low emittance (~0.05), providing significant insulation benefits. These low-emittance surfaces facing the interior also help to further lower the SHGC, as a greater fraction of the energy absorbed in the films is rejected to the outside.

PROJECT RESULTS/FINDINGS

The liquid applied solar control film technology that was the subject of this study did not produce measurable total energy savings for the retrofitted building in St. Louis, MO, when applied, as intended, to the interior of the existing double pane bronze tint windows. Some zones showed small cooling energy savings (~8% or less), while other zones had no cooling savings and the increased heating energy consumption associated with the film exceeded any cooling energy savings in all cases. Total energy consumption (heating plus cooling) increased 10% or greater in those zones with the interior applied film.

While three of the five monitored zones in the St. Louis office had the liquid applied film installed on the interior side of the existing double pane windows (the intended position for this product), in the other two zones we explored the performance implications of installing the same film on the exterior side of the existing double pane windows. The measured data confirmed the engineering calculations based on measured film properties, that an absorbing film placed on the interior of a double glazed window will have minimal savings and show less cooling load impact than the identical film applied to an exterior glass surface. In the cases with the film applied to the exterior of the bronze double pane base window, measured cooling energy savings averaged about 30% for both of the exterior coated monitored zones over the February to August monitoring period. However, even though this retrofit position demonstrated a much larger cooling energy savings potential compared to the interior film position, the passive solar heating energy sacrificed during the test period increased the required heating and still outweighed the energy savings on cooling, for this particular building and climate. Total thermal energy consumption (heating plus cooling) increased for exterior applied films by 3-7%, in both monitored zones.

Table E1. Measured energy consumption change for liquid applied solar control film in St. Louis, MO for representative monitored zones (negative % change values represent energy savings)

	Interior film on double glazing (test group 4)			Exterior film on double glazing (test group 2)		
	measured kWh delivered		percent change	measured kWh delivered		percent change
	Control	Interior film		Control	Exterior film	
Zone Heating Energy	123	430	250% ↑	621	1100	77% ↑
Zone Cooling Energy	1688	1555	-8% ↓	1527	1109	-27% ↓
Total Energy	1810	1986	10% ↑	2148	2209	3% ↑

The net energy comparisons in Table E1 were computed on the basis of the measured thermal energy of heating and cooling air flows at the variable air volume (VAV) box serving each zone. Thus, the zonal energy differences measured are representative of the different thermal energy flows through the windows in the coated and uncoated zones. To convert zonal energy flows to building level consumption (and energy cost) requires the introduction of other factors, such as heating and cooling equipment efficiency, the relative cost of fuel types, and time of use electricity pricing. Since there were no measurable net savings, we did not explore these additional factors in detail as they were unlikely to change the study conclusions. A rough analysis including these factors, to the extent possible with the limited information available, indicates that the conclusions would not change. Cooling system efficiencies are generally larger than heating efficiencies, but the cost of electricity is generally higher than the cost of gas. These effects nearly cancel each other for typical scenarios. Because the total energy consumption increased in both cases (for both interior and exterior liquid applied film), the total energy cost associated for the windows with applied film is expected to go up and there is no energy payback for the subject film in the particular building and climate studied with this test installation.

Although the installed solar control film did not produce energy savings, as tested, in this particular St. Louis building; for different buildings, with different base windows, in other climates, we would expect to see useful energy savings. The St. Louis climate was selected for the study to have access to a mixed heating and cooling demand in order to explore the manufacturer's claim of both heating and cooling energy savings.

To explore the potential in other climates and compare the subject film to competing products, the annual energy consumption for a generic commercial building perimeter zone was calculated for a selection of climates, base windows, and applied film products using the COMFEN software tool, which uses the EnergyPlus simulation engine (Table E2). Interior retrofits on single glazing, particularly clear single glazing, using the properties of the subject film demonstrate significantly higher energy savings potential than retrofitting double glazing. In warmer climates with mild winters (such as Houston, Phoenix and Miami – the cities chosen for this computer simulation study), the energy modeling results showed potential heating, ventilation and air conditioning (HVAC) energy and cost savings of about 20% for the subject film. The subject film was compared to two types of existing plastic substrate applied films, a simple tinted film and a higher performance spectrally selective applied film. The absorbing liquid applied film outperformed the less expensive, simple applied film tint in all the cases modeled. However the reflective, spectrally selective, applied film outperformed the subject film in all the cases modeled. These films are available from several suppliers at a similar total cost to the subject film. There are some subtle aesthetic and functional factors that may differentiate these two competing products in some applications, such as the external visible appearance of a reflective versus absorbing film, which might be important for a historic building, as well as issues of where the reflected energy is directed. A building with complicated wood window trim may experience a higher maintenance demand if additional reflected solar energy is directed onto the trim. Any spectrally selective film (whether plastic substrate or liquid applied) will provide more daylighting to the space, potentially reducing electric lighting requirements; however, this higher visible light transmission may also be associated with a greater likelihood of visible glare conditions compared to a film that is more heavily tinted, although there are usually also shades or blinds in place to address glare control.

Table E2. Annual energy computer modeling results for different base windows, climates and retrofit products, combined heating and cooling energy (positive numbers are energy savings)

Simulated results for a generalized commercial building perimeter zone		St. Louis		Houston	
Base Window	Film Type	Total Energy %savings	Total Cost %savings	Total Energy %savings	Total Cost %savings
Single Clear	Liquid applied absorbing film	12%	21%	19%	22%
	Reflective applied film	22%	30%	26%	28%
	Absorbing applied film	8%	12%	11%	12%
Double Bronze	Liquid applied absorbing film (interior)	3%	7%	7%	7%
	Liquid applied absorbing film (exterior)	6%	15%	15%	17%
	Reflective applied film	9%	14%	13%	13%
	Absorbing applied film	1%	3%	3%	3%

The annual energy savings results from COMFEN were slightly different than the energy savings from measured energy use for the case study in St. Louis. This is not unexpected as the COMFEN model used parameters for a typical office building perimeter zone and did not attempt to exactly represent all the details of the actual building tested in St. Louis (including shading type and operation, internal loads and occupant behavior, conditioning equipment details, etc.) However, the trends regarding interior and exterior placement of the film are similar, and the relative performance associated with climate and base window conditions are clearly revealed by this simulation exercise. The manufacturer's claim of both heating and cooling energy savings of 20-40% was not supported by the measured data or simulation results. Heating energy never decreased for windows with the subject film. The magnitude of increased heating demand with a retrofit film varies substantially with climate, internal loads and orientation.

High interior glass surface temperatures of 120–140 °F (50–60°C) were measured on the windows with films installed on the interior side. While elevated glass temperatures can pose a thermal comfort issue, occupants did not report increased discomfort, and globe radiant temperature measurements did not suggest an appreciable higher radiant temperature in rooms with interior absorbing films. This may be because the occupants were sufficiently distant from the windows or screened from the interior window glass temperature by the louvered blinds installed over them (which were typically down), or the distance to the window and the action of the air conditioning system diminished the effect. The measured glass temperatures were consistent with the WINDOW7 glazing performance modeling predictions.

A web-based survey was distributed to occupants of the retrofitted offices to acquire feedback regarding their thermal comfort before and after the retrofit. The results of the survey are limited, and should not be considered statistically significant, because of the inherently small potential occupant sample size associated with this study. Only 3 survey responses were received (there were only 4 private offices and 1 training/multipurpose room that received the window treatment). Occupants did not object to the aesthetics of the installations (most did not notice any change) and they did not report a significant change in thermal comfort, except for one report of more frequently feeling cold.

CONCLUSIONS

- The liquid applied solar control film on the interior of the bronze double glazed base windows tested in St. Louis, MO, produced only very modest cooling energy savings measurements (from 0% - 8% cooling savings). However, the increase in heating energy consumption offset any cooling energy savings, resulting in a net increase of total HVAC energy consumption in all cases. High glass surface temperatures 120–140 °F (50–60°C) were measured on the room side of the interior coated windows, as a result of the highly absorbing nature of the film. This may negatively affect the comfort of occupants in the summer, but there was no discomfort reported in the limited survey.
- The same solar control film applied on the exterior of identical baseline windows had higher measured cooling energy savings (about 30%). However, for this building and climate the cooling savings were again exceeded by the increased heating energy use, resulting in increased total energy consumption in all cases. This part of the study demonstrated the impact of position on the performance of an absorbing film on double glazing. The subject film is not designed or warranted for use as an exterior applied film. The manufacturer of the film used in this study indicates that a new version of its liquid applied film is under development for exterior applications.
- Additional conclusions were drawn based on simulation results exploring the energy savings potential for the subject film, and other competitive applied film products, on different base windows and in different climates. The annual energy use for a generic commercial building perimeter zone (not the exact building condition measured) was calculated using COMFEN, a computer modeling tool using the EnergyPlus simulation engine.
- COMFEN modeling, based on a typical commercial office building perimeter zone in the St. Louis climate, predicted a small total energy savings for the subject film. This difference compared to the measured data result can be explained by the unique factors to the monitored building that were not captured in the generalized model. The trend of higher savings for the film applied to the exterior side of the existing glass was consistent between both measurement and modeling.
- The simulation results are most useful for comparing trends for competing products across different climates and base window conditions. Modeling results indicate a significantly higher potential energy savings for the subject film as a retrofit for single glazing, particularly clear single glazing.
- In warmer climates with mild winters (Houston, Phoenix and Miami), the energy modeling results showed potential energy and cost savings (including both heating and cooling effects) of about 20% for the subject film on single clear glass.
- Simple payback analysis suggests a payback between 5 and 15 years for the four climates modeled, assuming single glazing base windows. Paybacks associated with double glazing were generally longer, unless a reflective applied film is used or an absorbing film is installed on the exterior.

- The subject film outperformed a conventional tinted applied film (a less expensive product) in all climate/configuration cases simulated with an annual energy model. However, a reflective spectrally selective applied film outperformed the subject film in all the cases modeled. The reflective applied film has roughly the same material and installation cost as the subject film. However, the subject film may achieve 20-25% cost reductions with a change to domestic production and there may be other differentiating factors, such as warranty, durability, aesthetics, and impacts of reflected radiation, when selecting between these two products.
- When evaluating a solar control window retrofit, or any type of window retrofit, a site specific analysis, including an annual energy model, is recommended to evaluate alternatives and select the highest performing solutions for a given building application. Both heating and cooling impacts should be considered. As in the case of the subject building in St. Louis, modest benefits in cooling energy savings can be overshadowed by additional heating energy requirements resulting from lost passive solar gains during heating periods.
- Manufacturer claims of heating energy savings in addition to cooling energy savings are not supported by measured data at the test site, nor by annual energy modeling results. Heating energy consumption was never lower than that of the base case window for the subject film, and, for some climates, heating energy was significantly higher. The lack of heating energy savings is consistent with the engineering analysis of the physical properties of the film.
- The installed retrofit film maintains a nearly indistinguishable window aesthetic to the base window, and the installation can be performed quickly with minimal disruption to building occupants. These attributes are similar for competitive applied film products. There may be a durability advantage to the different application method offered by the subject film, but there is not yet enough market history to support that claim. Both approaches are available with warranties up to 15 years and should offer a durable service life if properly installed.
- Occupants did not report significant changes in thermal comfort or glare, but interior blinds were used frequently in the perimeter offices. Occupant survey size was very small so results are anecdotal only. Applied films are often specified to provide glare control and thermal comfort in highly glazed spaces without adequate shading. Applied films are available with a wide range of optical properties, so it is not possible to specify the ability of the film to control glare or thermal comfort without more specifics on the product, the site and interior furnishings.

II. Background

A. WINDOW ENERGY SAVINGS OPPORTUNITY

Windows present a significant energy load to buildings, especially in older buildings with poorly insulating windows and inadequate solar control. Previous work by Lawrence Berkley National Laboratory (LBNL) has estimated that, averaged over the contemporary building stock in the United States, roughly 39% of heating energy BTUs consumed in commercial buildings annually, or 0.96 quadrillion BTUs (quads) out of 2.45 quads, is associated with windows. Windows are also a significant factor in the cooling energy used in buildings, with 0.52 out of 1.9 quads, or 28%, of building cooling energy demand attributed to windows (Apte 2006, see Table 1). For context, the entire U.S. annual energy consumption has been close to 100 quads for several recent years, and one quad is equivalent to the annual energy consumed by roughly 5.5 million U.S. households (US EIA 2012).

It has been estimated that replacing the entire existing commercial building window stock with typical low-e double pane windows (U=0.4 BTU/hr-ft^2-F and SHGC=0.29) could save 0.32 quads (or 62%) of the annual commercial building cooling energy (Apte 2006). While it is possible to replace existing window systems with modern products to improve energy efficiency, replacement is often complicated and expensive, depending on the design of the existing construction. Therefore, it is also important to consider retrofit options that provide equivalent energy performance gains while making use of the existing installed glass and framing. The case for energy savings associated with insulating window retrofits, such as low-e storm panel attachments, is compelling. However, in warmer climates and buildings dominated by the cooling energy load, it is possible to achieve a significant energy savings with solar control window retrofit applied films alone. Most applied window films do not improve the insulating value of the window (heat transfer due to an interior-exterior temperature difference), however there are some applied films available with a durable low emittance surface that will improve the insulation performance, although that is not the case for the product examined in this study.

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

	Building HVAC energy consumption	Window-related energy consumption	Percent of building HVAC energy-related to windows
Heating	2.45	0.96	39%
Cooling	1.90	0.52	28%
Total	4.35	1.48	34%

Applied window films are intended to reduce the solar heat gain through the window and the cooling energy requirements in the building during the summer. However, it is important to recognize that the reduction of solar heat gain can also increase the heating demand in the winter. For this reason, it is valuable to use a climate specific whole building annual energy model, such as those based on the EnergyPlus simulation engine, to assess the annual energy impacts of the window treatment on both cooling and heating energy. Furthermore, windows provide valuable natural daylight services to buildings by displacing electric lighting loads, which can result in further energy savings as well as improve the quality of the work environment for the occupant. Changes in visible transmission, and the associated electric lighting load associated with an applied window film, should be considered as part of the energy analysis. Criteria that identify buildings with the best energy savings potential from solar control films include warmer climates (hot summers and mild winters), large window areas relative to floor area, windows exposed to direct sun without overhangs or exterior shading, and dominant glazing area on south, east and west orientations. Selectively retrofitting solar control films into buildings with these attributes will achieve the greatest potential savings, but it is always advised to use annual energy modeling with the local climate and building configuration to confirm the savings potential for a particular application.

Roughly half of the United States' existing commercial window stock is estimated to be double pane glass, with the remainder single pane, and the majority are mounted in aluminum frames (Apte 2006). As a large commercial building owner with diverse holdings, it is a reasonable assumption that the U.S. General Services Administration (GSA) window stock has a similar percentage of single and double glazed windows. While an applied solar control film does not provide all the energy performance gains associated with a solar control low-e double glazed retrofit glazing unit (estimated to provide an average 62% cooling energy savings potential), roughly half of that cooling energy savings is expected to be achievable with solar control film retrofits alone over the GSA building stock. Some locations will have more potential than others and colder climates should be carefully analyzed to avoid trading cooling energy costs for heating energy costs.

The GSA is a leader among federal agencies in aggressively pursuing energy efficiency opportunities for its facilities and installing renewable energy systems to provide heating, cooling, and power to these facilities. GSA's Public Buildings Service (PBS) has jurisdiction, custody or control over more than 9,600 assets and is responsible for managing an inventory of diverse Federal buildings totaling more than 354 million square feet. This includes approximately 400 buildings listed in or eligible for listing in the National Register of Historic Places, and more than 800 buildings that are over 50 years old. GSA has an abiding interest in examining the technical performance and cost-effectiveness of different energy-efficient technologies in its existing building portfolio, as well as in those buildings currently proposed for construction. Given that the large majority of GSA's buildings include office spaces, identifying appropriate energy-efficient solutions has been a high priority for GSA, as well as for other Federal agencies. It is expected that GSA's large portfolio of buildings in warmer climates has a significant energy savings potential associated with solar control window film retrofits. However, there is significant variability in the existing window configurations and climates in this portfolio and no single solar control film is expected to be applicable in all cases. The subject film is expected to conform to standards for historic places.

B. STATE OF THE ART WINDOW TECHNOLOGY

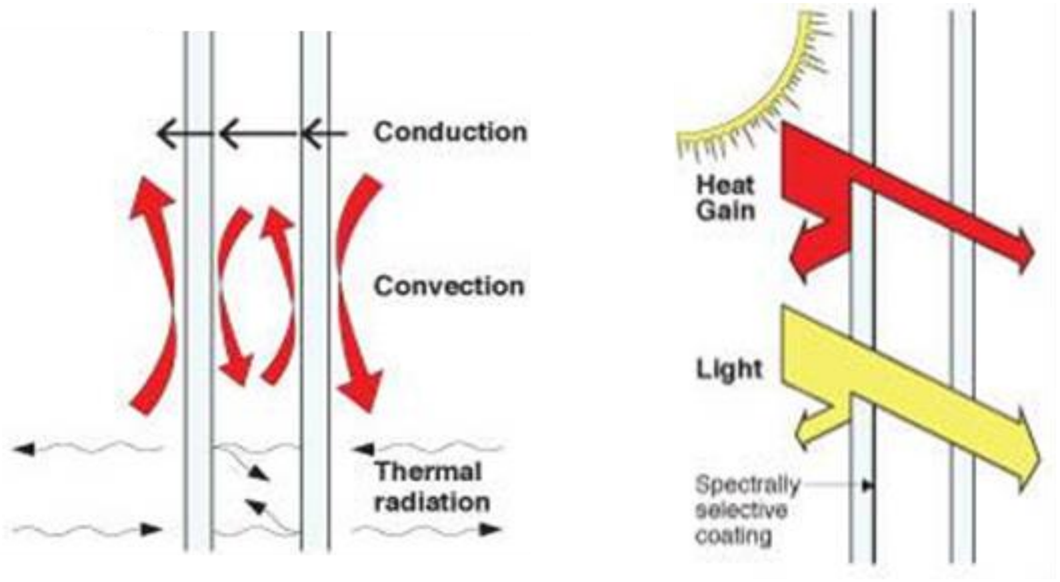
Many years of high-performance window technology development have achieved significant reductions of heat flow through windows by means of controlling thermal conduction, convection, and radiation (see Figure 1, left). Some of the established high-performance design elements include multiple glazing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

Compared to opaque wall insulations, windows have additional performance criteria to consider. Windows can transmit a large fraction of incident solar radiation to the interior of a building. The amount of this type of energy flow through the window is reported by the solar heat gain coefficient (SHGC), a unitless number from zero to one that represents the fraction of solar energy incident on the exterior of a window and frame that is transmitted to the interior. The SHGC includes both the directly transmitted solar radiation (which is subsequently absorbed and reflected on interior surfaces of the room), as well as any portion of the heat from solar radiation that is absorbed in the window glass layers and frame, and subsequently propagated into the room (called the inward flowing fraction). Another factor to consider is the visible light transmission (Tvis) of a window. Visible light transmission through windows can reduce electric lighting loads and improve the quality of light and occupant enjoyment of the space, while too much direct light transmission can cause discomfort from glare. Air infiltration, or leakage around joints and gaskets, is important and highly variable, especially in older buildings with worn operable windows. Retrofit panels, such as storm window panels, cover the window and frame with an additional glass/plastic layer and can help improve air tightness without replacing the entire window. Coatings and films applied just to the glass can alter the solar optical properties of the window, but they do not alter the air infiltration characteristics of the base window on which they are installed, and they typically do not improve the insulating value of the window (U-factor), unless they include a durable exposed low-e coating.

The room-side glass surface temperature that a window reaches under typical environmental conditions is an indicator of its thermal insulating performance and has an impact on the thermal comfort of building occupants when they are near the windows. When there is a large indoor-outdoor temperature difference, a more insulating window will have a room-side glass surface temperature closer to room temperature, providing a more comfortable work space near the window and effectively increasing usable space in the building. The room side window surface temperature also determines the likelihood that condensation will form on the glass under various indoor air humidity conditions. Direct solar radiation and the optical properties of the glass and any coatings/films on the window can have an impact on room side glass temperature and occupant thermal comfort. Windows with strong solar absorption will reach higher glass temperatures than windows with high transmission or reflection of solar radiation. It is important to consider which layer in a multilayer window glazing system has high absorption. The insulating properties of an air space between glass layers will restrict the potential for heat flow in that direction. For that reason, an absorbing glass layer or film on the exterior side of a double pane window has a lower solar heat gain than the same absorbing layer on the interior of a double pane window.

Low-emissivity (low-e) coatings are a common (typically factory installed) window technology used to improve the insulating performance of double pane windows (*i.e.*, lowering U-factor). Low-e coatings function by reducing the long wave infrared radiation exchange between glazing layers that would otherwise occur under a layer to layer temperature difference. Low-e coatings can be designed to reflect portions of the solar spectrum, as well, resulting in lower solar heat gains, without large rises in glass temperature. A low-e coating with these properties is called a spectrally selective, or low solar gain, low-e coating. It preserves a relatively high visible transmission, maintaining the look of clear glass, while reflecting most of the invisible, near-solar infrared, portion of sunlight, which carries about half of the radiant energy in the solar spectrum (see Figure 1, right). This combination of properties, available in low-e coatings, can reduce both heating and cooling loads in buildings, leading to energy savings potential in both winter and summer. Rejection of solar gain when direct sunlight falls on a window also reduces peak cooling loads at the time of day when electrical demand on the grid is at its maximum. While low-e coatings are typically factory sealed between the layers of a double pane window unit, there are many applied film products that provide the spectrally selective visible and solar optical properties associated with solar control low-e products in the form of a field applied film. These products reflect the solar infrared instead of absorbing it and the layers do not have a large temperature rise. Most of these spectrally selective, reflective, applied films do not include the long-wave infrared low-e properties that reduce thermal radiation exchange due to surface temperature differences, and thus, they do not change the U-factor, insulating value, of the window, just the solar gain characteristics. A few newly available applied films do have a durable exposed long-wave infrared red (IR) low-e coating allowing those applied films to offer both solar control and increased insulation properties.

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



Despite the cooling energy savings associated with low solar gain windows, in some climates the building energy balance will benefit from high solar gain low-e coatings, which can help offset heating energy demand, by providing passive solar gain. Commercial buildings with high internal heat loads from people and equipment are often dominated by cooling energy in many climates and are, thus, not frequently considered for accepting passive solar gain. As revealed by the data in Table 1, however, more energy is consumed nationally to heat commercial buildings than to cool them, suggesting potentially large opportunities to take advantage of passive solar heating in commercial buildings. In the case of a retrofit, it is important to determine if a building is already benefiting from passive solar gains that will be diminished by the selection of a low solar gain retrofit. In some cases the cooling energy saved will be outweighed by the increased heating energy demanded, although details of fuel types, relative fuel costs and time of use pricing should be factored into the cost effectiveness analysis. Selection of higher solar gain windows (or declining a low gain retrofit), where appropriate, should be accompanied by consideration for mitigating that solar gain when it is undesirable. Often the most optimal solution can be found when a window system includes some form of dynamic/seasonal solar control, including south facing overhangs with the right solar geometry, deployable shading systems, electrochromic or thermochromic coatings, or deciduous trees, etc. Passive solar gain should be employed when the building, window orientation, shading, and climate are well suited to this practice. Whole building annual energy analysis of particular buildings under local conditions is advised, including assessment of seasonal shading or other means to control solar gain at the appropriate time.

It should be recognized that a single window performance criteria (*e.g.*, U-factor, SHGC, or Tvis) is never the optimal choice for all conditions of building type, climate, season, orientation, and local shading. It is best practice to evaluate window performance choices for particular climates and individual building applications. The high degree of variability in commercial building design favors the use of whole-building annual energy simulations using local climate data when selecting the optimal window properties for a building, making use of the specific climate, orientation, and shading criteria for the application. In addition, it is valuable to consider the performance implications of window systems with dynamic shading (solar control) properties where they are practical.

III. Project Installation and Evaluation

A. OVERVIEW OF RETROFIT TECHNOLOGY

The retrofit solar control window film installed for this study is a relatively new and unique retrofit product, most notably in the manner it is formulated and applied. Beginning as a fluid with nanoparticle suspension, the film is installed by pumping the liquid through an application nozzle and flowing it down the glass such that it cures (in 30 minutes) into an 8 micron durable film, adhered to the glass with solar control optical properties.

Although there are versions of the product with different levels of visible transmission, the film is generally spectrally selective, in that is has relatively high transmission in the visible spectrum compared to the high absorption in the solar infrared portion of the spectrum. The film does not appear strongly tinted and it does not appreciably reduce daylight availability in the room, at least for the high visible transmission version of the product. There are also versions with a slight tint in the visible spectrum. The solar control property of the film is nearly exclusively in the solar infrared portion of the spectrum where only 30% of incident solar infrared is transmitted (see Figure 2).

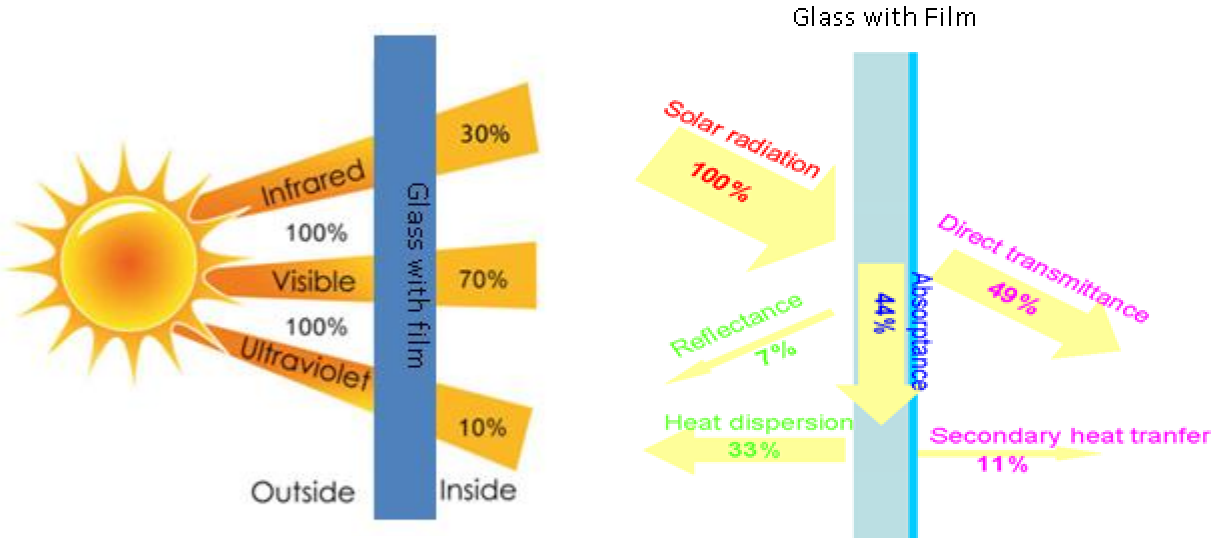
Roughly half of the energy in the solar spectrum is in the near infrared wavelengths, so a significant amount of solar heat gain control can be achieved without reducing the visible light transmission. When installed on a single piece of clear glass, the version of the film used in this study has a visible transmission (Tvis) of 0.64 and a solar transmission (Tsol) of 0.36 (visible plus solar infrared). The solar heat gain coefficient (SHGC), calculated to include the portion of absorbed energy in the glass that propagates into the room is 0.54. The same film installed on the inside of the double pane bronze tinted base window used in this study has a Tvis=0.34, Tsol=0.18, and SHGC=0.44.

The film achieves its solar control by absorption and not reflection. This is important because the final energy balance, including where the absorbed energy is dissipated, depends on the construction of the original window (single versus double glazing), as well as environmental factors, such as the interior and exterior air temperatures and velocities near the window. Because the position of an absorbing film is important for double glazing, testing was also conducted with the coated applied to the exterior of the double glazing. The direct transmissions (Tvis and Tsol) are the same as the interior case; however, the SHGC drops from 0.44 to 0.32, because the absorbed energy is more readily dissipated to the exterior when the absorbing layer is on the exterior of a double glazing.

The product under study was tested in both interior and exterior configurations to confirm the energy implications predicted by modeling, and demonstrate that the position of an absorbing layer within a double glazing system is a significant factor in overall performance. However, the product is not currently designed for exterior application and was only installed with an exterior position for research purposes in this project. Future products may be introduced that allow exterior film of existing glass; however, there are more difficult problems of access and maintaining a clean application environment during installation for exterior cases.

While not as large of a component of total solar energy as the infrared, it is worth noting that the ultraviolet (UV) transmission is dramatically reduced to 10% of the incident radiation. Blockage of this portion of the spectrum is important to reduce damaging UV rays from fading carpets, furniture and other surfaces in the room. Plastic substrate applied films (competing products) also reduce UV transmission, usually close to 1%.

Figure 2. Two depictions of solar control properties of the retrofit window film. Left, solar optical transmission properties by wave length bands (film applied on 5mm clear glass substrate). Right, example energy balance of incident solar radiation (single glazing, exact values depend on base window construction and environmental conditions). Images provided by manufacturer.



The film is intended for installation on the interior (*i.e.*, the room side) of an existing single or double pane window that does not already have strong solar heat gain mitigating properties. Installation begins with masking and cleaning the window. A specially formulated liquid material containing a suspension of nanoparticles is pumped through an applicator nozzle and dispensed onto the top of the window (see figure 3). The liquid flows down the glass by gravity spreading into a thin layer that cures in 30 minutes into a hard durable film with solar absorbing properties. Compared to complete window and framing system replacement, installation disruptions to building occupants are minimal as work can take place after hours without major impacts to the office space. Applying film on many windows in a large building can proceed in stages during unoccupied times. The product can be applied to fixed and operable windows alike and it does not interfere with the operation of any existing window shades/blinds.

Figure 3. Installation of poured in place solar control film retrofit

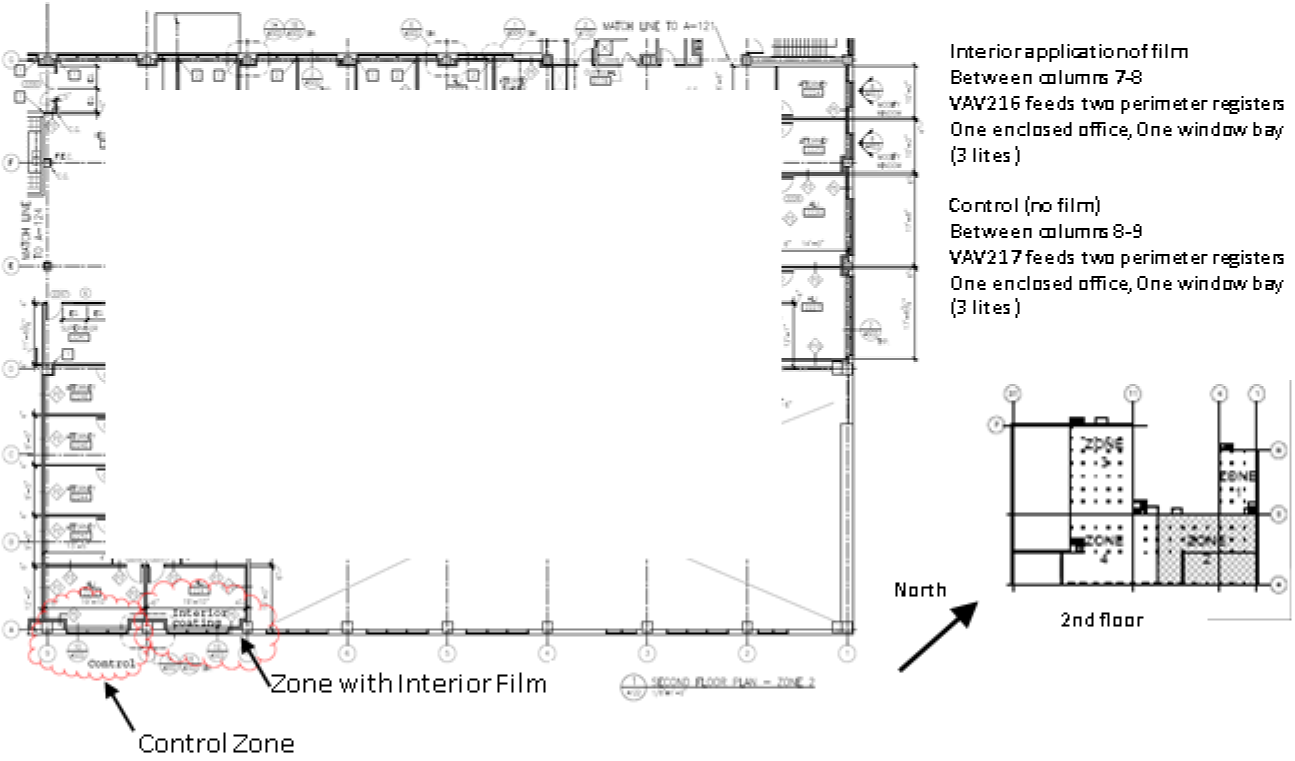
B.   DEMONSTRATION PROJECT LOCATION AND DESCRIPTION

The project evaluation site is a 135,500 square foot, three story office building operated by GSA in the Goodfellow Federal Center, St. Louis, Missouri, and is identified as Building 110 on that campus. The location (climate) was selected to provide a mixed heating and cooling demand to test the applied film under both conditions in accordance with liquid applied film manufacturer’s claims of both heating and cooling energy savings. The existing building has double pane windows with a bronze tint (no low-e coating). Most of the windows in the building are located on the southeast façade. Although four rows of windows are stacked in each array, only two rows are actually transparent windows (one row for each of two floors). The other two rows are opaque and internally insulated behind wall elements of the rooms (see Figure 4). Many of the windows in the study were in enclosed offices where the window-to-wall area ratio is approximately 30-40%. Occupants of the enclosed offices generally sat within about 5-6 feet of the windows in their office.

It was desired to make both heating and cooling energy comparisons with only one winter and summer season during the monitoring period. For this reason, rather than retrofitting the entire building and monitoring it before and after the retrofit, five side by side zones were selected for focused comparison. An example floor plan is illustrated in figure 5 (all floor plans provided in the appendix). Each of the five comparisons consisted of a control for reference (a room that received no window retrofit) and a similar room by size, use and window area, where the window film under study was installed. A variable air volume (VAV) heating and cooling system conditions the air in the spaces. The areas under study were matched by how they were served by individual VAV boxes, such that data from the building automation system could be used to compare the heating and cooling energy supplied to each of the spaces.

Figure 4. Window configuration on the Southeast façade of the building where most of the study was focused.

Figure 5. Example side by side test and control office floor plan. Red clouds indicated windows/offices under study. North direction is indicated.



Interior application of film
Between columns 7-8
VAV216 feeds two perimeter registers
One enclosed office, One window bay
(3 lites)

Control (no film)
Between columns 8-9
VAV217 feeds two perimeter registers
One enclosed office, One window bay
(3 lites)

C. TEST AND INSTRUMENTATION PLAN

Evaluation of the retrofit film product began with laboratory testing of coated glass samples to measure the solar optical and long wave infrared emittance of the film. This measurement was consistent with the National Fenestration Rating Council (NRFC) procedures for determining glazing layer properties for use in WINDOW7 window product rating software. This measurement allowed modeling the film performance on various base window configurations, including the one in the subject building, as well as expanding the scope of both product level and whole building annual energy modeling comparisons beyond the particular window and climate of the test location in St. Louis, MO.

For the physical testing in an office building, it was necessary to decide whether to coat all the windows in the entire building or just a portion of the building. To compare the performance of the window film retrofit over the entire building to that of the existing condition, during both heating and cooling conditions, a period of monitoring including two winters and two summers would be required. There was not enough time in the study schedule to accommodate such a long monitoring period, so a side by side experimental design was used instead, comparing similar zones in the building to allow a parallel process that could be completed in one winter and one summer. The side by side monitoring approach also eliminated the need to correct for weather variations during pre- and post-retrofit monitoring periods. The window films were installed in October of 2012. Additional logging instrumentation for the study was installed from December 2012 through August 2013. The building automation system logging of the VAV box data did not start until February 2013 and ran through August 2013. The later start for the VAV box data was a result of delayed execution of the programming request by the building energy contractor.

Table 2. Measured parameters from the existing building automation system

VAV box measurements	
8 parameters logged at 15 min minutes intervals for 16 VAV boxes, data provided from the existing building automation system	Room Temperature
	Demand Mode
	Cooling Setpoint
	Heating Setpoint
	Desired Flow
	Actual Flow
	Actual Heating Valve Position
	Supply Air Temperature

The existing building automation system in Building 110 supports detailed logging of many parameters, including the local VAV box level where the conditioned air is metered into different building zones. A list of the parameters that were logged with 15 minute intervals is presented in Table 2. By measuring the temperature difference between the room temperature and the supply air temperature, as well as the air flow volume into the room, the cooling and heating energy delivered to the room can be calculated for a given period. It is important to note that this energy is the actual thermal energy in the flow of air to the room and does not include the factors of the central plant heating and cooling efficiencies. For instance, a gas-fired boiler will have an efficiency less than one and an air conditioner, because it is a heat pump, can move more thermal energy than it consumes (coefficient of performance (COP) >1).

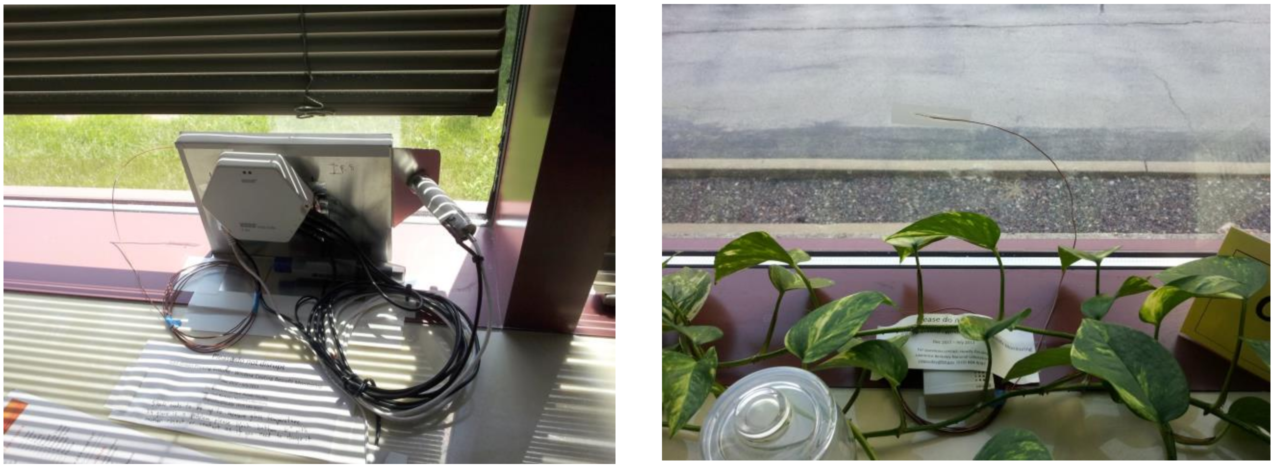
In addition to the building automation system data, a series of autonomous datalogging sensors were deployed with 10-30 minute monitoring intervals. While most of these sensors stored months of data read out upon completion, some of the sensors used wireless transmission to a laptop computer operating in the building. This computer provided a remote connection that allowed live monitoring of some of the data to confirm that measurements were proceeding successfully. A summary of additional measurements is presented in Table 3. Environmental conditions, including solar radiation and outdoor temperature and wind speed, were collected on the roof as well as the southeast façade. Interior room air temperatures, relative humidity and globe temperatures were logged in the five rooms with coated glass, as well as the five corresponding reference rooms that did not receive window films. Globe temperatures, a measure of the mean radiant temperature, or a temperature that is more heavily influenced by the surrounding room surface temperatures rather than the air temperature, were collected in all ten rooms to assess any change in thermal comfort associated with an elevated glass surface temperature associated with the film (pictured as a gray sphere on a slender stand in figure 6.

Figure 6. Globe temperature sensor on cabinet near occupant to measure effective radiant temperature, important to thermal comfort

Interior glass surface temperatures were monitored with both non-contact spot infrared (IR) sensors and fine wire (30 gauge type T) thermocouples taped to the glass surface with clear tape. It can be challenging to measure a glass temperature with a contact sensor when the glass is receiving solar radiation because any change in the local optical properties (transmission, absorption, reflection) changes the local temperature. This is especially true for large temperature sensors and sensors applied with a large area of opaque glue or tape. Infrared measurements require some correction to be accurate because the radiation viewed by the sensor is a combination of emitted and reflected components and the background temperature component must be removed from the measurement to get and accurate surface temperature. To this purpose, the IR sensor was mounted on a stand positioned on the window sill at an angle such that an adjacent white surface served as the background of the IR measurement. A contact thermistor probe was embedded in the surface measuring this background plate temperature for the IR glass temperature correction (Figure 7). Two of the background plates had additional black absorber plate areas with a separate temperature sensor adjacent to the white area to serve as a basic solar “radiometer” behind the glass.

During the final summer site visit in August 2013, an infrared camera was used to measure window surface temperatures and provide visual imagery of surface temperature distributions. The quantitative thermography laboratory techniques described in previous thermography work (Griffith 2000) were adapted under the constraints of the field test environment. Global infrared background corrections were made assuming a relatively uniform room enclosure surface temperature.

Figure 7. Infrared surface temperature station on window sill with data logger and contact thermocouple sensor



Left image infrared non-contact surface temperature station, Right image fine thermocouple wire on glass.

Table 3. Summary of logged measurements over eight months, December to August

Location	Sensor Placement	Measurements Taken
Exterior	Building Roof	• Air temperature • Relative humidity • Wind speed • Horizontal solar pyranometer
	Southeast façade	• Air temperature • Relative humidity • Vertical solar pyranometer • Vertical photometer (visible spectrum)
Interior: one set in each of the five rooms with films, as well as in each of the five reference rooms without films	Window sill	• Infrared non-contact glass surface temperature • White absorber (IR background) surface • Air temperature • Contact glass surface temperature (30 gauge type T thermocouple)
	On desk 5-8 feet from window (height approx. 4 feet from floor)	• Air temperature • Globe temperature (MRT) • Relative humidity
Additional interior measurements in one or two rooms only	Window sill	• Black absorber surface temperature • Vertical solar pyranometer • Vertical photometer (visible spectrum)

IV. Project Results/Findings

A. DIRECT MEASUREMENTS

Laboratory solar optical measurements made at LBNL on samples of coated glass are graphed in Figure 8a and 8b. The manufacturer provided two different formulas of the film that were tested using a bench top spectrophotometer. The samples were labeled HPS40 and HPS60. HPS40 is the version of the film installed in St. Louis and will subsequently be referred to as Film A in this report. As can be seen in the transmission plot, the transmission is highest in the visible spectrum and falls in the near IR portion of the solar spectrum, consistent with a spectrally selective material. There is no significant IR reflection. Rather, the IR portion of sunlight that is not transmitted is mostly absorbed in the film. Beyond five microns wavelength the film behaves very close to glass. The surface emittance of the film in the long wave infrared is 0.88, very close to that of bar glass (0.84). This measured spectral data was used in the calculation of glazing system optical properties and whole building annual energy modeling that is presented in the computer simulations results.

Figure 8a. Solar optical data measured in the lab for the poured in place solar control retrofit film. HPS40 (film A), the subject film installed in the St. Louis test building in this study (T is transmission, Rf is front surface reflection, Rb is back surface reflection, Af is the absorption)

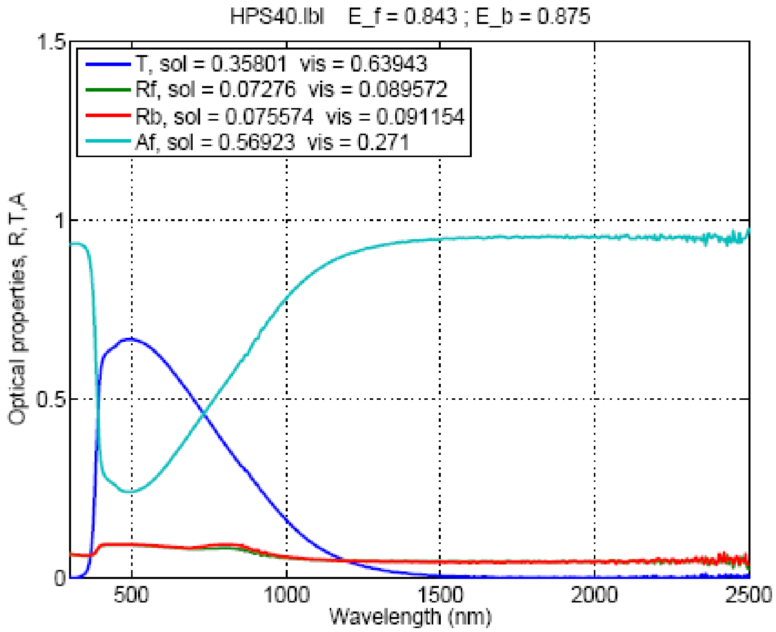


Figure 8b. Solar optical data measured in the lab for film sample HPS60 (T is transmission, Rf is front surface reflection, Rb is back surface reflection, Af is the absorption)

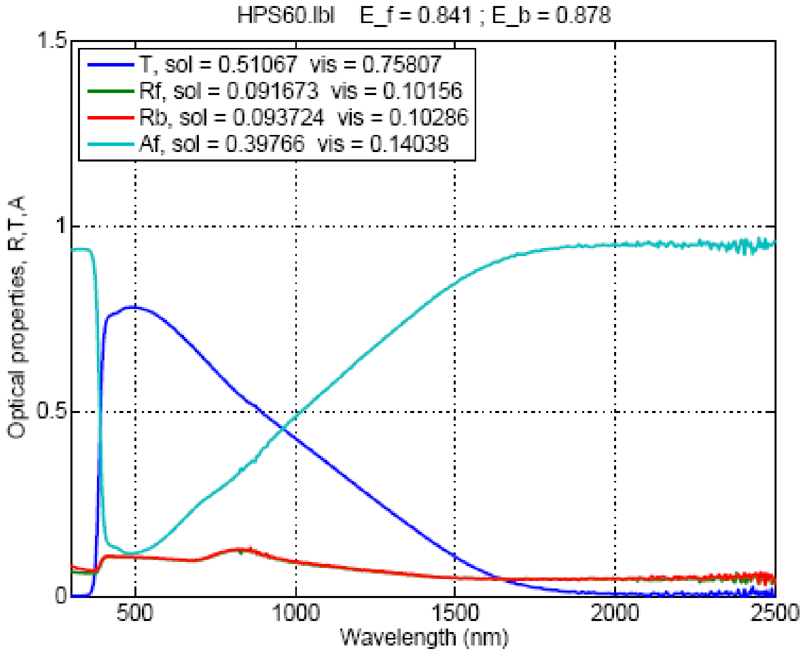


Figure 9 shows an IR image of the interior coated double bronze windows in August. The 120°F (50°C) surface temperature is consistent with the modeled results and is considerably higher than room air temperature and the surrounding wall temperatures. The exterior temperature was 84°F (29°C) and the interior temperature was 72°F (22°C). Figure 10 shows IR images of uncoated and exterior coated windows on the same day and same orientation. The uncoated and exterior coated cases have room side window surfaces temperatures that are nearly identical at about 33°C, even though the exterior coated window reduces solar heat gain into the building. The interior film on double glazing absorbs solar energy behind the insulating layers of the double glazing. As a result, the occupants are exposed to the higher room side glass surface temperature, which can be a thermal comfort issue. Absorbing energy on the interior of a double pane window reduces the solar control potential because it is more difficult to reject the absorbed energy to the exterior. To demonstrate the change in transmitted solar radiation of the coated windows, Figure 11 shows an IR image of the floor surface temperatures where patches of direct sunlight warm the carpet. It can be seen that the coated window is reducing the directly transmitted energy in the sunlight that reaches the interior room surfaces.

Figure 9. Infrared thermogram showing room-side window surface temperature of interior coated double bronze windows in August Exterior temperature 84°F (29°C). Room temperature was 72°F (22°C).

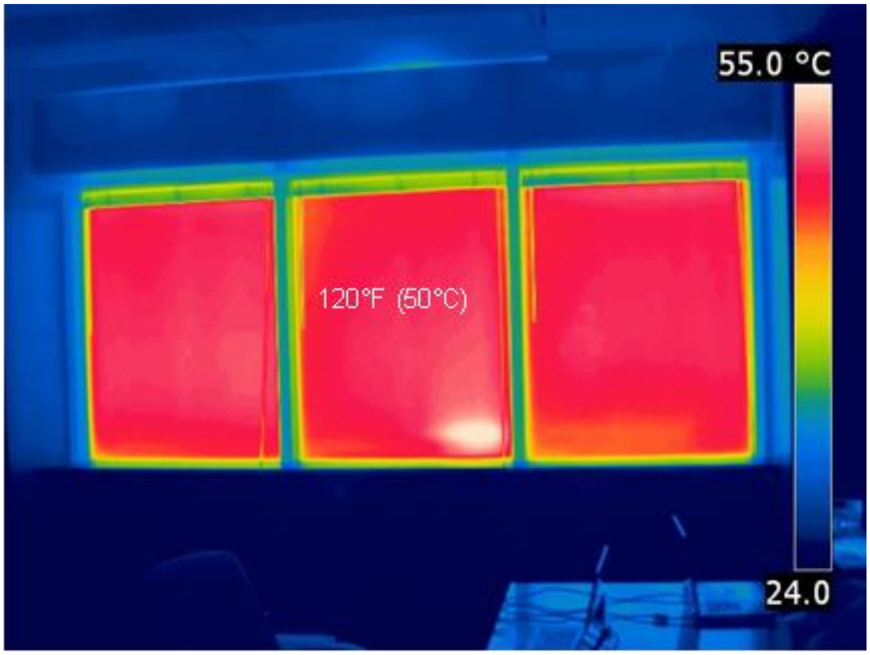
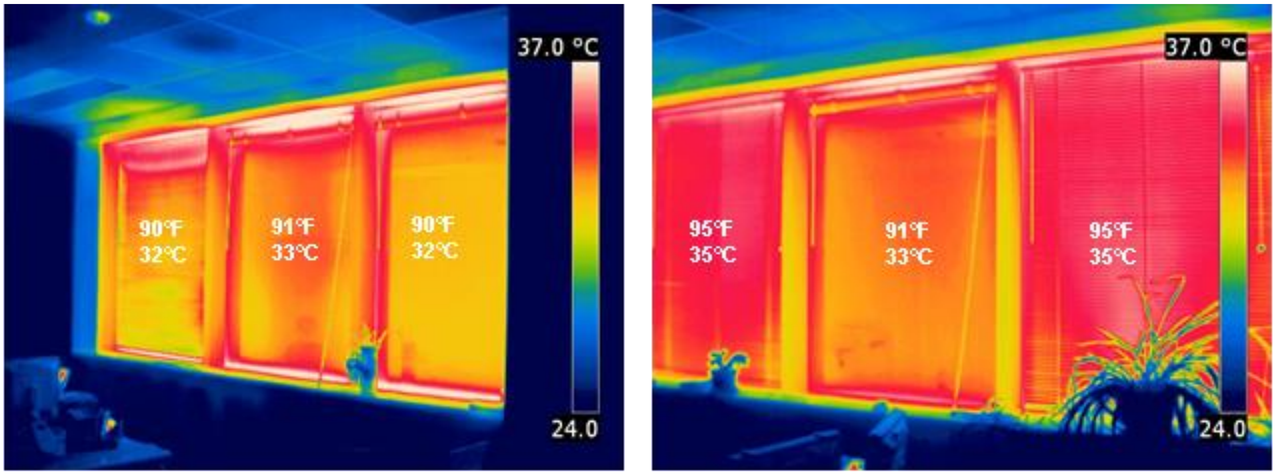
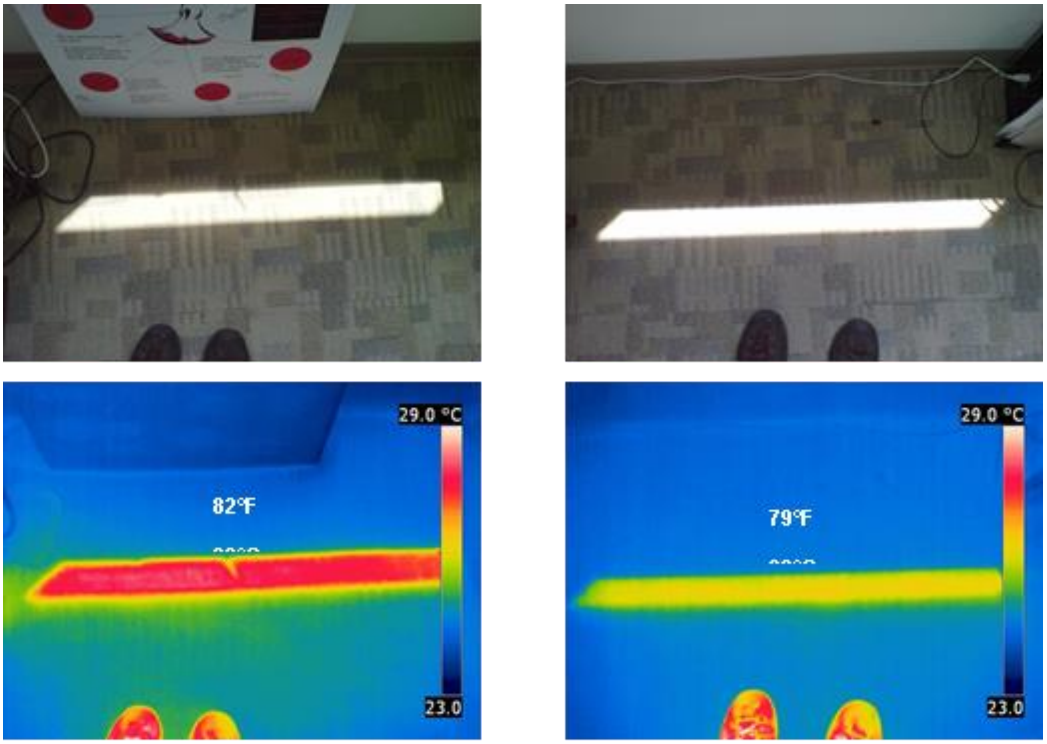


Figure 10. Infrared thermogram showing the room-side window surface temperature of double bronze windows with and without exterior film in August. Exterior temperature 84°F (29°C). Room temperature was 72°F (22°C).



Left image no film, Right image exterior film.

Figure 11. Infrared images of direct solar radiation patches on the floor below uncoated and exterior coated windows.

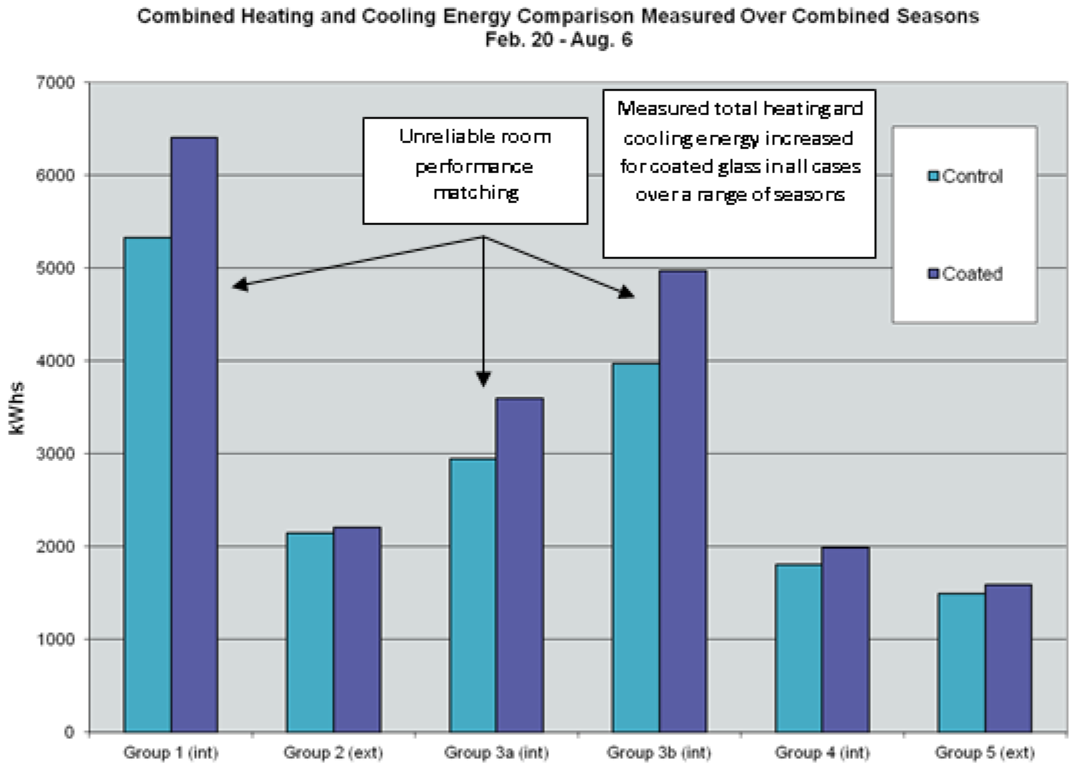


Left image no film, Right image exterior film.
Top images are visible spectrum versions of the infrared images below.

A summary of the total measured heating and cooling energy delivered to the five zones compared to their reference spaces is presented in Figure 12. This data is for the entire monitoring period from Feb. 20 to Aug. 6. The baseline equivalence of the control and retrofit spaces in Groups 1 and 3 turned out to be poorer than expected and the confidence in those two comparisons is low. For instance, the cooling load of the group 1 reference room (control) had a large consistent offset in the amount of cooling that was not observed for other pairs of rooms. This offset could be explained by an occupancy difference, equipment loads or a difference in how the zone is controlled. Group 3 was the large training and multi-purpose rooms on the second floor. Each of the treatment and control zones in this case was divided into two rooms by a movable barrier (not moved during the experiment) and each of these rooms was served by more than one VAV box. Unfortunately, there were a couple of VAV boxes with missing data, so the entire spaces could not be compared (the building energy contractor did not program all the VAV data logging locations requested).

Fortunately, because the study had redundant measurement groups, there was enough good data for both the exterior and interior film cases, despite the reported problems. The data presented shows group 3a, which is one of the treated rooms, versus the correspond room (half) of the control for that zone. Group 3b adds the VAV box data for one of the two VAV boxes in the other room (half) of the two zones, but since this data is incomplete, and the use of these rooms is less consistent and comparable than the smaller enclosed offices, it is generally less reliable.

Figure 12. Total heating and cooling energy by monitoring zone for the period Feb.20 – Aug. 6. (kWhs are equivalent thermal energy in heating and cooling air stream to room, no equipment factors)



The VAV box energy monitoring results indicate that the rooms with films installed used more energy over the entire monitoring period than the rooms without films when both heating and cooling energy were combined for that period. This was consistent for rooms with films on the interior as well as the exterior of the glass, and can be attributed to the relatively large heating demand of the building, related to its climate, occupancy and internal loads. Even though some zones with the film in place used less cooling energy during hotter periods, the net energy consumption increased. Zones with the film installed experienced increased heating load as a result of the sacrificed passive solar heating during colder periods that outweighed the cooling energy savings during the hotter periods of the year in this particular building and climate. While this particular building in the St. Louis climate did not provide the optimal conditions to demonstrate the solar control cooling energy savings potential of applied films, it was useful to have the mixed climate to demonstrate the impact on heating energy and test the manufacturer’s claims of heating energy savings. These claims were not realized in the testing, as heating energy increased rather than decreased with the liquid applied film.

It is worth noting that the method of metering the heating and cooling energy via the VAV box data is not reporting the “billed” amount of heating or cooling energy (in kWh) because it only reports the thermal energy delivered to the space and does not include the system efficiency of the equipment used to condition the air. A typical gas-fired boiler will have an efficiency less than 1 (unless heating is accomplished with a heat pump), and the air conditioning will have a coefficient of performance (COP) greater than 1, because it is based on a heat pump cycle that can move more heat energy than the electricity it consumes. With typical efficiencies, there will be a roughly 3 to 1 ratio between the actual heating energy consumed and the actual cooling energy consumed for the same amount of heating or cooling energy in the VAV box air stream, making the heating energy consumption even greater than that reported here relative to the cooling energy. Because the cost of electricity per unit energy is typically about 3 times higher than gas for the same unit of energy, these factors cancel when considering the total cost of heating and cooling energy consumed to evaluate if there is an energy payback. Due to the conflicting impacts on heating and cooling, based on the measured data for this particular building and zones, there does not appear to be an energy payback in the St. Louis climate for this product. There are still other useful results to take from the direct measurements of energy delivered to the buildings. One is the trend over different seasons during the monitoring period. Additional plots similar to Figure 12, are presented in the appendix Figure AD2-AD4, for three periods (winter, spring and summer). The data are presented in another way in Figures 13 and 14 to show the trend of various seasons for total heating and cooling energy, for one zone at a time. Figure 13 is an exterior case and figure 14 is an interior case.

Table 4 reports the heating, cooling and combined energy for each zone and its corresponding control. When looking at cooling energy only, the exterior film position saved about 30% over the whole monitoring period and more for hot seasons. The interior film still saves cooling energy, but it was considerably lower at about 8% for the whole monitoring period. The interior film appears to have more success reducing cooling energy during seasons when the ambient temperature was low, which is consistent with the difficultly of dissipating absorbed energy from behind the insulating double glazing. When the outdoor temperature is low, it is easier for some of the absorbed energy on the interior pane to propagate to the exterior and reduce the solar gain, but when the outside temperature is hot, more of the absorbed energy is propagated to the room. The change in absolute value is more informative than the percent savings for cases with small baseline energy, which result in unusually large percent change figures.

Figure 13. Total heating and cooling energy for zone 2 (exterior film) by season.

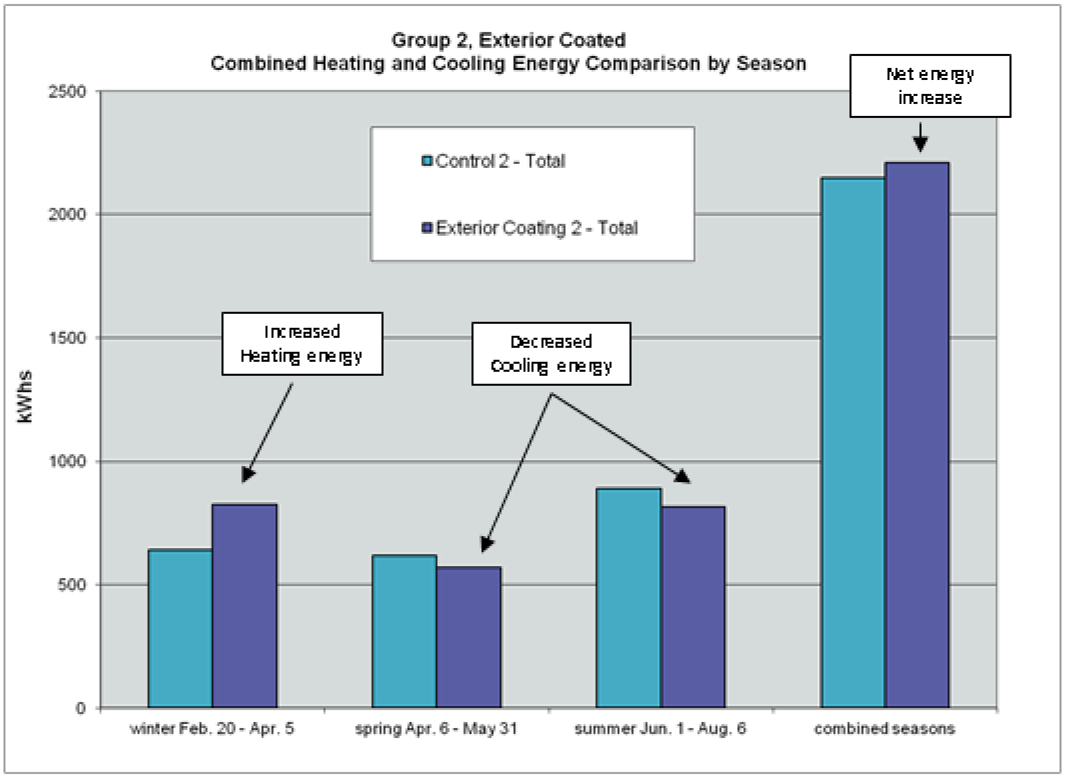


Figure 14. Total heating and cooling energy for zone 4 (interior film) by season.

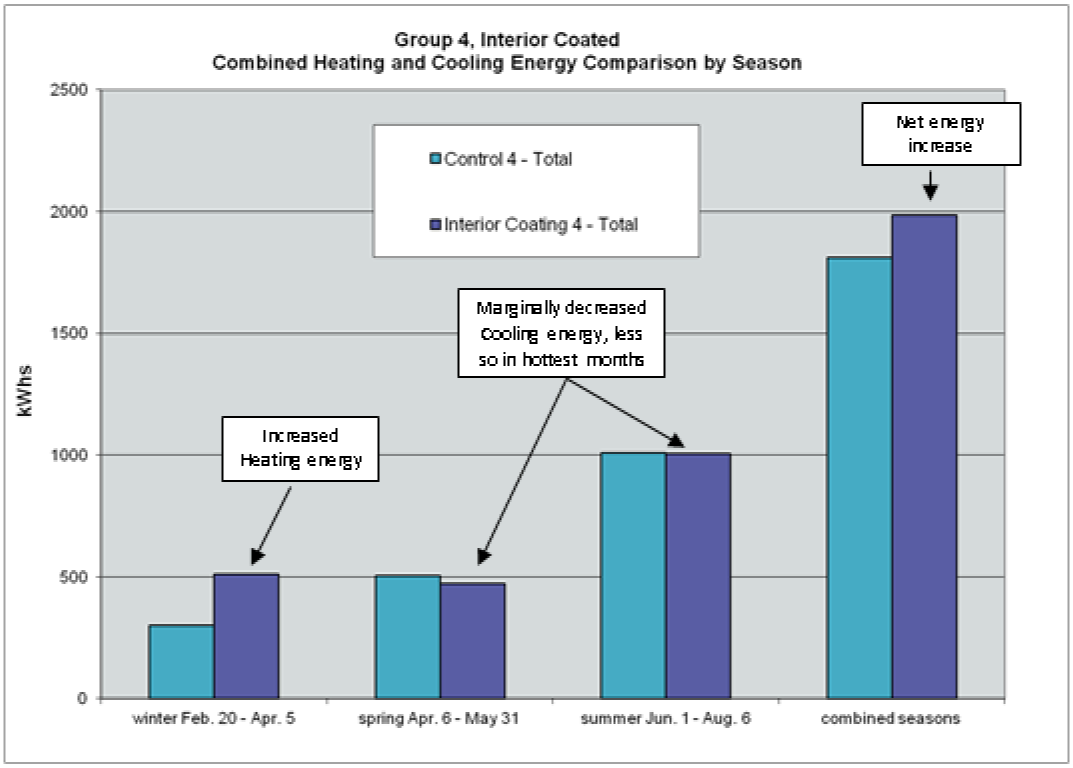


Table 4. Summary of measured VAV box heating and cooling energy delivered (positive savings % numbers are increased energy use, negative are decreased energy use)

	Heating (kWh)	Cooling (kWh)	Total (kWh)	Heating (kWh)	Cooling (kWh)	Total (kWh)	heating savings %	cooling savings %	total savings %
	Group 1 - Control - VAV136			Group 1 - Interior Film - VAV157					
Combined seasons	258	5067	5324	4386	2017	6403	1603%	-60%	20%
Winter Feb. 20 - Apr. 5	51	961	1013	2242	121	2363	4254%	-87%	133%
Spring Apr. 6 - May 31	89	1722	1811	1254	580	1834	1310%	-66%	1%
Summer Jun. 1 - Aug. 6	117	2383	2501	890	1316	2206	660%	-45%	-12%
	Group 2 - Control - VAV142			Group 2 - Exterior Film - VAV143					
Combined seasons	621	1527	2148	1100	1109	2209	77%	-27%	3%
Winter Feb. 20 - Apr. 5	381	260	641	688	137	825	81%	-47%	29%
Spring Apr. 6 - May 31	156	461	617	231	339	570	49%	-27%	-8%
Summer Jun. 1 - Aug. 6	84	806	890	181	634	815	114%	-21%	-8%
	Group 3a - Control - VAV286/288			Group 3a - Interior Film - VAV285/283					
Combined seasons	334	2614	2948	828	2771	3599	148%	6%	22%
Winter Feb. 20 - Apr. 5	306	284	590	447	316	763	46%	11%	29%
Spring Apr. 6 - May 31	27	758	785	242	767	1009	793%	1%	28%
Summer Jun. 1 - Aug. 6	1	1573	1574	140	1688	1827	21096%	7%	16%

Notes: (1) Groups 1 and 3 had issues with control and treatment baseline comparability that resulted in low confidence in the results for these zones. (2) Percent savings, as reported above, can be very sensitive to small magnitude baseline (control) measurements. For cases with unusually large percent savings, it is more informative to consider the absolute values of control versus treatment.

Table 4 (continued). Summary of measured VAV box heating and cooling energy delivered (positive savings % numbers are increased energy use, negative are decreased energy use)

	Heating (kWh)	Cooling (kWh)	Total (kWh)	Heating (kWh)	Cooling (kWh)	Total (kWh)	heating savings %	cooling savings %	total savings %
	Group 3b - Control - VAV286/288/290			Group 3b - Interior Film - VAV285/283/282					
Combined seasons	469	3505	3974	985	3986	4971	110%	14%	25%
Winter Feb. 20 - Apr. 5	439	347	786	549	477	1026	25%	37%	31%
Spring Apr. 6 - May 31	30	1001	1031	258	1214	1472	773%	21%	43%
Summer Jun. 1 - Aug. 6	1	2157	2158	178	2295	2473	16831%	6%	15%
	Group 4 - Control - VAV217			Group 4 - Interior Film - VAV216					
Combined seasons	123	1688	1810	430	1555	1986	250%	-8%	10%
Winter Feb. 20 - Apr. 5	112	187	299	394	116	510	250%	-38%	70%
Spring Apr. 6 - May 31	10	493	503	22	449	471	123%	-9%	-6%
Summer Jun. 1 - Aug. 6	1	1007	1008	14	991	1005	2648%	-2%	0%
	Group 5 - Control - VAV181			Group 5 - Exterior Film - VAV185					
Combined seasons	604	892	1496	976	617	1594	62%	-31%	7%
Winter Feb. 20 - Apr. 5	504	53	557	714	31	745	42%	-42%	34%
Spring Apr. 6 - May 31	93	260	353	196	187	383	111%	-28%	9%
Summer Jun. 1 - Aug. 6	7	579	587	66	400	466	820%	-31%	-21%

Notes: (1) Groups 1 and 3 had issues with control and treatment baseline comparability that resulted in low confidence in the results for these zones. (2) Percent savings, as reported above, can be very sensitive to small magnitude baseline (control) measurements. For cases with unusually large percent savings, it is more informative to consider the absolute values of control versus treatment.

B. MODELED WINDOW PERFORMANCE RESULTS

With the full spectrum of solar optical data measured for the film, as well as the long-wave emittance of the exposed film surface, window glazing assemblies of various multiple layer configurations can be calculated using the WINDOW7 software. This software was developed with the support of the U.S. Department of Energy and is available at no cost to users. The National Fenestration Rating Council (NFRC) uses this window modeling software to calculate the performance of window assemblies for performance rating purposes. For center of glass properties, WINDOW7 can calculate the U-factor, solar heat gain coefficient (SHGC), visible transmittance (Tvis), and solar transmission (Tsol) of multiple layer window assemblies defined by the user, pulling data for thousands of glass and film layers from the International Glazing Database (IGDB). The modeling techniques for multi-layer specular glazings and films are mature and well validated. With both measured data and modeling results, this study will make further comparisons. Modeled results are particularly useful for examining incremental changes resulting from different glazing choices because the changes in the model can be carefully limited and are, thus, less prone to some of the variability of physical measurements that have many more parameters that are often difficult to hold consistent or apply appropriate corrections.

Window glazing system properties for the center of glass area are tabulated in Table 5 from WINDOW7 calculations using the double glazing window with a bronze tint as the base configuration for a variety of retrofit applied films. Film A is the subject film of this study (the one that was installed in Building 110). It is presented calculated for both the interior and exterior positions studied. Film B is a typical spectrally selective reflective applied film for comparison and Film C is an absorbing applied film product with similar visible transmission to the others. Films B and C are presented to provide a comparison to competitive applied film retrofit solar control products that are not poured in place as is Film A.

The U-factor is essentially the same for all of the retrofits because applied films do not typically change the U-factor unless there is a significantly lower surface emittance associated with the film. Film B does have a lower emittance, so it has a slightly lower U-factor. Applied films are available with much lower emittance (~0.05), enabling significant insulating improvements with the retrofit film. This study is more concerned with the solar control performance, so it is most useful to consider the solar heat gain coefficient (SHGC), which is modestly reduced for the interior absorbing Films (A and C) and more significantly reduced for the exterior application of Film A and the reflective Film B because the reflected energy can more easily dissipate to the exterior compared to the absorbed energy on the internal pane of the double pane window.

Figures AB1-AB4 in the appendix detail relative solar gain characteristics based on film position base window and environmental conditions. The solar heat gain coefficient is sensitive to the interior and exterior air temperature and air speeds, as this influences the rate of surface heat transfer on each side of the window and, thus, where absorbed energy can more readily flow. Figures AB5 and AB6 in the appendix compare the model predicted surface temperature rise of the room side glass for different film configurations. Additional base window configurations were calculated and listed in appendix Table AC1. The properties for a single clear base window are presented in that table. Single clear is likely a rare occurrence in typical commercial buildings, but it does demonstrate a high potential for reducing solar gain with an applied film. Single glazing with a moderate bronze tint is presented, as well. This is more likely the type of single glazing encountered in commercial buildings and it still demonstrates greater potential for applied films than the interior of a double glazing.

Table 5. Window glazing system properties in the center of glass area for the subject building base window plus various films and positions

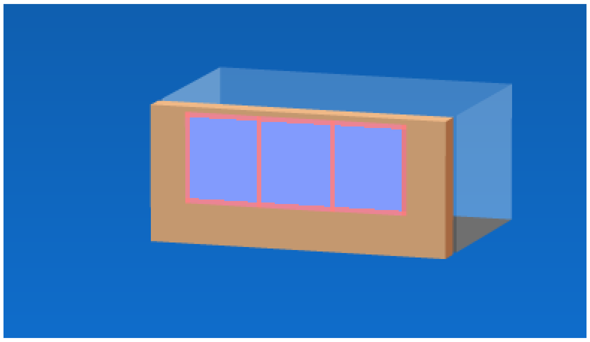
ID	Type of film on double bronze	# of layers	U-factor (BTU/h-ft-F)	SHGC	Tsol	Tvis	Room side Emittance
9	Double Bronze base window	2	0.47	0.50	0.38	0.47	0.84
10	Film A (interior)	2	0.48	0.44	0.18	0.34	0.87
11	Film B	2	0.43	0.36	0.18	0.37	0.53
12	Film C	2	0.48	0.48	0.32	0.38	0.85
13	Film A (exterior)	2	0.47	0.32	0.18	0.34	0.87* Exterior

Film A: Subject Film, Film B: Spectrally Selective Film, Film C: Absorbing Film.

C. ANNUAL ENERGY SIMULATION

With knowledge of the window system performance and other parameters of the building, a whole building annual energy simulation program, such as those utilizing the EnergyPlus simulation engine, can be run using typical weather files for a particular climate, providing whole building annual energy savings results for different configurations. COMFEN is a freely available software front end, developed by LBNL with funding from DOE, that is designed to simplify the annual energy modeling problem for commercial buildings, while still providing powerful tools to evaluate the many impacts of different window choices for a particular building. COMFEN simulates a single perimeter zone portion of a large commercial façade, providing heating, cooling, fan and lighting energy implications, as well as other analysis. It should not be expected that the energy consumption predictions from COMFEN will exactly match utility bills for a real building. Instead, COMFEN is primarily useful for exploring relative changes related to different window choices for a particular building orientation, shading and climate application. A schematic of the façade configuration modeled to represent the enclosed offices studied in Building 110 is drawn in figure 15. The window to wall ratio is 42% in this model. Default COMFEN electricity and gas energy costs were replaced with appropriate average annual values for each state taken from the 2013 Energy Information Administration reports. The retail commercial electricity and gas prices used are summarized in the appendix, Table AC2.

Figure 15. Schematic model of the perimeter zone modeled by COMFEN.



The predicted annual energy savings for the subject film (Film A) in St. Louis is small, but it is a few percent savings, where the measurements were a net increase in energy use. Rather than compare the absolute values of measurement and modeling, it is more informative to consider the relative energy performance of models using different window retrofit products and base windows. To demonstrate the potential for solar control films on more compelling base windows and climates, Table 6 collects the total annual energy savings and energy cost savings for single clear, single bronze and double bronze base windows in four climates: St. Louis, Houston, Phoenix, and Miami. See Tables AC3 - AC6 in the appendix for more detailed modeling results for these climates.

Table 6. COMFEN energy and cost savings for different base windows and climates (positive numbers are energy savings)

	St. Louis		Houston		Phoenix		Miami	
	Total Energy %savings	Total Cost %savings	Total Energy %savings	Total Cost %savings	Total Energy %savings	Total Cost %savings	Total Energy %savings	Total Cost %savings
Single Clear								
Film A	12%	21%	19%	22%	21%	21%	20%	20%
Film B	22%	30%	26%	28%	29%	29%	25%	25%
Film C	8%	12%	11%	12%	11%	11%	11%	11%
Single Bronze								
Film A	3%	12%	12%	14%	13%	14%	14%	14%
Film B	14%	21%	19%	20%	22%	22%	19%	19%
Film C	2%	6%	6%	7%	6%	7%	6%	6%
Double Bronze								
Film A (interior)	3%	7%	7%	7%	7%	7%	7%	7%
Film A (exterior)	6%	15%	15%	17%	17%	17%	15%	15%
Film B	9%	14%	13%	13%	15%	15%	12%	12%
Film C	1%	3%	3%	3%	3%	3%	3%	3%

Film B (spectrally selective reflective plastic film) and Film C (absorbing applied plastic film) were added to compare competitive products. Single clear and single bronze base windows show stronger potential for retrofit with an absorbing film than interior placement of an absorbing film on double bronze. Exterior placement of an absorbing film on double glazing provides better performance, but the liquid-applied film measured in this work is not currently intended for exterior installation. There are some plastic substrate solar control applied films available on the market. The interior mounted reflective film has better savings potential compared to the interior mounted absorbing products in all cases.

D. PAYBACK OPTIMIZATION

The potential cost payback for solar control film retrofit products will vary substantially depending on the particular building, climate and other factors. The specific payback information for the St. Louis, MO, test case was not particularly compelling, because that particular building and climate requires enough heating energy that the cooling energy savings were outweighed by the loss of passive solar heating energy. The COMFEN models showed a small net energy savings potential in St. Louis, based on the internal load assumptions used in the model and other building specific factors that may not have exactly matched the measured facility in St. Louis. When evaluating the potential for payback, it is useful to keep in mind that higher window-to-wall ratios, climates with a sunny, hot summers and moderate winters, as well as buildings with a large area of unshaded glass exposure are most likely to benefit from a solar control film retrofit, and have a more rapid payback using a solar control film retrofit product.

The manufacturer provided a material and installation cost for the liquid applied film of \$10/ft^2. This figure is similar to that of the higher end traditional applied films on a plastic substrate, such as spectrally selective reflective applied films. The material for the liquid applied film is currently imported. There are additional costs associated with importing the material. Domestic production of the materials are anticipated and expected to reduce costs by 20-25%. The liquid applied film is potentially more durable over time, as plastic films can peel and blister if improperly installed, but a quality applied film installation typically has a warranty of 6-15 years and can have a longer useful life. If the long term durability of the liquid applied film proves to be superior to plastic substrate applied films, there is a possible life cycle cost benefit associated with the longevity of the liquid applied film compared to the average applied plastic film based retrofit. However, there is not sufficient data from this test or general market history, to make this conclusion at the present time. The manufacturer of the liquid applied film offers a 15 year warranty. Other cost factors may enter into the evaluation for specific cases, such as historic buildings with detailed wood window trim that requires expensive maintenance. A reflective film may increase the frequency and cost of maintenance compared to an absorbing film that would not expose the frame to reflected energy. There are subtle aesthetic differences between absorbing and reflective solar control films. A historic building may more easily maintain the original look of the glass with a spectrally selective absorbing film like the one studied in this work compared to a spectrally selective reflective film such as the example used for comparison in the modeling results.

Measured energy savings data was not available for the entire year, so the measured savings are not directly comparable to the modeled savings (also the model is not a perfect representation of the building tested). The discrepancy between measured and modeled savings is likely within the margin of error of both the modeling and measurement techniques. It should be noted that there was a shorter period of winter weather in the measured data compared to the period of summer weather. Despite the lighter weight on the winter season, the sacrificed heating energy still outweighed the cooling savings over the monitored period, indicating that it was a strong factor for the St. Louis climate.

A simple payback analysis was conducted for the four climates and three applied films modeled using COMFEN. The energy cost savings per square foot relative to the base case was multiplied by the 300 square feet of floor area in the modeled perimeter zone. The cost of the installed film per square foot was multiplied by the 84 square feet of window modeled in the same zone (0.42 window-to-wall ratio). The assumed installed cost per square foot was $10, $10 and $6.4 respectively for retrofit Films A, B and C. Because of the potential for Film A to become less expensive when it is produce domestically rather than imported, a second calculation is provided for Film A with $8 per square foot installed cost, a 20% reduction.

Single glazed base windows provide opportunities for applied film retrofit with the fastest payback. Single clear ranges between 5-10 years, and single bronze about 8-16 years. Most of the cases on double bronze glazing are longer than 20 year payback, but there may be other reasons to install the film (such as glare control and privacy). The exterior film position and some of the reflective interior film cases are the most compelling for the double bronze case, with paybacks in the 10-18 year range. These model based payback calculations are provided primarily for rough guidance and relative comparisons. Any individual project should be evaluated based on the particular climate and building characteristics including window area (window-to-wall ratio), orientation, shading, base window configuration, etc.

Table 7. Simple payback in years based on COMFEN modeling of perimeter zone energy cost savings versus installed cost of three applied films.

	St. Louis	Houston	Phoenix	Miami
Single Clear				
Film A	10.1	11.7	6.8	9.4
Film A (-20% cost)	8.1	9.4	5.4	7.6
Film B	7.3	9.2	4.9	7.5
Film C	11.4	14.0	8.1	11.4
Single Bronze				
Film A	22.5	21.7	12.3	16.6
Film A (-20% cost)	18.0	17.4	9.8	13.3
Film B	12.7	15.1	7.6	12.1
Film C	28.2	29.3	16.6	23.3
Double Bronze				
Film A	48.0	47.7	28.1	36.5
Film A (-20% cost)	38.4	38.1	22.5	29.2
Film B	23.2	26.7	14.0	20.6
Film C	72.4	73.3	44.0	56.4
Film A Exterior	21.4	21.2	12.2	16.5
Film A Exterior (-20% cost)	17.1	17.0	9.8	13.2

Film A: Subject Film, Film B: Spectrally Selective Film, Film C: Absorbing Film.

E. OCCUPANT RESPONSE SURVEY

A web-based survey was distributed to the occupants of the Building 110 offices that received window film retrofits. The survey was conducted at a single time, after they had experienced the pre-retrofit and post-retrofit conditions in both winter and summer. Because four of the five coated zones were private offices with one occupant, there was a small pool of people to survey. One of the coated rooms was a training and multi-purpose room, but it was difficult to connect with the right occupants who had consistent experience in that room. The response rate was relatively high given the small pool of potential subjects, but with only three total responses the survey results are still quite limited and should be considered anecdotal, not statistically significant. The 10 survey questions and the summary data collected are presented in the appendix (Table AE1). The survey confirms that occupants sit close to windows (less than 15 feet), and mostly had no objection to the appearance of the window treatment, as well as no change in visual glare discomfort before and after the retrofit. One occupant reported being too cold more frequently following the retrofit, but there was not a change in the frequency of occupants reporting being too hot before and after the retrofit.

F. ASSOCIATED OBSERVATIONS

In the process of monitoring window performance over several months, non-window related observations were made to assess general energy efficiency measures in the building. Weekend and holiday temperature setbacks appeared to occur reliably, as expected. There was, however, a surprising amount of rapidly oscillating mixed heating and cooling behavior observed in the VAV box data, which suggests that the system may not be operating as efficiently as possible. This observation has been followed up with a project to further understand and remedy this building management issue. It stands as a useful reminder that the intended subject for energy retrofit in a building is not always an isolated consideration, and that it is always wise to diagnose and understand the operation of a building comprehensively to provide the necessary context for appropriate energy efficiency upgrade decisions.

V. Conclusions and Recommendations

The subject of this study, a liquid applied solar control film technology, did not produce measurable total energy savings for the retrofitted building in St. Louis, MO, in either interior or exterior application to the existing double pane bronze tint windows. This climate was selected to provide a mixed heating and cooling demand to test the liquid applied film under both heating and cooling condition. Because the total energy consumption went up in both cases, the total energy cost associated with the coated windows also rises, resulting in the conclusion that there is no energy payback for the liquid applied film in the particular building and climate tested.

Multiple building zones were monitored, two with exterior applied films and three with interior applied films (the intended position for this product). The subject film is not designed, and does not carry a warranty, for use as an exterior applied film. It was useful to demonstrate the measured relative energy savings of the same film in two positions on a double pane base window. On double glazing, an exterior absorbing applied film will provide better solar control than an interior application. The manufacturer of the film used in this study has stated that they are in the process of developing exterior application product and that this option may be available in the future. There are commercially available solar control plastic substrate films for exterior applications available at this time.

The manufacturer’s claim of both heating and cooling energy savings (20-40%) was not supported by the measured data or simulation results. Heating energy consumption went up in all climates and window configurations for windows with the film in place. Solar control films should be marketed with awareness that the loss of passive solar gains may outweigh the benefits of solar control and cooling energy savings in some buildings and climates.

The liquid applied solar control film on the interior of the bronze double glazed base windows tested in St. Louis, MO, produced only very modest cooling energy savings measurements (from 0% - 8% cooling savings). However, the increase in heating energy consumption offset any cooling energy savings, resulting in net increased total energy consumption in all cases.

The same solar control film applied on the exterior of identical baseline windows had higher measured cooling energy savings (about 30%). However, for this building and climate, the cooling savings were again exceeded by the increased heating energy use, resulting in increased total energy consumption in all cases.

Although the installed solar control film did not produce energy savings as tested in St. Louis, different buildings, base windows, and climates have appropriate applications with useful savings. To explore this potential and compare the subject film to competing products, the annual energy for a generic commercial building perimeter zone was calculated for a selection of climates, base windows, and applied films using the COMFEN computer software interface to the EnergyPlus simulation engine. Retrofitting single glazing, particularly clear single glazing, shows significantly higher potential than retrofitting double glazing for absorbing products. In warmer climates with mild winters like Houston, Phoenix, and Miami, the energy modeling results showed potential energy and cost savings of about 20% (heating and cooling combined) for the subject film. See Tables AC4, AC5 and AC6 in the appendix for more detail modeling results for these climates.

The subject film outperformed a simple applied film tint (a less expensive product) in all the cases modeled. However, a reflective, spectrally selective, applied film outperformed the subject film in all the cases modeled. The reflective applied film is a competitive product with a similar total cost to the subject film. There are subtle aesthetic differences between spectrally selective retrofit films based on absorbing vs. reflective properties. Some applications, such as historical buildings, may favor the absorbing product to maintain a more original appearance and to reduce reflected energy on intricate wood framing details that might require additional maintenance if exposed to additional reflected solar energy.

The modeled results show some savings (3%) for the subject film in St. Louis while the measured data indicated a net increase in total energy consumption. The level of discrepancy is likely in the margin of error of both the modeling and the measurement techniques. The model was not a perfect representation of the configuration of the subject building in St. Louis, and the measured data could have included room-to-room difference that did not relate to the windows. More than predicting the exact savings for particular building (when a generalized building definition is used), the modeling results are most useful to indicate the larger trends of the relative performance regarding different base windows, retrofit films and climates.

Because there was a net increase in energy use and unknown factors about the HVAC equipment efficiencies associated with the measured data, a cost savings analysis was conducted using an annual energy computer model. This allowed the inclusion of comparisons in climates other than St. Louis. Application specific factors, including base window performance, window-to-wall area ratio, climate, and energy cost, will influence the cost effectiveness and payback period for any particular project. While no energy savings payback for the installation cost was apparent for the test climate using measured data, modeling results indicate that hotter climates with mild winters like Houston, Phoenix, and Miami, and different base window conditions (single glazing) will more readily provide an attractive payback for solar control film window film retrofits. Energy and cost savings for the subject film on single clear glazing was about 20% for these three hotter climates.

Simple payback analysis, based on the COMFEN perimeter zone modeling results, suggest a payback between 5 and 15 years for the climates considered, using single glazing base windows. Paybacks associated with double glazing were generally longer, unless a reflective applied film is used or an absorbing film is installed on the exterior.

When evaluating a solar control window retrofit, or any type of window retrofit, a site specific analysis including an annual energy model is recommended to evaluate alternatives and select the highest performing solutions for a given building application. Both heating and cooling impacts should be considered. As in the case of the subject building in St. Louis, the modest benefits of solar control cooling energy savings can be overshadowed by the additional heating energy requirements resulting from lost passive solar gains during heating periods in some climates.

The installed retrofit film maintains a nearly indistinguishable window aesthetic to the base window, and the installation can be performed quickly with minimal disruption to building occupants (these attributes are similar for competitive applied film products). Occupants did not report significant changes in thermal comfort or glare, but interior blinds were frequently used in the perimeter offices, which diminished direct exposure of the occupants to the changes in the window properties/performance. Applied films are often specified to provide glare control and thermal comfort in highly glazed spaces without adequate shading.

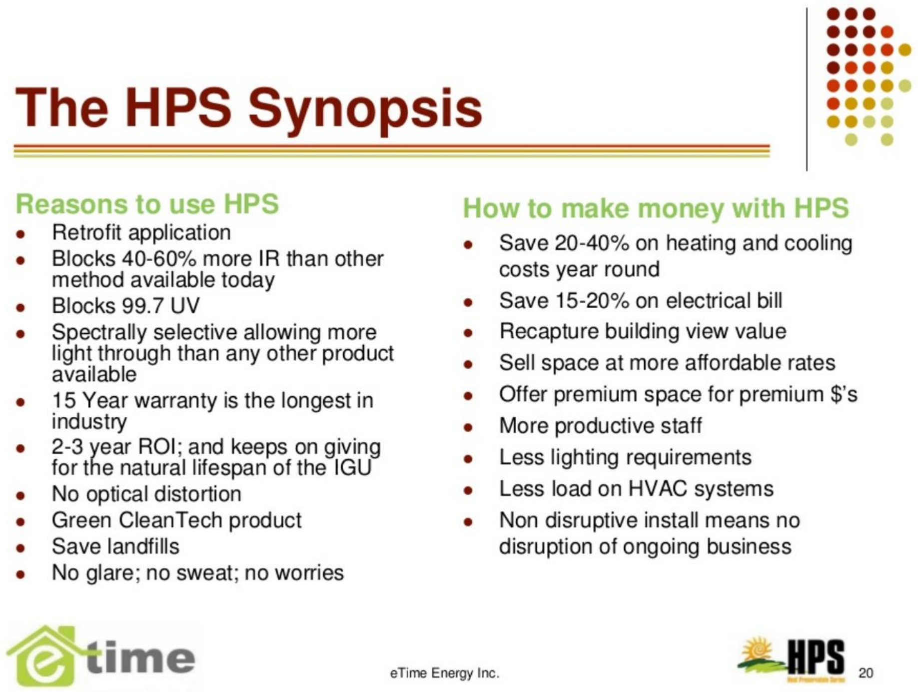
The net energy comparisons above were computed on the basis of the measured thermal energy of heating and cooling air flows at the (VAV) box serving each zone. Thus, the energy differences reported are representative of the different thermal energy flows through the windows in the coated and uncoated zones. Factors of heating and cooling equipment efficiency, the relative cost of fuel types, and time of use pricing were not included. A similar result is expected under typical scenarios when equipment efficiency differences offset fuel source price differences.

High interior glass surface temperatures of 120–140°F (50–60°C) were observed on the windows with films installed on the interior side. Occupants did not report increased discomfort, and globe radiant temperature measurements did not resolve an appreciable higher radiant temperature in rooms with interior films. This may be because the occupants were sufficiently screened from the window glass temperature by the louvered blinds installed over them (which were typically down), or the distance to the window and the action of the conditioning system diminished the effect. The measured glass temperatures (both contact and non-contact infrared measurements) were consistent with the WINDOW7 glazing performance modeling predictions.

A web-based survey was distributed to occupants of the retrofitted offices to acquire feedback regarding their thermal comfort before and after the retrofit. Occupants did not voice aesthetic objections to the installation (most did not notice the change) and they did not report a significant change in thermal comfort, except for one report of more frequently feeling cold. The survey results should be considered anecdotal and not statistically significant, as the number of responses to the survey was very low (3 responses). This actually represents a fairly high response rate of eligible occupants, though, because it was only possible to survey the occupants of the zones that received window films, 4 private offices and 1 training/multipurpose room.

VI. Appendices

A. TECHNOLOGY SPECIFICATION



The HPS Synopsis

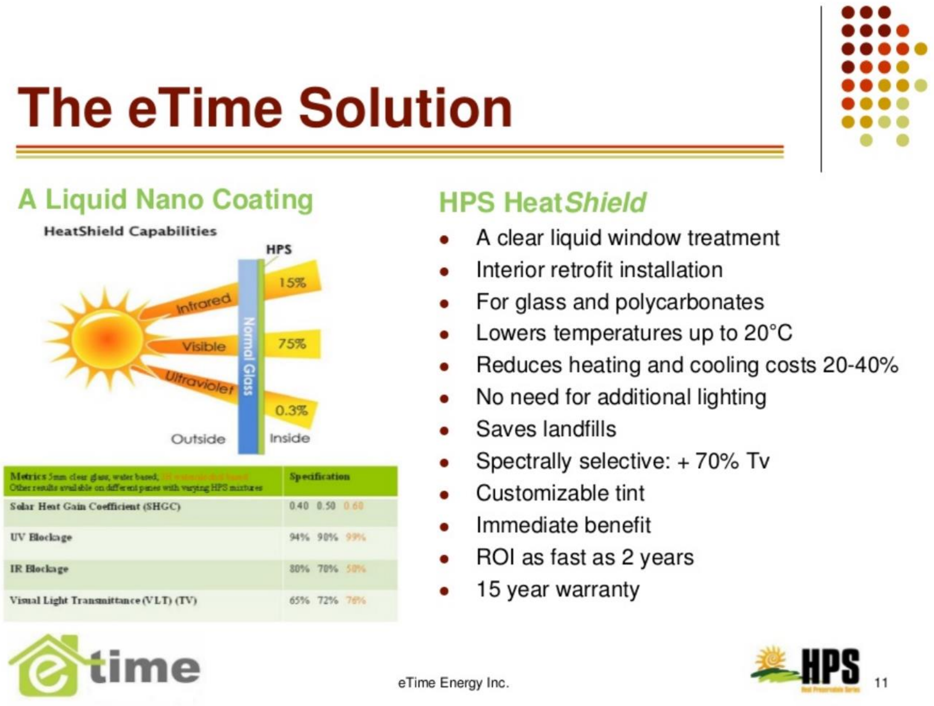
Reasons to use HPS

- Retrofit application
- Blocks 40-60% more IR than other method available today
- Blocks 99.7 UV
- Spectrally selective allowing more light through than any other product available
- 15 Year warranty is the longest in industry
- 2-3 year ROI; and keeps on giving for the natural lifespan of the IGU
- No optical distortion
- Green CleanTech product
- Save landfills
- No glare; no sweat; no worries

How to make money with HPS

- Save 20-40% on heating and cooling costs year round
- Save 15-20% on electrical bill
- Recapture building view value
- Sell space at more affordable rates
- Offer premium space for premium $'s
- More productive staff
- Less lighting requirements
- Less load on HVAC systems
- Non disruptive install means no disruption of ongoing business

eTime Energy Inc. 20



The eTime Solution

A Liquid Nano Coating

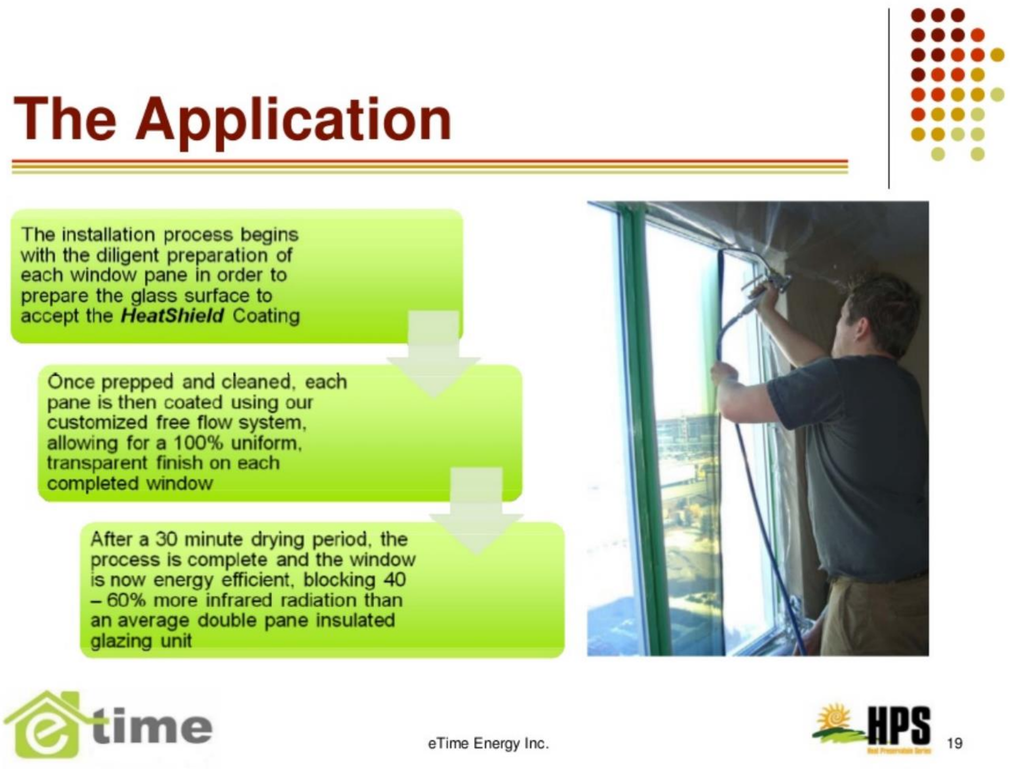
HeatShield Capabilities

Metrics 5mm clear glass, water based, [illegible] Other results available on different panes with varying HPS mixtures	Specification
Solar Heat Gain Coefficient (SHGC)	0.40 0.50 0.60
UV Blockage	94% 90% 99%
IR Blockage	80% 70% 50%
Visual Light Transmittance (VLT) (TV)	65% 72% 76%

HPS Heat*Shield*

- A clear liquid window treatment
- Interior retrofit installation
- For glass and polycarbonates
- Lowers temperatures up to 20°C
- Reduces heating and cooling costs 20-40%
- No need for additional lighting
- Saves landfills
- Spectrally selective: + 70% Tv
- Customizable tint
- Immediate benefit
- ROI as fast as 2 years
- 15 year warranty

eTime Energy Inc. 11



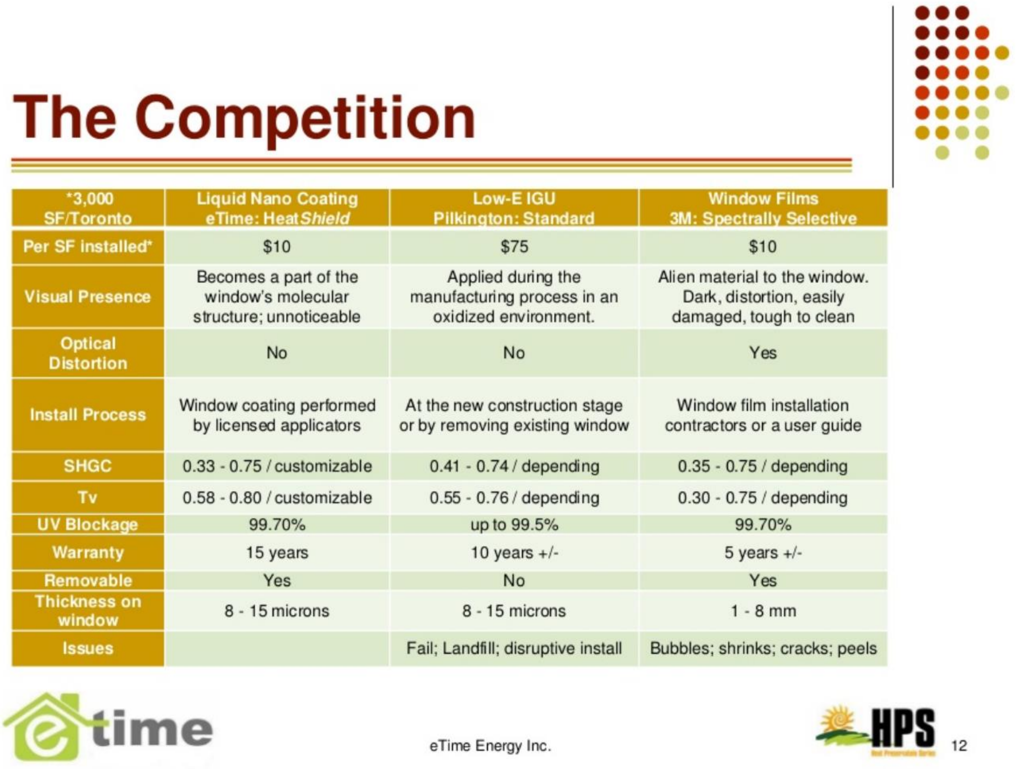
The Application

The installation process begins with the diligent preparation of each window pane in order to prepare the glass surface to accept the ***HeatShield*** Coating

Once prepped and cleaned, each pane is then coated using our customized free flow system, allowing for a 100% uniform, transparent finish on each completed window

After a 30 minute drying period, the process is complete and the window is now energy efficient, blocking 40 – 60% more infrared radiation than an average double pane insulated glazing unit

eTime Energy Inc.



The Competition

*3,000 SF/Toronto	Liquid Nano Coating eTime: Heat*Shield*	Low-E IGU Pilkington: Standard	Window Films 3M: Spectrally Selective
Per SF installed*	$10	$75	$10
Visual Presence	Becomes a part of the window's molecular structure; unnoticeable	Applied during the manufacturing process in an oxidized environment.	Alien material to the window. Dark, distortion, easily damaged, tough to clean
Optical Distortion	No	No	Yes
Install Process	Window coating performed by licensed applicators	At the new construction stage or by removing existing window	Window film installation contractors or a user guide
SHGC	0.33 - 0.75 / customizable	0.41 - 0.74 / depending	0.35 - 0.75 / depending
Tv	0.58 - 0.80 / customizable	0.55 - 0.76 / depending	0.30 - 0.75 / depending
UV Blockage	99.70%	up to 99.5%	99.70%
Warranty	15 years	10 years +/-	5 years +/-
Removable	Yes	No	Yes
Thickness on window	8 - 15 microns	8 - 15 microns	1 - 8 mm
Issues		Fail; Landfill; disruptive install	Bubbles; shrinks; cracks; peels

eTime Energy Inc.

B. WINDOW7 GLAZING PERFORMANCE COMPARISON

Table AB1. SHGC of single glazing with interior film: room side absorbing films can be effective to reduce solar gain on single glazing. Single clear is somewhat uncommon, most commercial glass has some additional tint or reflection. The amount of absorbed radiation dissipated outside depends on outdoor and indoor temperature and air speed.

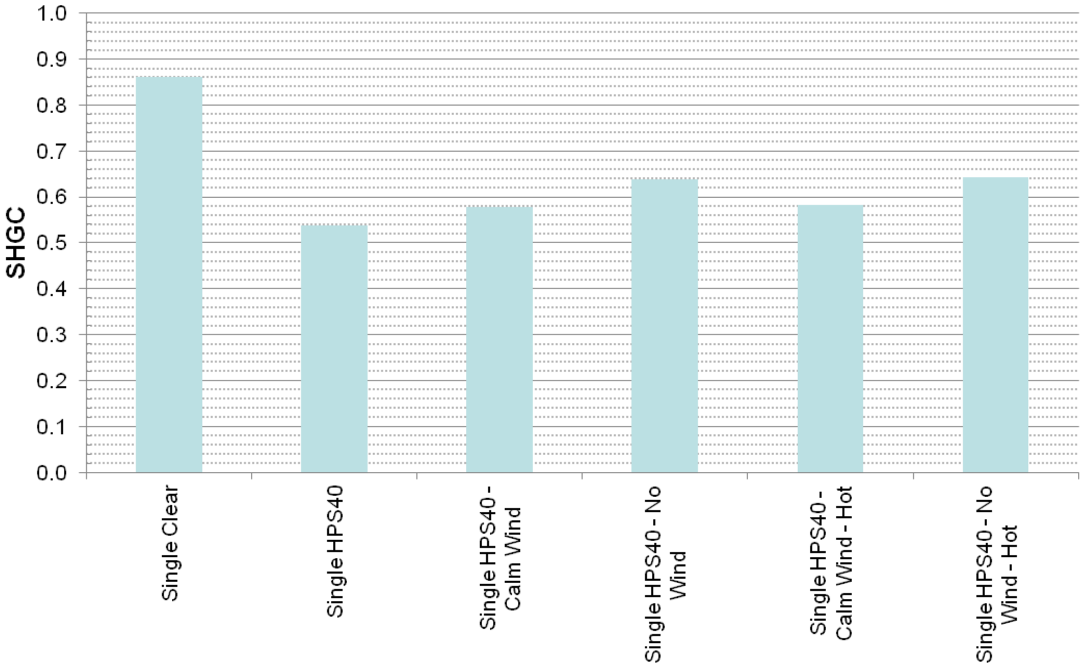


Table AB2. SHGC of double glazing with interior film: room side absorbing layers on double glazing trap most of the absorbed energy in the room, resulting in modest reductions of SHGC. Ambient conditions have a significant impact on SHGC.

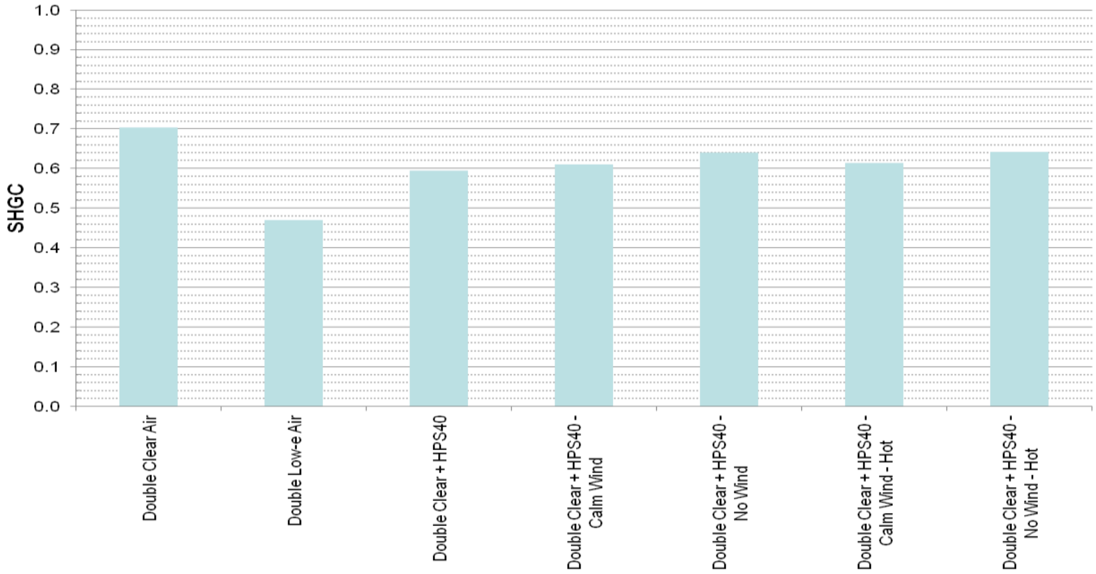


Table AB3. SHGC of double glazing with exterior film: exterior absorbing layers on double glazing provide lower SHGC because they can more easily dissipate absorbed energy to the exterior.

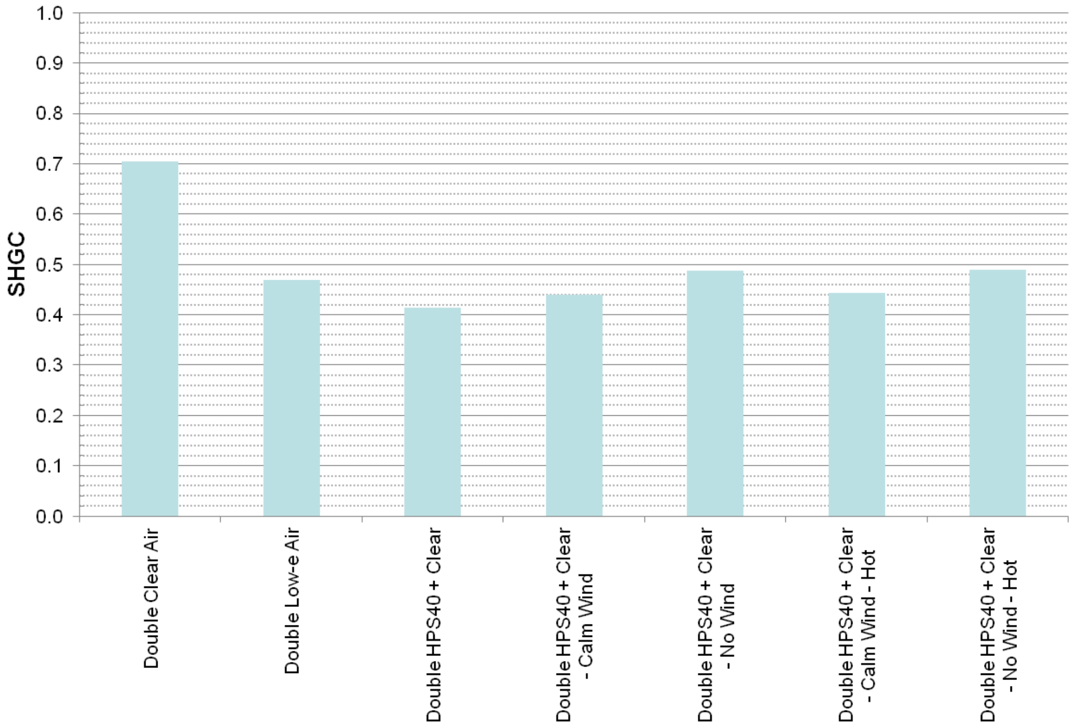


Table AB4. Surface temperatures of single glazing with interior film: room side surface temperatures are increased with the use of absorbing layers.

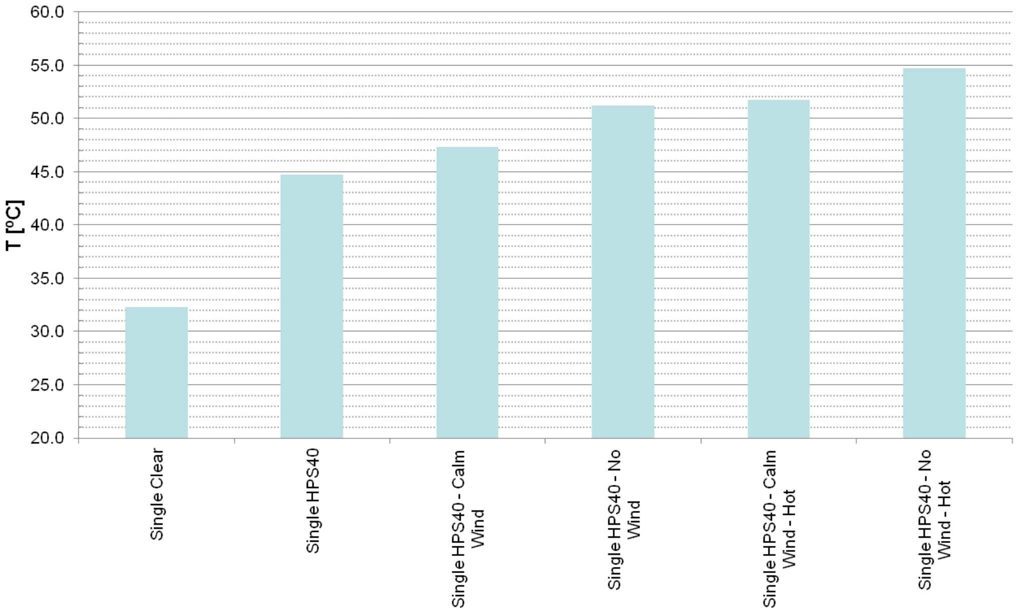


Table AB5. Surface temperatures of double glazing with interior film: room side surface temperatures are increased further with the use of absorbing layers on the room side of double glazing.

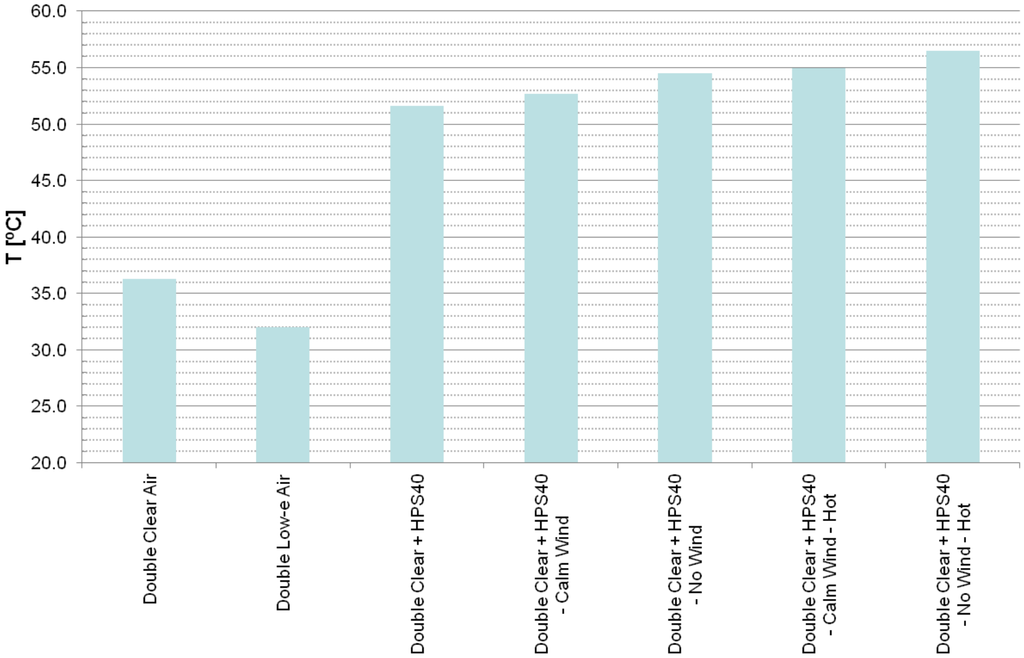
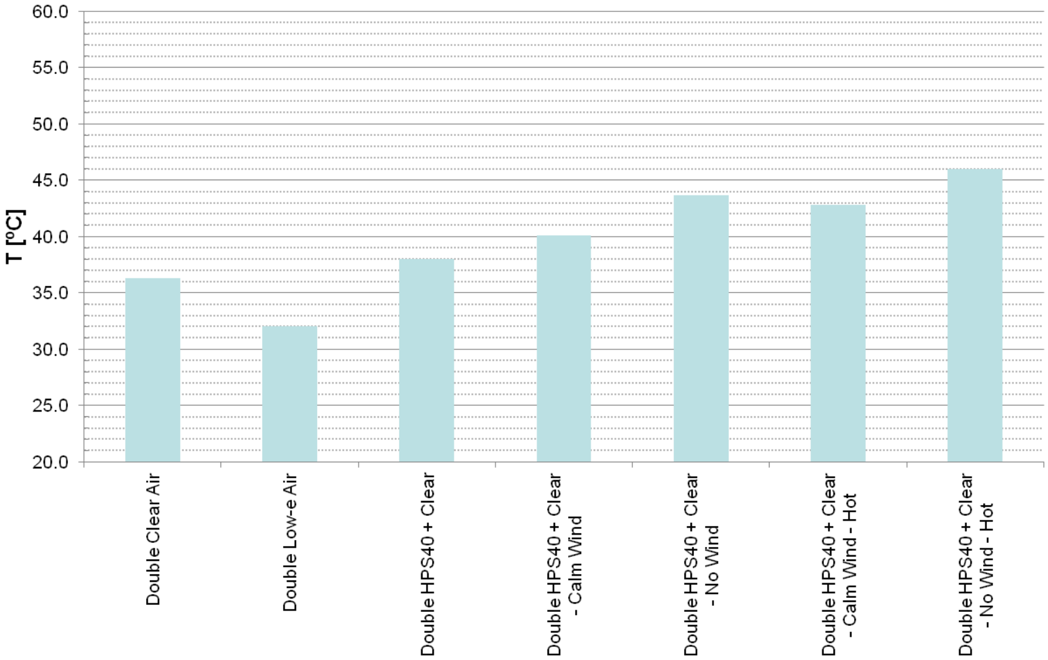


Table AB6. Surface temperatures of double glazing with exterior film: exterior absorbing layers on double glazing raise the room side surface temperature of the window modestly.



C. COMFEN MODELING SPECIFICATION AND RESULTS

Table AC1. Window system solar/optical properties if various applied films and films on three base window substrates. Film A is the subject film in the study, film B is an infrared reflective applied film, film C is an absorbing applied film

ID	Glazing System Name	# of layers	U-factor (BTU/h-ft-F)	SHGC	Tsol	Tvis	Room side Emittance
1	Single Clear	1	1.02	0.82	0.77	0.88	0.84
2	Single Clear + Film A	1	1.04	0.54	0.36	0.64	0.87
3	Single Clear + Film B	1	0.86	0.45	0.34	0.67	0.53
4	Single Clear + Film C	1	1.03	0.69	0.58	0.69	0.85
5	Single Bronze	1	1.02	0.63	0.49	0.53	0.84
6	Single Bronze + Film A	1	1.04	0.45	0.22	0.38	0.87
7	Single Bronze + Film B	1	0.86	0.38	0.21	0.40	0.53
8	Single Bronze + Film C	1	1.03	0.55	0.37	0.41	0.85
9	Double Bronze	2	0.47	0.50	0.38	0.47	0.84
10	Double Bronze + Film A	2	0.48	0.44	0.18	0.34	0.87
11	Double Bronze + Film B	2	0.43	0.36	0.18	0.37	0.53
12	Double Bronze + Film C	2	0.48	0.48	0.32	0.38	0.85
13	Double Bronze + Film A Outside	2	0.47	0.32	0.18	0.34	0.87* Exterior side

Table AC2. Commercial Retail Electricity and gas prices, by state, used to calculate energy cost savings and payback. Source EIA 2013 (annual average)

	Electricity $/kWh	Gas $/1000cu.ft.	Gas $/therm
Missouri (St. Louis)	$0.0759	$9.00	$0.8780
Texas (Houston)	$0.0797	$7.25	$0.7073
Arizona (Phoenix)	$0.0924	$8.76	$0.8546
Florida (Miami)	$0.0954	$10.87	$1.0605

Table AC3. COMFEN Results for glazing systems described in Table A1. Climate: St. Louis, MO

ID	Case	Heating (kBtu/ft2-yr)	Cooling (kBtu/ft2-yr)	Fan (kBtu/ft2-yr)	Total Energy (kBtu/ft2-yr)	Total Cost $/ft^2-yr	Peak Electric (W/sf)
1	Single Clear	14.32	27.73	24.60	66.66	$1.29	9.61
2	Single Clear + Film A	21.68	18.37	18.65	58.69	$1.01	7.78
3	Single Clear + Film B	18.76	16.95	16.36	52.06	$0.91	7.17
4	Single Clear + Film C	17.59	22.60	21.36	61.55	$1.13	8.64
5	Single Bronze	19.24	20.41	19.92	59.56	$1.07	8.18
6	Single Bronze + Film A	25.17	15.65	16.74	57.56	$0.94	7.19
7	Single Bronze + Film B	21.70	14.57	14.85	51.12	$0.84	6.74
8	Single Bronze + Film C	21.64	18.11	18.41	58.16	$1.00	7.71
9	Double Bronze	11.74	18.18	15.88	45.80	$0.86	7.13
10	Double Bronze + Film A	13.93	15.92	14.66	44.51	$0.80	6.72
11	Double Bronze + Film B	13.51	14.61	13.33	41.46	$0.74	6.36
12	Double Bronze + Film C	12.71	17.20	15.37	45.28	$0.84	6.96
13	Double Bronze + Film A Outside	16.67	13.47	12.76	42.90	$0.73	6.17

Table AC4. COMFEN Results for glazing systems described in Table A1. Climate: Houston, TX

ID	Case	Heating (kBtu/ft2-yr)	Cooling (kBtu/ft2-yr)	Fan (kBtu/ft2-yr)	Total Energy (kBtu/ft2-yr)	Total Cost $/ft^2-yr	Peak Electric (W/sf)
1	Single Clear	1.85	33.42	12.98	48.25	$1.10	6.78
2	Single Clear + Film A	3.05	25.15	10.67	38.87	$0.86	6.03
3	Single Clear + Film B	2.37	23.54	9.67	35.58	$0.79	5.68
4	Single Clear + Film C	2.36	29.02	11.75	43.13	$0.97	6.38
5	Single Bronze	2.63	27.04	11.19	40.86	$0.91	6.19
6	Single Bronze + Film A	3.70	22.47	9.91	36.08	$0.78	5.78
7	Single Bronze + Film B	2.88	21.14	9.07	33.09	$0.73	5.48
8	Single Bronze + Film C	3.03	24.90	10.58	38.52	$0.85	6.00
9	Double Bronze	1.26	24.24	9.19	34.69	$0.79	5.49
10	Double Bronze + Film A	1.58	22.11	8.71	32.39	$0.73	5.33
11	Double Bronze + Film B	1.45	20.73	8.14	30.33	$0.68	5.13
12	Double Bronze + Film C	1.40	23.34	9.00	33.74	$0.77	5.42
13	Double Bronze + Film A Outside	1.98	19.62	7.94	29.54	$0.66	5.09

Table AC5. COMFEN Results for glazing systems described in Table A1. Climate: Phoenix, AZ

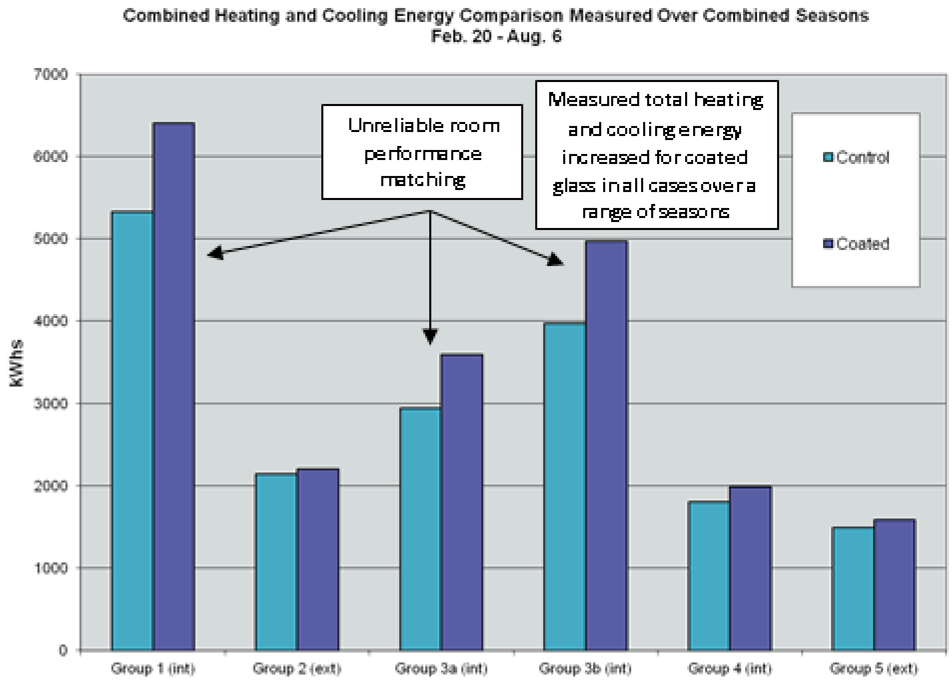
ID	Case	Heating (kBtu/ft2-yr)	Cooling (kBtu/ft2-yr)	Fan (kBtu/ft2-yr)	Total Energy (kBtu/ft2-yr)	Total Cost $/ft^2-yr	Peak Electric (W/sf)
1	Single Clear	0.59	52.30	20.18	73.08	$1.97	8.82
2	Single Clear + Film A	0.97	40.31	16.74	58.02	$1.55	7.55
3	Single Clear + Film B	0.70	36.39	14.77	51.86	$1.39	6.90
4	Single Clear + Film C	0.75	45.91	18.35	65.02	$1.75	8.13
5	Single Bronze	0.83	43.02	17.50	61.35	$1.65	7.82
6	Single Bronze + Film A	1.17	36.39	15.61	53.16	$1.42	7.11
7	Single Bronze + Film B	0.85	33.06	13.84	47.75	$1.28	6.52
8	Single Bronze + Film C	0.96	39.91	16.60	57.46	$1.54	7.50
9	Double Bronze	0.35	36.27	13.69	50.31	$1.36	6.59
10	Double Bronze + Film A	0.43	33.30	12.96	46.69	$1.26	6.32
11	Double Bronze + Film B	0.37	30.65	11.92	42.94	$1.16	5.94
12	Double Bronze + Film C	0.39	35.05	13.40	48.83	$1.31	6.48
13	Double Bronze + Film A Outside	0.52	29.59	11.83	41.95	$1.13	5.85

Table AC6. COMFEN Results for glazing systems described in Table A1. Climate: Miami, FL

ID	Case	Heating (kBtu/ft2-yr)	Cooling (kBtu/ft2-yr)	Fan (kBtu/ft2-yr)	Total Energy (kBtu/ft2-yr)	Total Cost \$/ft^2-yr	Peak Electric (W/sf)
1	Single Clear	0.05	41.17	11.26	52.48	$1.47	5.80
2	Single Clear + Film A	0.08	32.59	9.22	41.89	$1.17	5.17
3	Single Clear + Film B	0.06	30.68	8.47	39.20	$1.09	4.91
4	Single Clear + Film C	0.06	36.64	10.16	46.86	$1.31	5.46
5	Single Bronze	0.07	34.53	9.66	44.26	$1.24	5.30
6	Single Bronze + Film A	0.09	29.64	8.52	38.25	$1.07	4.94
7	Single Bronze + Film B	0.07	28.02	7.88	35.96	$1.00	4.72
8	Single Bronze + Film C	0.08	32.30	9.14	41.52	$1.16	5.14
9	Double Bronze	0.04	31.08	8.21	39.33	$1.10	4.82
10	Double Bronze + Film A	0.04	28.82	7.72	36.58	$1.02	4.66
11	Double Bronze + Film B	0.04	27.18	7.24	34.46	$0.96	4.50
12	Double Bronze + Film C	0.04	30.14	8.01	38.19	$1.07	4.76
13	Double Bronze + Film A Outside	0.05	26.14	7.06	33.25	$0.93	4.45

D. MEASURED ENERGY DELIVERED

Table AD1. VAV box metered energy data Feb. 20-Aug. 6

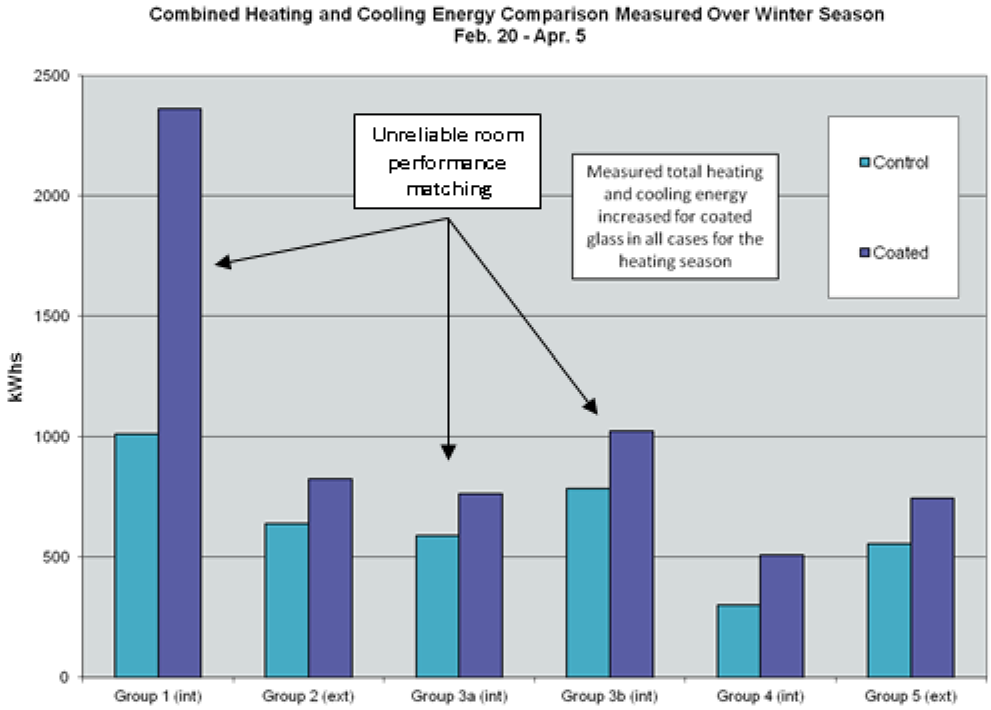


Combined Heating and Cooling Energy Comparison Measured Over Combined Seasons
Feb. 20 - Aug. 6

Unreliable room performance matching

Measured total heating and cooling energy increased for coated glass in all cases over a range of seasons

Table AD2. VAV box metered energy data Feb. 20-Apr. 5



Combined Heating and Cooling Energy Comparison Measured Over Winter Season
Feb. 20 - Apr. 5

Unreliable room performance matching

Measured total heating and cooling energy increased for coated glass in all cases for the heating season

Table AD3. VAV box metered energy data Apr. 6-May. 31

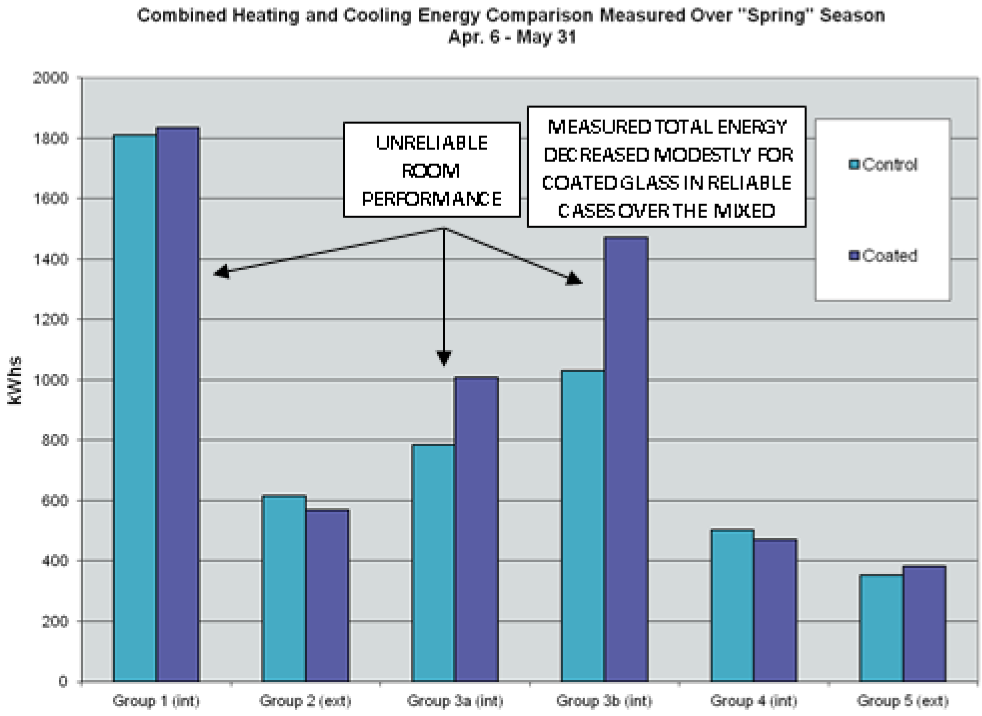
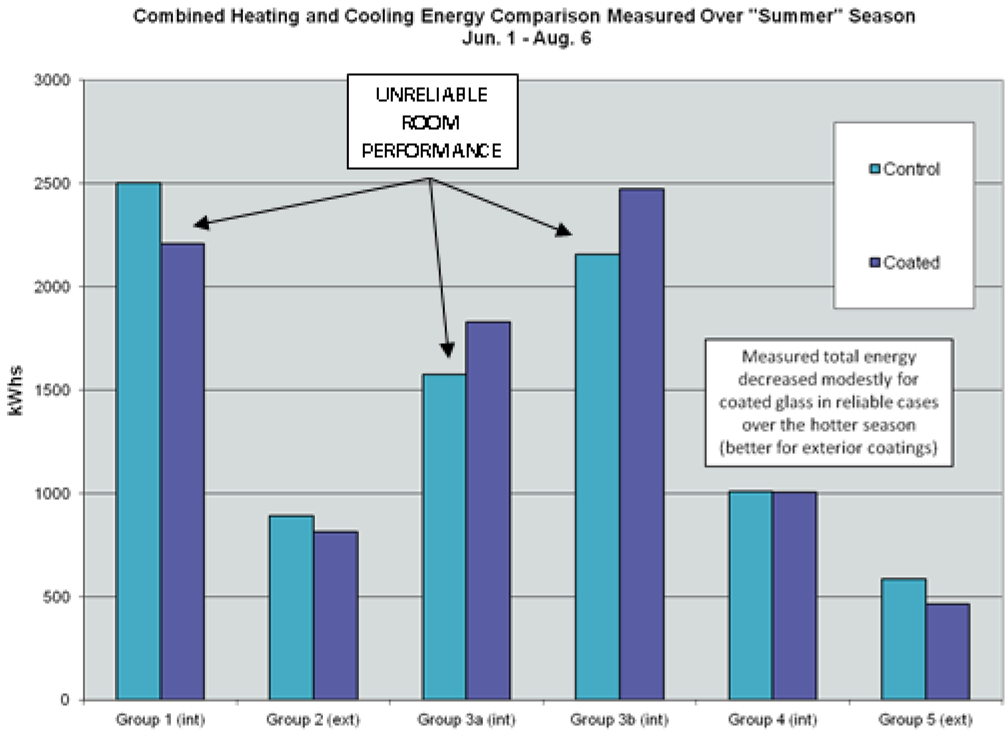


Table AD4. VAV box metered energy data Jun. 1-Aug. 6



E. OCCUPANT SURVEY

Table AE1. Survey questions and answers regarding user retrofit experience

1. How close to a window do you sit to perform the majority of your work?		
less than 15 feet	100%	
	3	
15 - 30 feet	0%	
	0	
greater than 30 feet	0%	
	0	
Total	3	
2. In which locations did you experience the retrofitted solar control window film? (you may select more than one)		
private office	100%	
private office training room	3	
	33%	
training room break/lunch room	1	
	0%	

3. How often were you thermally uncomfortable in retrofitted work spaces before and after the window retrofit, Oct. 2012? (you may select more than one answer in each row)

	frequently too cold	occasionally too cold	never too cold	never too hot	occasionally too hot	frequently too hot	Total
before retrofit	0%	67%	0%	0%	67%	0%	
	0	2	0	0	2	0	3
after retrofit	33%	33%	0%	0%	67%	0%	
	1	1	0	0	2	0	3

4. How often did retrofitted windows cause visual discomfort (glare) before and after the window retrofit, Oct. 2012?

	frequently too bright (glare)	occasionally too bright (glare)	never too bright (no glare)	Total
before retrofit	0%	67%	33%	
	0	2	1	3
after retrofit	0%	67%	33%	
	0	2	1	3

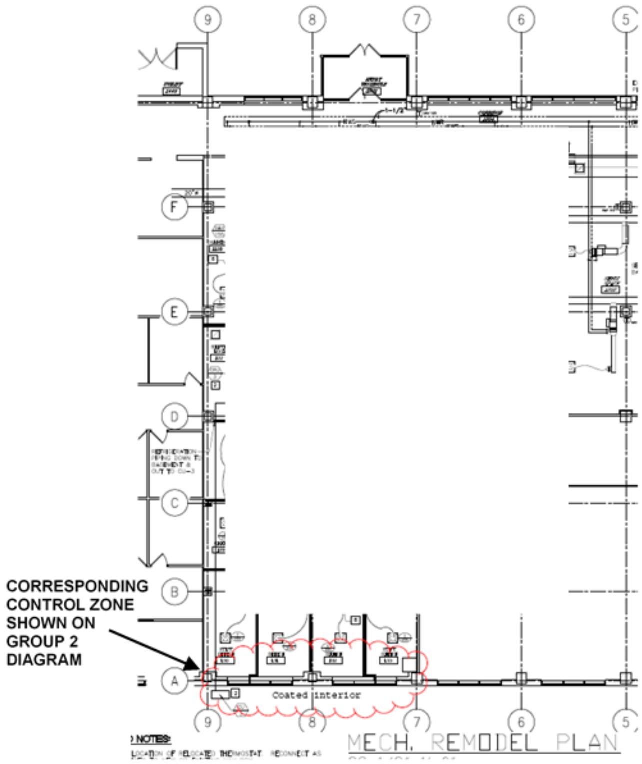
5. What is your preferred position for the window blinds in your work space? (you may select more than one answer)		
up, clear window view	0%	
	0	
down, slats horizontal (open)	67%	
	2	
down, slats tilted (partially open)	33%	
	1	
down, slats vertical (closed)	33%	
	1	
no preference	0%	
	0	
don't have a window or window blinds in my work space	0%	
	0	
Total	3	

6. How often do you adjust the position of the window blinds in your work space?		
frequently adjust blinds	0% 0	
occasionally adjust blinds	50% 1	
never adjust blinds	50% 1	
don't have a window or window blinds in my work space	0% 0	
Total	2	

7. What factors motivate your adjustment of the window blinds in your work space? (you may select more than one answer)		
adjusting light level (glare control)	67% 2	
thermal management	0% 0	
privacy	33% 1	
don't have a window or window blinds in my work space	0% 0	
Other (please specify)	0% 0	

8. Based on your experience with the window retrofit in your building, would you recommend similar retrofits elsewhere?		
strongly recommend	0%	
	0	
recommend	33%	
	1	
no opinion	67%	
	2	
don't recommend	0%	
	0	
Total	3	
9. How would you characterize the visual appearance of the window retrofit?		
no noticeable difference in appearance	67%	
	2	
noticeable, but acceptable difference in appearance	0%	
	0	
negative impact on appearance	33%	
	1	
Total	3	
10. How would you characterize the visual appearance of the window retrofit?		
Darkens office a bit. Prefer brightness. Darkness affects mood at times.		
Total	1	

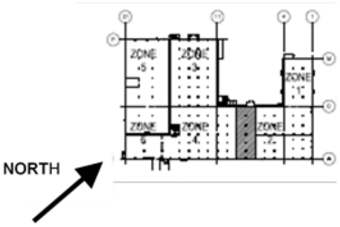
F. TEST GROUP FLOOR PLANS

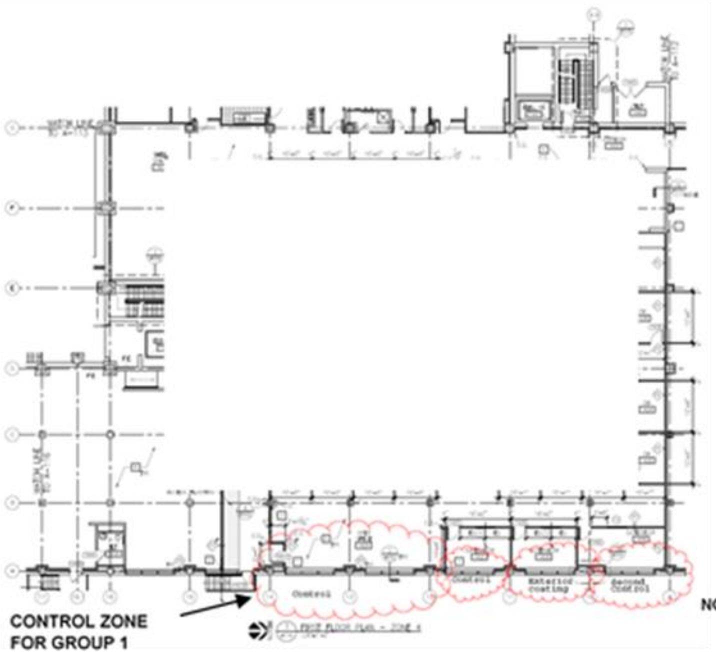


TEST GROUP 1

INTERIOR APPLICATION OF FILM
Between columns 7-9 (New remodel)
VAV157 feeds four perimeter registers
Two open, two enclosed offices
Two window bays split (1 lite, 2 lites, 2 lites, 1 lite = 6 lites)

Control (no film)
Between columns 12-14
VAV136 feeds four perimeter registers
Two windows bays with three lites each



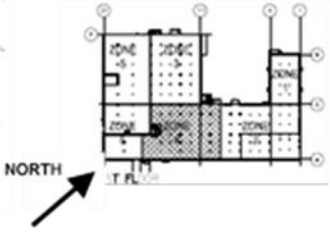


TEST GROUP 2

EXTERIOR APPLICATION OF FILM
Between columns 10-11
VAV143 feeds two perimeter registers
One enclosed office
One window bay (3 lites)

Control (no film)
Between columns 11-12
VAV142 feeds two perimeter registers
One enclosed office
One window bay (3lites)

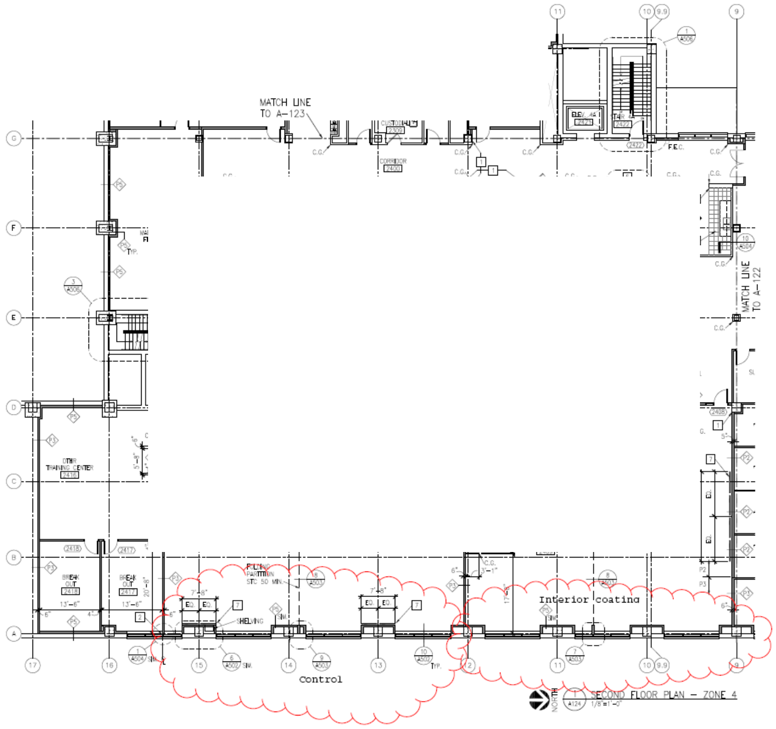
Secondary control (no film)
Between columns 9-10
VAV146 feeds two perimeter registers
One enclosed office (slightly larger)
One window bay (3lites)

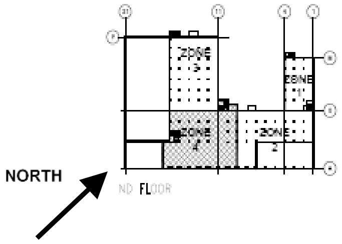


TEST GROUP 3

INTERIOR APPLICATION OF FILM
Between columns 9-12
VAV281 (missing data) feeds two perimeter registers (VAV282 core)
VAV285 feeds three perimeter registers (VAV283 core)
Large multipurpose room with movable partition
Three window bays split (4 lites, and 5 lites = 9 lites)

Control (no film)
Between columns 12-15 (plus one lite toward 16)
VAV291 feeds two perimeter registers (VAV290 core)
VAV286 feeds three perimeter registers (VAV288 core)
Large multipurpose room with movable partition
Three window bays plus one lite split (4 lites, and 6 lites)

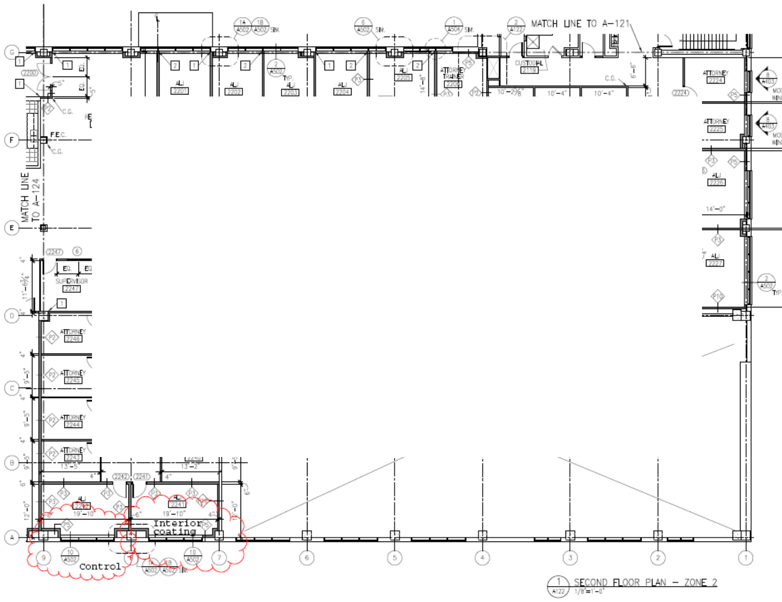


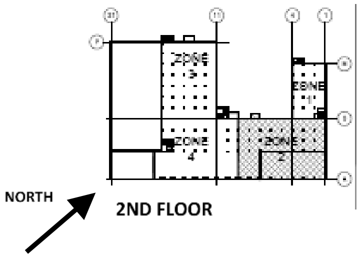


TEST GROUP 4

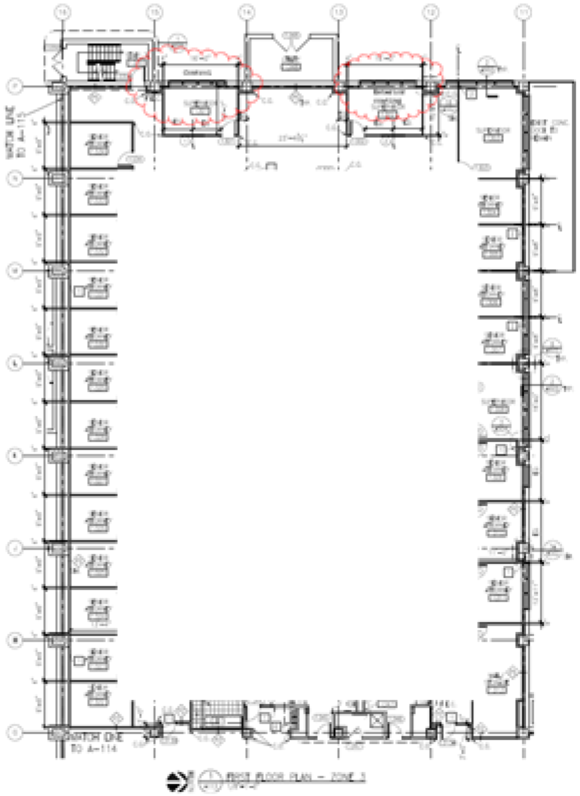
INTERIOR APPLICATION OF FILM
Between columns 7-8
VAV216 feeds two perimeter registers
One enclosed office, One window bay (3 lites)

Control (no film)
Between columns 8-9
VAV217 feeds two perimeter registers
One enclosed office, One window bay (3 lites)



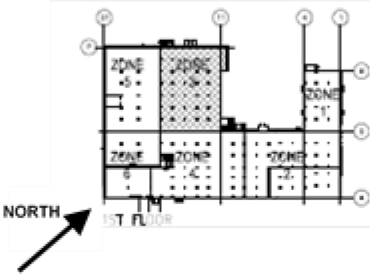


TEST GROUP 5



EXTERIOR APPLICATION OF FILM
Between columns 12-13
VAV185 feeds two perimeter registers
One enclosed office
One window bay (4 lites)

Control (no film)
Between columns 14-15
VAV181 feeds two perimeter registers
One enclosed office
One window bay (4 lites)



G. REFERENCES

Apte, J., Arasteh, D. (2006), Window-Related Energy Consumption in the US Residential and Commercial Building Stock. Berkeley, CA: Lawrence Berkeley National Laboratory report, LBNL-60146 http://gaia.lbl.gov/btech/papers/60146.pdf

Griffith, B.,Turler, D., Goudey, H. (2000), Infrared Thermography Systems, in The Encyclopedia of Imaging Science and Technology (vol. I), New York: John Wiley and Sons, LBNL-46590 http://gaia.lbl.gov/btech/papers/46590.pdf

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

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

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

2013 EIA annual average gas price by state (interactive) http://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_m.htm

2013 EIA annual average electricity price by state
Table 5.6.A http://www.eia.gov/electricity/monthly/current_year/february2014.pdf

H. GLOSSARY

Term	Definition
Low-emittance, or low-emissivity (Low-E) coating	Microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window or skylight glazing surface primarily to reduce the U-factor by suppressing radiative heat flow. A low-e coating can be highly transparent in the solar spectrum (visible light and short-wave infrared radiation) and reflective of long-wave infrared radiation. Low-e coatings are also often combined with solar heat gain control features that maintain high visible transmission, while reflecting most of the short-wave infrared in the solar spectrum.
U-factor (U-value)	A measure of the rate of non-solar heat loss or gain through a material or assembly. It is expressed in units of BTU/hr-ft^2-°F (US) or W/m^2-°K (metric). Values are normally given for NFRC/ASHRAE winter conditions of 0° F (-18° C) outdoor temperature, 70° F (21° C) indoor temperature, 15 mph wind, and no solar load. The U-factor may be expressed for the glass alone or the entire window, which includes the effect of the frame and the spacer materials. The lower the U-factor, the greater a window's resistance to heat flow and the better its insulating value.
Solar heat gain coefficient (SHGC)	The fraction of solar radiation admitted through a window or skylight, both directly transmitted, and absorbed and subsequently released inward. The solar heat gain coefficient has replaced the shading coefficient as the standard indicator of a window's shading ability. It is expressed as a number between 0 and 1. The lower a window's solar heat gain coefficient, the less solar heat it transmits, and the greater its shading ability. SHGC can be expressed in terms of the glass alone or can refer to the entire window assembly.
Visible transmission (Tvis, or VT)	The fraction of incident light that passes through a window or skylight. Only the portion of the solar spectrum that is visible to the human eye.
Solar transmission (Tsol)	The fraction of incident solar radiation that passes through a window or skylight. The entire solar spectrum (UV, visible and near infrared) are included in this transmission. Represent the total fraction of incident solar energy that enters the rooms by direct transmission.
Insulating Glass (IG) Insulating Glass Unit (IGU)	A combination of two or more panes of glass with a hermetically sealed air space between the panes of glass, separated by a spacer. This space may or may not be filled with an inert gas, such as argon.
Conduction	Thermal heat transfer through a solid material. Heat flows from high temperature portions of the solid toward the cooler temperature portions.

Term	Definition
Convection	Thermal heat transfer in a fluid (including gases) resulting from bulk motion of the fluid resulting from a temperature difference in the fluid inducing buoyancy driven flows (warmer portions of the fluid have a different density than cooler portions of the fluid).
Radiation	Thermal heat transfer propagated by electromagnetic radiation (light waves) across an air/gas gap or vacuum. Warmer objects radiate more energy than cooler objects, resulting in a net heat flow between warm/cool surfaces. Surface material properties can change the amount of radiation emitted (see low-emittance surface above).
Infrared	The portion of the electromagnetic spectrum (light waves) with longer wavelengths than visible light. Infrared includes parts of the solar spectrum (near infrared, or solar infrared), as well as longer wavelengths emitted by room temperature objects (long-wave infrared).
Thermogram	An image of surface temperatures (each pixel is a numerical surface temperature), collected with a thermal camera. Typically the surface temperature data is presented using a false color temperature scale (red on the hot end and blue on the cool end), although the color scale is arbitrary
Variable Air Volume (VAV) system	A variable air volume heating and cooling system has a central conditioning system providing relatively constant supply air temperature to a series of distributed variable air volume (VAV) boxes the serve smaller zones of the building, modulating the locally required heating and cooling demands by adjusting the volume of air supplies to the space rather that the temperature of the air.
Quad	One-quadrillion (10^{15}) BTUs, a very large unit of energy commonly used to express national annual energy consumption. US annual energy consumption is roughly 100 quads.
Applied window film	Fenestration attachment products which consist of a flexible adhesive-backed polymer film which may be applied to the interior or exterior surface of an existing glazing system. See Fenestration Attachment.
Nanoparticle suspension	Small particles (diameter of particles measured in nanometers) suspended in a liquid, forming base material for the liquid applied film.
Solar reflectance	The ratio of the reflected solar radiation to the incident solar radiation
Solar absorption	The ratio of the absorbed solar radiation to the incident solar radiation
Double glazed	Glazing system in a window, consisting of two glass panes.

Term	Definition
Bronze tint	Bronze colored glazing, manufactured by incorporation of additives in the molten glass.
HVAC	An acronym for Heating, Ventilation and Air-Conditioning equipment, referring to all the building mechanical systems that produce and deliver temperature and humidity conditioned air and fresh air supply within a building.