


Low-E Retrofit Demonstration and Educational Program

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Quanta Technologies, Inc.

AGC Flat Glass North America, Inc.

Home Innovation Research Labs, Inc.

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Larson Manufacturing Company

Pilkington North America, Inc. - NSG Group

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Primary Contractor: Quanta Technologies Inc.

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Executive Summary

The objective of this project was to demonstrate the capability of low-emissivity (low-E) storm windows / panels and low-E retrofit glazing systems to significantly and cost effectively improve the energy efficiency of both existing residential and commercial buildings. Supporting objectives included (a) determination of real world energy savings and other benefits associated with this technology, (b) identification of any market or technical barriers that may hinder widespread application, and (c) development of an educational program and materials to facilitate rapid expansion and replication on a state-by-state or regional basis. The key outcomes are listed below:

Residential Case Studies

- A residential case study in two large multifamily apartment buildings in Philadelphia showed a substantial 18-22% reduction in heating energy use and a 9% reduction in cooling energy use by replacing old clear glass storm windows with modern low-E storm windows. Furthermore, the new low-E storm windows reduced the overall apartment air leakage by an average of 10%.
- Air leakage testing on interior low-E panels installed in a New York City multifamily building over windows with and without AC units showed that the effective leakage area of the windows was reduced by 77-95%.
- To study the use of low-E storm windows in a warmer mixed climate with a balance of both heating and cooling, 10 older homes near Atlanta with single pane windows were tested with three types of exterior storm windows: clear glass, low-E glass with high solar heat gain, and low-E glass with lower solar heat gain. The storm windows significantly reduced the overall home air leakage by an average of 17%, or 3.7 ACH_{50}. Considerably high variability in the data made it difficult to draw strong conclusions about the overall energy usage, but for heating periods, the low-E storm windows showed approximately 15% heating energy savings, whereas clear storm windows were neutral in performance. For cooling periods, the low-E storm windows showed a wide range of performance from 2% to over 30% cooling energy savings. Overall, the study showed the potential for significantly more energy savings from using low-E glass versus no storm window or clear glass storm windows in warmer mixed climates, but it is difficult to conclusively say whether one type of low-E performed better than the other.

Commercial Case Studies

- A 12-story office building in Philadelphia was retrofitted by adding a double-pane low-E insulating glass unit to the existing single pane windows, to create a triple glazed low-E system. A detailed side-by-side comparison in two pairs of perimeter offices facing north and east showed a 39-60% reduction in heating energy use, a 9-36% reduction in cooling energy use, and a 10% reduction in peak electrical cooling demand. An analysis of utility bills estimated the whole building heating and cooling energy use was reduced by over 25%. Additionally, the retrofit window temperatures were commonly 20 degrees warmer on winter days, and 10-20 degrees cooler on summer days, leading to increased occupant comfort.

- Two large 4-story office buildings in New Jersey were retrofitted with a similar system, but using two low-E coatings in the retrofit system. The energy savings are being monitored by a separate GPIC project; this work quantified the changes in glass surface temperatures, thermal comfort, and potential glass thermal stress. The low-E retrofit panels greatly reduced daily variations in the interior window surface temperatures, lowering the maximum temperature and raising the minimum temperature by over 20°F compared to the original single pane windows with window film. The number of hours of potential thermal discomfort, as measured by deviation between mean radiant temperature and ambient air temperature by more than 3°F, were reduced by 93 percent on the south orientation and over two-thirds on the west orientation. Overall, the low-E retrofit led to substantially improved occupant comfort with less periods of both overheating and feeling cold.
- No significant thermal stress was observed in the New Jersey office building test window when using the low-E retrofit system over a variety of weather conditions. The surface temperature difference only exceeded 10°F (500 psi thermal stress) for less than 1.5% of the monitored time, and in all cases, the maximum surface temperature difference never exceeded 35°F (1,750 psi thermal stress).

Low-E Storm Window Outreach and Education Program

- The project team assisted the State of Pennsylvania in adding low-E storm windows as a cost effective weatherization measure on its priority list for the state weatherization assistance program.
- No technical barriers that could hinder widespread application were identified in the case studies. However, educational barriers have been identified, in that weatherization personnel commonly misunderstand how the application of low-E storm windows is very different than much more expensive full window replacement. This needs to be addressed with further outreach activities.
- A package of educational materials was developed to help communicate the benefits of low-E storm windows and retrofits as a cost effective tool for weatherization personnel.
- Using detailed thermal simulations, more accurate U-factor and solar heat gain coefficient (SHGC) values were determined for low-E storm windows installed over different primary windows.

Overall, this work confirmed the potential for low-E storm windows, panels, and retrofit systems to provide significant energy savings, reductions in air leakage, and improvements in thermal comfort in both residential and commercial existing buildings.

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The project team included:

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Contents

1. Introduction and Background

The existing building stock consumes a vast amount of energy, yet the rate at which energy efficiency is being improved is inadequately slow. On the residential side, there are approximately 111 million homes and 19 billion ft^2 of existing windows in the U.S., of which 76% were built prior to 1990 when low-E windows were not widely prevalent.[1] Furthermore, it is estimated that 43% of all residential windows have single pane glass.[2] Prior to the recent recession, approximately 1.5 million new homes were built each year, representing approximately 1.3% of the total homes.[3] Therefore, total new window installation including the replacement market accounts for less than 2-3% of all the existing windows per year. At this rate, it could conceivably take well over 50 years to incorporate energy efficient windows into all residential buildings. This slow rate of improvement is supported by the fact that average energy consumption per household has not changed dramatically between 1984 and 2005, hovering around 100 MBtu per household.[4]

A similar story exists for the commercial building sector where 53% of commercial buildings still have single glazing, yet over a 23 year period between 1980 and 2003, only 6.7% of buildings replaced their windows.[5]

The slow rate of improvement makes it clear that it is not sufficient to simply require improved energy efficiency for new products and buildings – the existing building stock must be addressed in a rapid and cost effective manner. One significant new opportunity is to use existing low-E glass technology in a new, cost effective application method – retrofitting buildings by adding a durable low-E glazing panel over the existing glazing, without the need to remove and replace the existing window.

For residential homes, this is simply an inexpensive and easily installed exterior or interior storm window using a durable low-E glass. Although it may sound obvious, this application has been underutilized, and prior to this project, virtually all storm windows were manufactured with clear, uncoated glass. While the use of low-E coatings in double-pane, sealed insulating glass windows has become commonplace over the last decade, its use in the storm window market was previously limited to special orders and less than 1% of the market. This missed opportunity hit lower income families especially hard in that these same households have a disproportionately higher amount of single glazing, and can least afford new replacement windows or high energy costs.

For commercial applications, traditional rip-out and replacement of glazing is expensive and causes significant disruption to business tenants, creating an economic barrier to widespread improvement of the existing building stock. Attaching an interior low-E glazing panel or insulating glazing to existing single glazing can significantly improve energy efficiency at less than half the installed cost of a traditional rip-out and replacement.

A retrofit application where the low-E coating may be exposed to environmental conditions and humidity requires a durable low-E technology. Pyrolytic low-E coatings based on ceramic transparent conductive oxides such as fluorine-doped tin oxide satisfy this requirement. This type of low-E has been available for roughly 25 years, but because low-E glass first penetrated higher value segments which also used sealed insulating glass (IG) units, its use in exposed applications such as storm windows or retrofit glazing was underutilized. Furthermore, the development of alternate silver-based low-E coatings, which are moisture sensitive, added to the perception that all low-E coatings must be sealed in an IG unit. As a result, even those who are knowledgeable about low-E glass often do not realize it can be used in these applications. This has created an artificial barrier to widespread application – a barrier that can be overcome with proper demonstration and education.

For residential applications, Lawrence Berkeley National Laboratory (LBNL) tested the initial concept in 2002 by performing physical measurements of low-e storm windows over a single glazed residential window in their Mobile Window Thermal Test (MoWiTT) Facility.[2] This study found that the use of a low-E storm window reduced the U-factor of the prime window by 36-46% and resulted in performance comparable to a replacement window, even when the underlying window was made intentionally leaky. Based upon this success, a 2006 field study involving HUD, DOE, NAHB Research Center, and LBNL was completed on six low income homes in the Chicago area.[6] In this study, low-E storm windows reduced the overall winter heating load of the home by 21%, whereas normal clear glass storm windows reduced the heating load by 13%. Furthermore, the low-E storm windows had a simple payback of 4.5 years, as compared to 10 years for normal storm windows, and much longer for replacement windows.

From this initial work, it was clear that low-E storm windows and retrofit panels offer the potential to cost effectively reduce energy consumption in existing buildings, but there were gaps that needed to be addressed in order to accelerate penetration of this energy saving measure. The objective of this project was to expand upon the prior work through case studies to demonstrate the performance of low-E storm windows and retrofit panels in more applications. This included a residential case study in multifamily apartment buildings, a residential case study of single family homes in a warmer climate with mixed heating and cooling, and commercial case studies in two large office buildings. Additionally, the project included an educational program to help increase adoption of this technology, as well as an objective to identify and overcome any technical and market barriers. This report describes the objectives and summary of outcomes for each area, followed by appendices that include the detailed research reports on each case study.

2. Low-E Storm Window Weatherization Educational Program

Objective: Track implementation of low-e storm windows installed on homes through Pennsylvania's weatherization program. Identify any technical or market barriers to wide scale use. Develop a model educational program that will set the basis for replication in other states.

In addition to the field case studies described in later sections, an important aspect of this project was educational outreach to help various interest groups (weatherization auditors and contractors, state and federal energy efficiency program personnel, utility weatherization program managers, historic preservation groups, consumers, etc.) become aware of this technology and understand the potential benefits for using low-E storm windows and panels to cost effectively improve the energy efficiency of existing buildings. This started as work with the state of Pennsylvania as an early adopter, followed by educational outreach in other states and regions. The sections below describe the outreach activities, the barriers encountered, and the package of educational materials developed. Additionally, to assist in outreach communications, new representative U-factor and solar heat gain coefficient (SHGC) values were determined for low-E storm windows installed over different primary windows.

2.1. Low-E Storm Windows in the Pennsylvania Weatherization Assistance Program

In the fall of 2010, the project team worked closely with the Pennsylvania Department of Community and Economic Development (DCED) to update their "priority list" used to direct weatherization subagencies which measures to include in the weatherization of a home. The project team worked with DCED, DOE, and Energetics to successfully update their priority list to include low-E storm windows as a priority weatherization measure, based on a detailed analysis using the National Energy Audit Tool (NEAT) to prove cost effectiveness. The NEAT analysis determined the savings-to-investment ratio (SIR) of using low-E storm windows in 37 model home types in four cities representing the four distinct PA climate zones. In all cases, low-E storm windows were qualified as a cost-effective weatherization measure with SIR values well over the minimum requirement of 1, the level required to qualify as a weatherization measure using state and federal funding. The SIR ranged from 1.4 to 2.2 when used over single-pane windows and ranged from 1.3 to 2.1 when used over double-pane metal-framed windows. As a result, the State of Pennsylvania added low-E storm windows to its weatherization measure selection priority list for single-family homes, with the approval of the U.S. Department of Energy. [7,8]

Pennsylvania's weatherization measure priority list directs weatherization subagencies to use low-E storm windows in all the following cases:

- adding low-E storm windows over all single glazed windows,

- adding low-E storm windows over all double glazed metal framed windows,
- replacing any deteriorated storm windows with new low-E storm windows.

This was a very important step to complete before low-E storm windows could start to be installed on a wide basis.

Following implementation of low-E storm windows in Pennsylvania's weatherization assistance program, team members spent hundreds of contact hours with auditors, specifiers, supervisors, and installers to make them aware of this new requirement and provide training on the background of this technology, its proper use, and its cost effective energy performance. The educational outreach covered not just low-income single-family housing in the weatherization assistance program, but also groups involved with historic preservation and multifamily buildings in the region.

Very importantly, the project team discovered that education presents a significant initial barrier that can slow widespread adoption of this technology, even with support at the state level. Despite DCED's directive to include low-E storm windows on their weatherization priority list, there was initial skepticism or lack of knowledge about this new technology with many auditors and installers at the subagency level. Weatherization personnel were consistently reluctant to embrace *anything* related to window improvements, due to historical experience where full window replacement turned out to not be cost effective in weatherization programs, creating a subsequent backlash. There was general confusion and misunderstanding how low-E storm windows are different than full window replacement, which is generally not cost effective under weatherization programs, whereas low-E storm windows are. As such, educational training must remain a major focus in deployment activities.

The inclusion of low-E storm windows on Pennsylvania's weatherization assistance program occurred simultaneously with a large infusion of funds from the American Recovery and Reinvestment Act of 2009 (ARRA), through which over 36,000 homes were weatherized in Pennsylvania. In the original project plan, the project team hoped to build a database together with the Pennsylvania DCED to track low-e storm window installation, taking advantage of their Hancock Energy Software used to track weatherization subagency activities and costs. However, problems with both the software and data entry by subagency personnel hindered the collection of accurate data regarding window retrofits. An attempt to use another potential source of data through the utility-based weatherization program administered by Philadelphia Gas Works was also unfruitful, due to concerns about publicizing the information. As a result, the project plan was modified after the first year to focus this task more on the educational training and expansion to multiple states, and less on creating a database for Pennsylvania. This was also more direct to the overall purpose of this task, expanding the implementation of this new technology.

Despite some of the educational barriers, storm window manufacturers observed a significant positive impact as a result of Pennsylvania's actions, including over a 300% increase in sales of low-E storm windows in Pennsylvania for one company during this period. This is described in a market study on low-E storm windows prepared by Pacific Northwest National Laboratory, in consultation with the team members on this project. [9] This also notes that although federal funding for weatherization assistance programs has now significantly decreased, one persisting benefit is the increased overall availability of this technology in the market, for all channels, not just through the weatherization assistance program.

2.2. Educational Outreach Expanded Beyond Pennsylvania

The project objectives also included development of an educational program to expand beyond the early adoption in Pennsylvania. This included outreach to specific state weatherization program personnel in New Jersey, Maryland, Delaware, New York, Illinois, Minnesota, North Dakota, Arizona, and Texas, as well as in national forums. Following the example of Pennsylvania, Arizona added low-E storm windows to their weatherization priority list for the cold mountain and high plain areas, and Texas has directed its program personnel to consider low-E storm windows in their audits. Many of the other states have also expressed interest, but with the decrease in federal funding for state weatherization assistance programs following the expiration of ARRA, most of the attention has shifted to utility and other efficiency programs.

One significant event was the 2011 DOE National Weatherization Training Conference, attended by over 3,000 weatherization personnel. The project team hosted a large display booth including thermal performance demonstrations and hands-on installation training. This was well attended by weatherization personnel from 37 different states/provinces (see Figure 1).

Craig Drumheller (NAHB Research Center) and Tom Culp (Birch Point Consulting) also made educational presentations at a session titled "Low-E Storm Windows for Weatherization" to describe previous testing and case studies, new case studies as part of this project, and the implementation of low-E storm windows on PA's weatherization priority list. These presentations have been incorporated along with other materials to form an educational package for weatherization personnel. Many of these materials are from collaboration with other interested parties including Building Green, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, Consortium for Energy Efficiency, and many others.

Figure 1. 2011 DOE National Weatherization Training Conference, New Orleans LA.

Overall, the package of available educational materials includes:

Introductory Materials

- New DOE EERE fact sheet on low-E storm windows aimed at consumers. Developed by the Building Green / LBNL Window Retrofit Project with our assistance. See www.efficientwindowcoverings.org and www.low-estormwindows.com/resources/DOE%20Fact%20Sheet%20Exterior_Low-e_Storm_Windows.pdf
- New brochure from DOE's Building America program on low-E storm windows. Aimed at utility and weatherization personnel, developed by Pacific Northwest National Laboratory. http://basc.pnnl.gov/sites/default/files/resource/BuildingAmerica_Low-E_StormWindow_Brochure_051413.pdf
- Consumer fact sheet on low-E storm windows, developed by the Alliance for Low-E Storm Windows. http://www.low-estormwindows.com/resources/LowE%20Storm%20Windows%20-%20Energy%20Efficiency%20the%20Easy%20Way.pdf
- "Introduction to Low-E Storm Windows" presentation at the 2011 DOE National Weatherization Training Conference http://www.waptac.org/data/files/Website_Docs/events/conferences/2011-DOE-National-Conference/Thursday/Th26P-Low-E-Storm-Windows-Culp.pdf

More in-depth materials (previous research papers, market studies, etc.)

- NAHB Research Center and LBNL case study in Chicago, "Field Evaluation of Low-E Storm Windows" (reference 6).
  http://www.toolbase.org/PDF/FieldEvaluations/existinghomes_fieldeval_low-e-stormwindows.pdf
- LBNL research paper "Measured Winter Performance of Low-E Storm Windows" (ref 2).
  http://www.low-estormwindows.com/resources/LBNL%20low-e%20storm%20window%20research.pdf
- Representative U-factor and SHGC values for low-E storm windows and panels over different primary windows. See next section.
  This will be posted to http://www.low-estormwindows.com and also included in
  http://basc.pnnl.gov/sites/default/files/resource/Culp%20ET%20Task%205_3_PNNL-22865_Final2.pdf
- PNNL market assessment for low-E storm windows (reference 9).
  http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22565.pdf
- New database of energy savings of low-E storm windows / panels in 22 cities across all U.S. climate zones. NEAT and RESFEN analysis conducted by PNNL and Birch Point Consulting for DOE's Building America program.
  http://basc.pnnl.gov/sites/default/files/resource/Culp%20ET%20Task%205_3_PNNL-22865_Final2.pdf
- NEAT evaluation of low-E storm windows for inclusion on Pennsylvania's weatherization measure priority list (reference 7).
  http://www.low-estormwindows.com/resources/PA%20Low-E%20Storm%20and%20R5%20Window%20Evaluation.pdf
- How to model low-E storm windows in NEAT and other software tools.
  http://www.low-estormwindows.com/resources/Modeling%20Parameters%20for%20Low-E%20Storm%20Windows.pdf

Additionally, the case study reports from this project will also be added to this list of growing resources.

As mentioned above, with the sudden decrease in federal funding, much of the attention has shifted to other efficiency programs. The project team has worked with the Consortium for Energy Efficiency to develop product overviews for low-E storm windows and panels, to be used by their utility members as an informational resource when establishing utility rebates and incentive programs.

The project team also worked with DOE's Home Performance with Energy Star program personnel to ensure that low-E storm windows are allowed to be included in home incentive evaluations under this program. However, it should be noted that the team continues to encounter similar educational barriers as with weatherization personnel, where local personnel mistakenly believe no window options are allowed, or mistakenly believe only replacement windows that meet Energy Star requirements are allowed (although the Energy Star Windows program does not apply to low-E storm windows). This will need to be an ongoing educational effort.

To this last point, the team has initiated discussions with EPA about establishing an Energy Star program for storm windows, and has worked with D&R International on a roadmap to determine what is needed to establish such a program. Part of this effort may require a standardized rating program for fenestration attachments. DOE is currently starting the process to help fund such a program.

Team members also made appearances on national media, including Weatherization TV from Montana State University and the HomeTalk USA - Michael King radio show.

2.3. Updated U-factor and SHGC Values for Different Low-E Storm Window Combinations

As part of the educational outreach activities, the project team was continually asked what the U-factor is for a low-E storm window over different types of windows. The team already had previous estimated values from a basic engineering analysis, but to help answer these questions and support this outreach work, an independent accredited laboratory (Architectural Testing Inc.) was used to conduct very detailed simulations to determine the U-factor and SHGC of both exterior and interior low-E storm windows installed in combination with different types of primary windows. ATI used WINDOW6 / THERM6 software from Lawrence Berkeley National Laboratory to perform detailed thermal simulations in accordance with NFRC procedures, but accounting for how low-E storm windows and panels are realistically attached over existing primary windows, such as onto the brickmold, trim pieces, and/or window sill. Table 1 and Table 2 below summarize the results.

With wood (or other nonmetal) base windows, the performance is not that sensitive to the mounting details, although interior panels consistently had a slightly lower U-factor than exterior panels. Low-E storm panels consistently provide significantly lower U-factor than clear storm panels (e.g. 60% vs. 47% reduction in U-factor over single pane wood windows, respectively).

With metal base windows, the performance is more sensitive to how exterior storm panels are mounted. Three mounting cases were simulated, ranging from the worst-case scenario where the metal storm panel is directly mounted to the metal window frame (direct thermal bridge), to the best scenario where the storm panel is mounted to the wood brickmold or other wood trim to create a thermal break with no direct metal-to-metal connection. The final U-factor can vary by 0.07 – 0.13 Btu/hr ft^2 F or 11-26% based on the mounting method. One example is shown in Table 3. The performance of the base window is still greatly improved by the addition of a low-E storm panel even with worst-case mounting, but for optimum thermal performance, ensuring a thermal break is the recommended practice.

This information has been used to update the educational materials listed in section 2.2.

Table 1: STORM PANELS OVER WOOD BASE WINDOWS

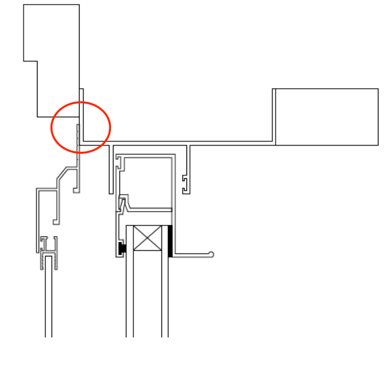
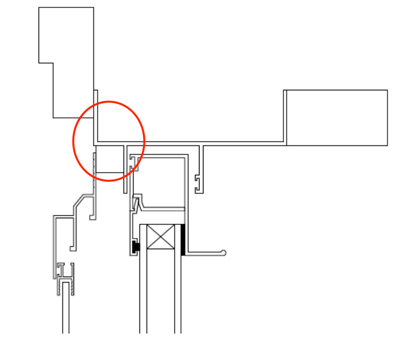
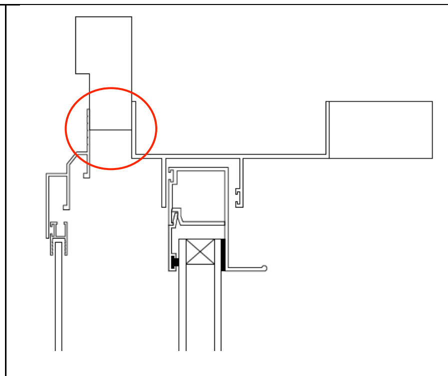
Base Window	Storm Type	U-Factor	SHGC	VT
Wood Double Hung, Single Glazed	--	0.88	0.61	0.66
	Clear, Exterior	0.47	0.54	0.57
	Clear, Interior	0.46	0.54	0.59
	Low-E, Exterior	**0.36**	0.46	0.52
	Low-E, Interior	**0.34**	0.50	0.54
Wood Double Hung, Double Glazed	--	0.51	0.57	0.61
	Clear, Exterior	0.34	0.49	0.53
	Clear, Interior	0.32	0.51	0.55
	Low-E, Exterior	**0.28**	0.42	0.48
	Low-E, Interior	**0.26**	0.47	0.50
Wood Fixed, Single Glazed	--	0.87	0.64	0.69
	Clear, Exterior	0.46	0.58	0.62
	Clear, Interior	0.45	0.56	0.62
	Low-E, Exterior	**0.34**	0.50	0.56
	Low-E, Interior	**0.34**	0.52	0.57
Wood Fixed, Double Glazed	--	0.47	0.60	0.64
	Clear, Exterior	0.32	0.53	0.57
	Clear, Interior	0.32	0.54	0.58
	Low-E, Exterior	**0.27**	0.46	0.52
	Low-E, Interior	**0.25**	0.50	0.53

Table 2: STORM PANELS OVER METAL BASE WINDOWS

Base Window	Storm Type	U-Factor	SHGC	VT
Aluminum Double Hung, Single Glazed	--	1.12	0.61	0.65
Worst case mounting	Clear, Exterior	0.67	0.56	0.58
Thermally broken mounting (recommended)	Clear, Exterior	0.58	0.56	0.59
	Clear, Interior	0.53	0.53	0.59
Worst case mounting	Low-E, Exterior	0.57	0.47	0.53
Thermally broken mounting (recommended)	**Low-E, Exterior**	**0.44**	0.48	0.54
	Low-E, Interior	**0.41**	0.50	0.54
Aluminum Double Hung, Double Glazed	--	0.75	0.58	0.60
Worst case mounting	Clear, Exterior	0.55	0.51	0.54
Thermally broken mounting (recommended)	Clear, Exterior	0.45	0.52	0.55
	Clear, Interior	0.41	0.51	0.55
Worst case mounting	Low-E, Exterior	0.49	0.44	0.49
Thermally broken mounting (recommended)	**Low-E, Exterior**	**0.36**	0.44	0.50
	Low-E, Interior	**0.32**	0.47	0.50
Aluminum Fixed, Single Glazed	--	1.06	0.72	0.77
Worst case mounting	Clear, Exterior	0.62	0.59	0.62
Thermally broken mounting (recommended)	Clear, Exterior	0.55	0.61	0.65
	Clear, Interior	0.51	0.60	0.66
Worst case mounting	Low-E, Exterior	0.51	0.50	0.57
Thermally broken mounting (recommended)	**Low-E, Exterior**	**0.42**	0.52	0.59
	Low-E, Interior	**0.38**	0.56	0.60
Aluminum Fixed, Double Glazed	--	0.62	0.67	0.71
Worst case mounting	Clear, Exterior	0.47	0.54	0.58
Thermally broken mounting (recommended)	Clear, Exterior	0.40	0.56	0.60
	Clear, Interior	0.36	0.57	0.61
Worst case mounting	Low-E, Exterior	0.42	0.47	0.52
Thermally broken mounting (recommended)	**Low-E, Exterior**	**0.33**	0.48	0.55
	Low-E, Interior	**0.29**	0.53	0.56

Table 3: Effect of mounting method over metal framed base window.

Exterior low-E storm panel over single glazed aluminum double hung window - head sections

		
Direct metal-to-metal mount	Wood blind stop mount, but some metal of base window still exposed to exterior	Brickmold mount with no direct metal-to-metal contact
Base window: U = 1.12	Base window: U = 1.12	Base window: U = 1.12
With Low-E Storm: U = 0.57	With Low-E Storm: U = 0.52	With Low-E Storm: U = 0.44

3. Residential Multifamily Building Case Study

Objective: Conduct a case study of low-E storm windows on large multifamily buildings in cold or mixed climates. Determine the heating and cooling energy savings and air infiltration benefits.

(Note: this work on multifamily apartment buildings was added in the last budget period in place of a 3rd commercial office building.)

3.1. Zion Garden Apartments, Philadelphia PA

In this case study, two large three-story multifamily apartment buildings located in downtown Philadelphia were retrofitted with new low-E exterior storm windows. These 50 year old subsidized housing buildings have a total of 101 apartment units with 4,720 ft^2 of window area. (See Figure 2.) The single-pane metal-framed windows already had old triple track, clear glass storm windows, which were then replaced with modern low-E storm windows. The upgrade was estimated to reduce the combined window U-factor by 61% relative to the single-pane primary window, and 24% compared to the single-pane window with the older traditional storm window. The SHGC was reduced by approximately 14%. Additionally, the new low-E storm windows were expected to reduce air infiltration compared to the older leakier windows.

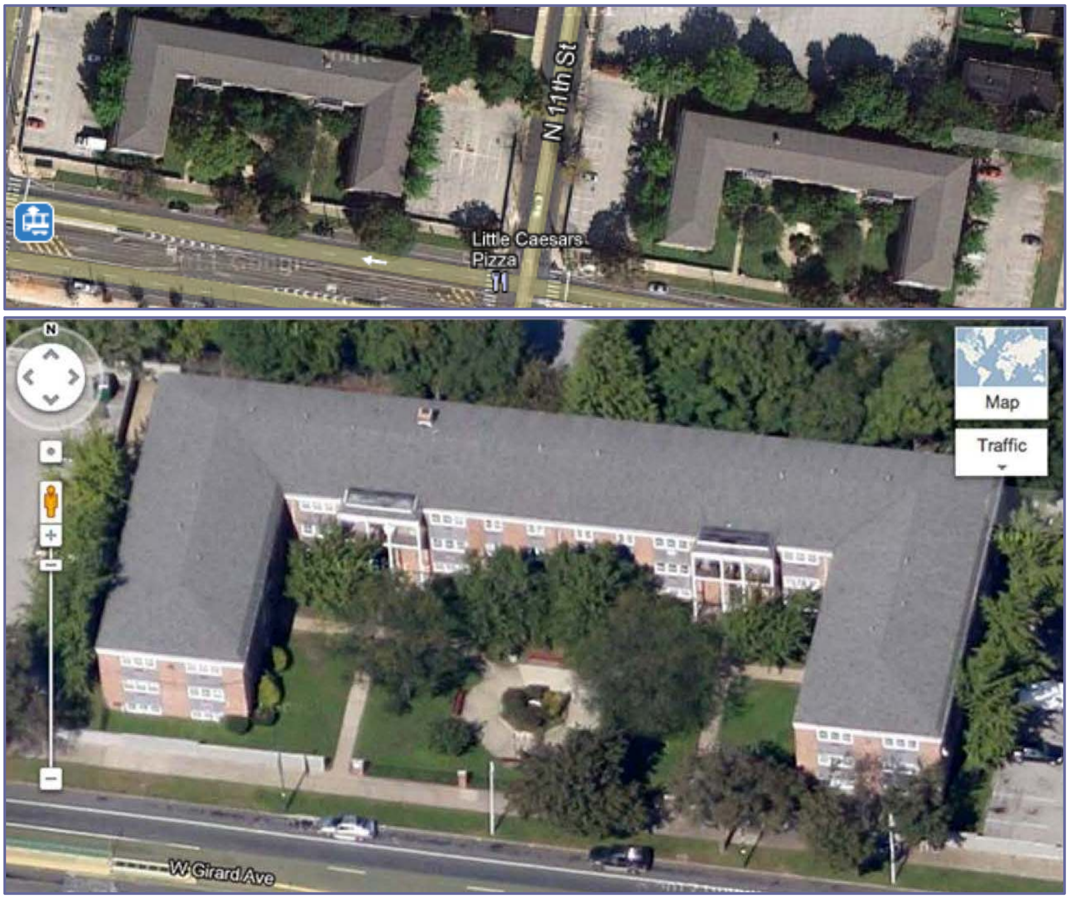


Figure 2: Multifamily apartment buildings upgraded with low-E exterior storm windows.

Improvements in the energy performance were assessed in two ways: blower door tests on representative apartment units to measure air infiltration reductions, and analysis of the utility bills for one of the two buildings. The detailed research report is provided in Appendix A, and results summarized here.

Blower door tests on representative apartment units demonstrated an **average 10% reduction in overall apartment air leakage from use of the new low-E storm windows**, or 3.2 cfm_{50} per square foot of window area. (See Figure 3.) It is important to note that this is the reduction in the overall apartment air leakage solely due to replacing the existing storm windows with modern low-E storm windows, and no other air sealing measures were applied. Of equal interest, the original old triple track storm windows showed no significant air tightness benefit (less than 1%), confirming the difference between old and new storm window designs.

These results are also generally consistent with other data on the air tightness benefits of modern storm windows. In the previous case study on Chicago weatherization homes, an average 7% reduction in overall home air leakage and 3.4 cfm_{50} per square foot of window area

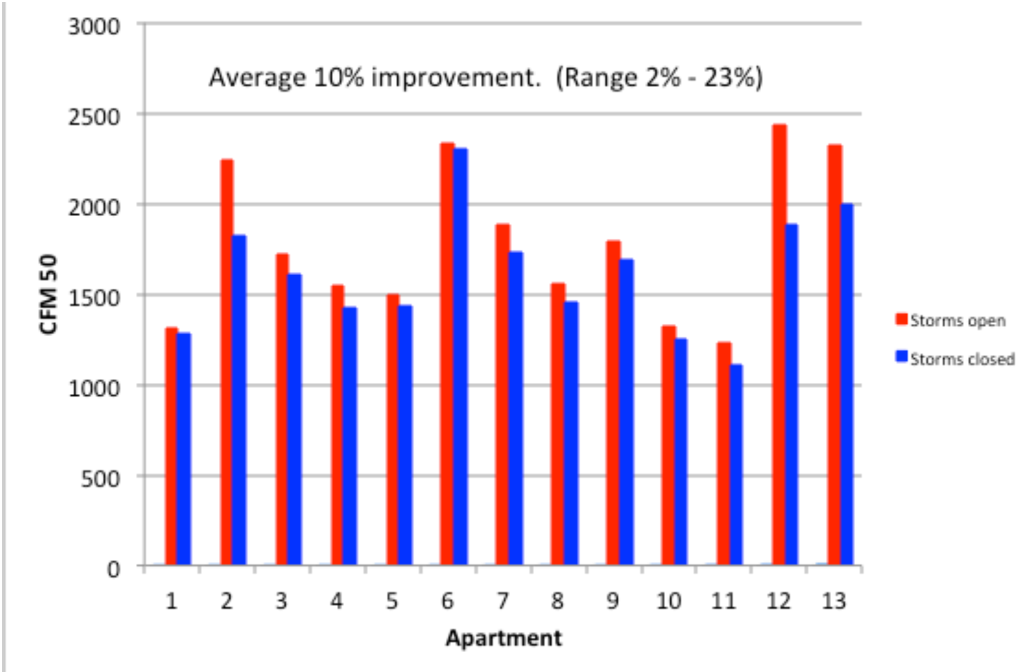


Figure 3: Zion Garden Apartments air leakage reduction due to low-E storm window retrofit.

was observed. [6] In the test homes in the Atlanta case study described in Section 4, an average 17% average reduction in overall home air leakage was observed. Section 3.2 also reports on the significant air leakage reduction for interior low-E panels in multifamily buildings.

Next, an analysis of the utility bills indicated that **replacing the existing old clear glass storm windows with new low-E storm windows provided an 18-22% reduction in heating energy use, and a 9% reduction in cooling energy use**. (See Figure 4 and **Table 4**.)
Note that this is relative to the base windows including the old storm windows, and the energy savings compared to just the single pane windows would be even higher. Furthermore, the use of interior low-E panels would provide even greater improvements in air tightness.

A whole building simulation using REM/Rate and calibrated to actual building gas meter data was also used to estimate the annual heating and cooling energy savings. The model estimated 20.3% annual heating energy savings, consistent with the measured results, of which the air leakage reduction contributed 11 ½ % and the improvement in window properties contributed 8 ½ %. On the other hand, the model estimated that the cooling energy savings should actually be higher, approximately 15%. This difference is attributed to the actual building having window air conditioning units which are used more inconsistently than if the building had centrally controlled air conditioning.

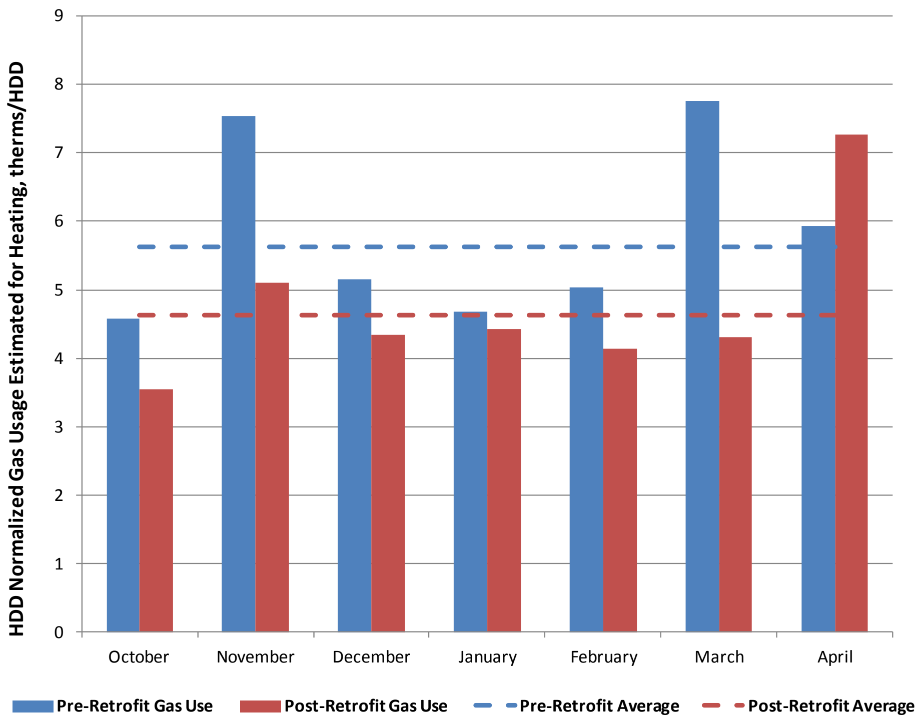


Figure 4: Monthly Normalized Heating Gas Use for Low-E Storm Window Pre- and Post-Retrofit

Table 4: Energy Use Comparison Based on Monthly Utility Billing

Heating	**October 2011 to April 2012 [A]**	**October 2012 to April 2013 [B]**
Heating Degree-Days, HDD	3,938	4,693
Heating Gas Use[C], therms	22,167	21,692
Normalized Gas Use, therms/HDD	5.63	4.62
Heating Savings Over Base		18%
Heating	**November 2011 to March 2012 [A]**	**November 2012 to March 2013 [B]**
Heating Degree-Days, HDD	3,309	4,058
Heating Gas Use [C], therms	18,808	18,023
Normalized Gas Use, therms/HDD	5.68	4.44
Heating Savings Over Base		22%

[A] Pre-window retrofit with old original clear glass storm windows
[B] Post-window retrofit with new low-E storm windows
[C] Heating Gas Use estimated by subtracting estimated hot water gas use in non-heating swing months.

3.2. Air Leakage Testing on Low-E Interior Panels, New York NY

In addition to the multifamily building case study in Philadelphia, we conducted air leakage tests on interior operable low-E panels installed in part of a 12-story apartment building in New York City. Interior operable low-E panels were installed over 32 year old, metal-framed, double pane clear windows, making sure the panels were thermally separated from the metal primary windows. A main benefit of this type of interior product is improved air tightness in addition to the insulating performance of low-E coated glass. While applicable to all building types, interior panels are particularly attractive for weatherizing mid- and high-rise multifamily buildings with much easier and less expensive installation than exterior panels.

Steven Winter Associates performed the testing using a field protocol to measure effective leakage area for windows with and without unit air conditioners, based on a modified blower door test.[1] The Effective Leakage Area (ELA) was reduced from 19.2 in^2 to 0.96 in^2 for window systems containing A/C units, and from 4.11 in^2 to 0.96 in^2 for window systems without A/C units. (See Figure 5.) This is a dramatic **77% reduction in air leakage for windows without AC units, and 95% reduction for windows with AC units**. Using these results, SWA estimated that the building's *total* air changes per hour (ACH) would be reduced by 35% if panels were installed on all of the windows, which would significantly reduce total energy use, especially when combined with the 60% reduction in U-factor.

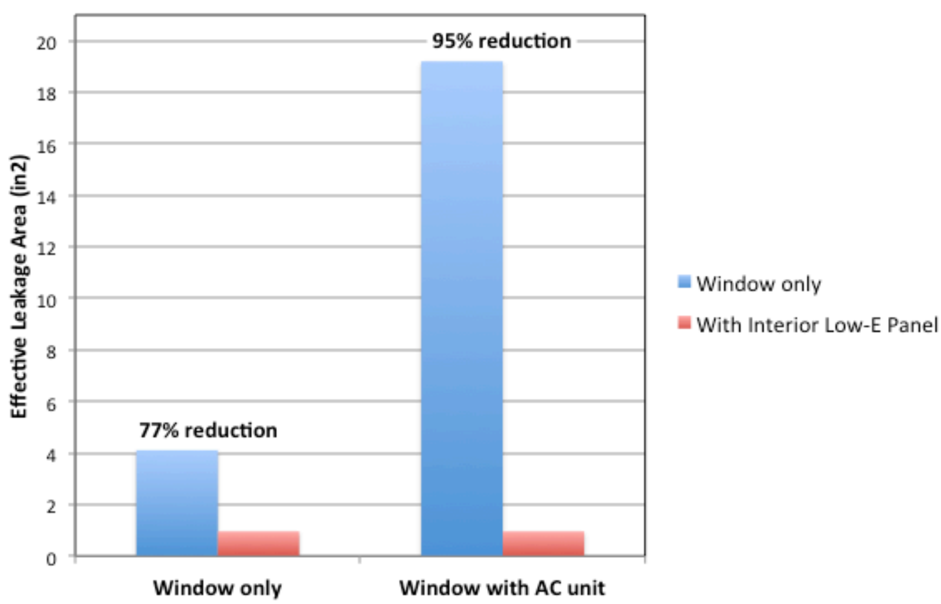


Figure 5: Reduction in window air leakage due to addition of interior low-E panel.

[1] http://urbangreencouncil.force.com/servlet/servlet.FileDownload?file=015U0000000VPu8

4. Residential Low-E Storm Window Case Study in a Warm / Mixed Climate

Objective: Conduct a field study on the use of low-e storm windows in a warm/mixed southern climate. Determine the year-round heating and cooling energy savings, air infiltration benefits, peak load benefits, cost effectiveness, and technical barriers.

In this case study, 10 older single-family homes near Atlanta were tested with three types of exterior storm windows: clear glass, low-E glass with high solar heat gain, and low-E glass with lower solar heat gain. Atlanta was selected as a follow-up to the previous cold climate case study in Chicago [6] to examine the use of low-E storm windows in a warm mixed climate with a balance of both cooling and heating.

The selected homes all had single glazing, ranged from 35-86 years old in mature neighborhoods, were single story (except one split level), and had an average living space just over 1,300 ft^2. The average window area per home is 143 ft^2. A total of 136 custom storm windows were provided by the project team. Example homes are shown in Figure 6, with storm windows installed.

Figure 6: Atlanta test homes, with storm windows installed.

Energy use of each home was monitored over a two-year period. The homes were divided into three groups to test the three glass types in the storm windows (clear, high solar gain low-E, or low solar gain low-E). The first year compared the energy performance when storm windows were used relative to the original single-pane windows by alternating each month with and without storm windows mounted while monitoring the heating and cooling energy use. During the second year, the performance of two different glass types was directly compared in each home by leaving the storm windows up all year, but alternating sashes with different glass types each month. Additionally, blower door tests were conducted to measure the reduction in air infiltration due to the use of modern storm windows. The detailed research report is provided in Appendix B, and results summarized here.

The addition of storm windows to the single pane windows was estimated to reduce the combined window U-factor by 47% for the clear glass storm window and 59% for the low-E storm windows. The SHGC was reduced by approximately 11% for the clear glass storm window, 25% for the high solar gain low-E storm window, and 44% for the low solar gain low-E storm window.

Blower door testing was conducted to measure the reduction in air leakage due to the addition of storm windows. The baseline measurements showed these older homes to be very leaky with noticeable leakage around the existing windows (total home air leakage ranged from 12-57 ACH_{50} before installation of the storm windows), representing a source of large energy loss. For comparison, the national average for homes of these vintages is approximately 22 ACH_{50}, whereas modern newly constructed homes are often under 5-7 ACH_{50}.

After installation of the storm windows, **storm windows significantly reduced the overall home air leakage by an average of 17%, or 3.7 ACH_{50}**, although with sizable variation between homes. See Figure 7. Note that this is the reduction in air infiltration for the entire home just by adding storm windows – no other air sealing or changes were made. These results are generally consistent with other studies: the case study of Chicago weatherization homes showed an average 7% reduction [6], and the case study of multifamily buildings in Philadelphia showed an average 10% reduction (Section 3.1). The results here show a larger average reduction, but also with more variation, which is not unexpected given the variability within the set of homes and different type of housing construction in the different case studies.

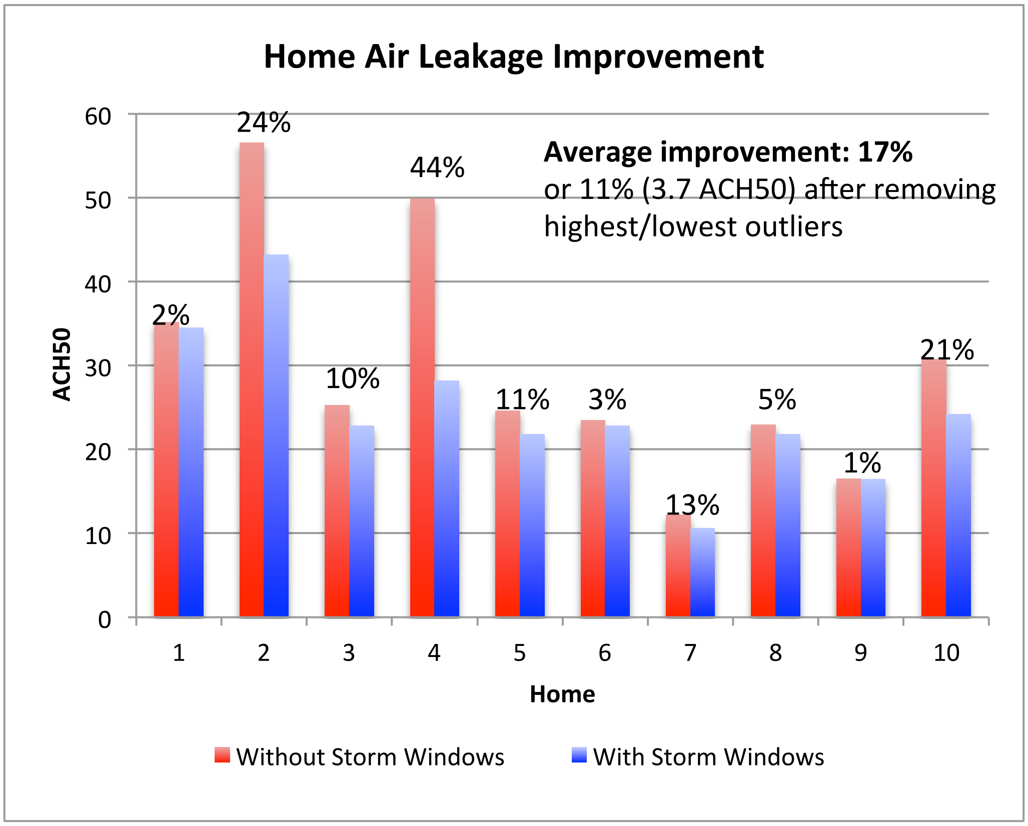


Figure 7: Reduction in air infiltration due to the use of storm windows in the Atlanta test homes.

The cumulative energy use was monitored over the two-year period, but considerably high variability was observed in the data across the sets of homes and at different periods, so the main analysis focused more narrowly on two 2-month heating periods and two 2-month cooling periods where more consistent demand in heating and cooling was observed.

An example of the heating energy use data for one set of homes is shown in Figure 8. While differences in the performance of each type of storm window is evident, there is also considerable scatter in the data. Similar high scatter was also observed in the cooling data. We believe there are several sources of the variability including home differences (also evidenced in the air leakage measurements), occupant behavior, and thermostat settings. Additionally, both winters were relatively mild with heating degree days lower than the historical average. The resulting low inside-outside temperature difference makes it difficult to highly correlate temperature to energy usage, and the variability in factors such as wind speed and solar intensity become of the same magnitude as conductive losses.

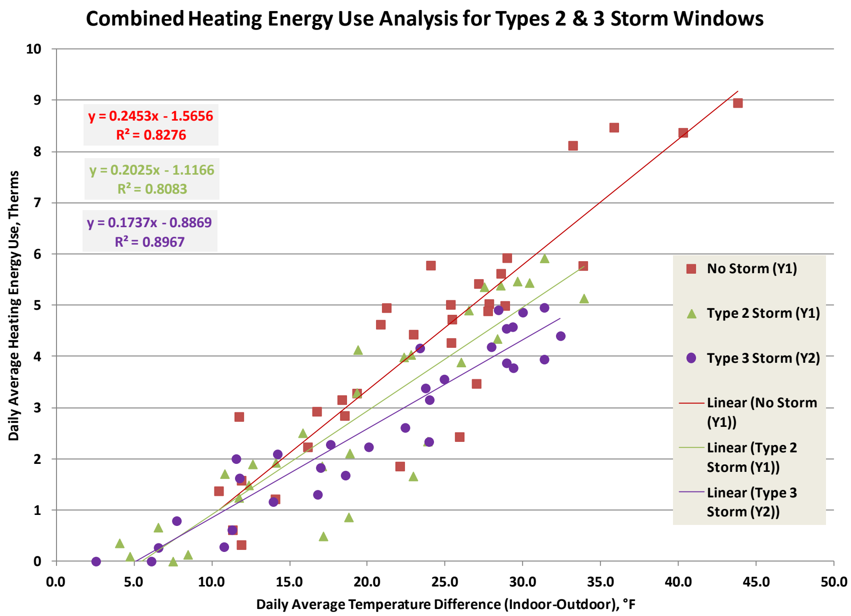


Figure 8: Example heating energy use data for one set of homes.
The Type 2 storm window has low solar gain low-E glass, and the Type 3 storm window has high solar gain low-E glass.

Nonetheless, a detailed analysis of the data does provide general information on the trends and relative performance of low-E and clear glass storm windows compared to the original single-pane windows.

For heating periods:

- The clear glass storm windows showed 2.5% lower heating energy use one year, and 3% higher heating energy use one year, resulting in overall neutral performance compared to the original windows.
- The low solar gain low-E storm windows showed heating energy savings ranging from 0-28%.
- The high solar gain low-E storm windows showed heating energy savings ranging from 2-34%.
- Due to variability in the data, it is difficult to conclusively say whether one type of low-E performed better than the other.
- When aggregating data for both low-E storm window types, **low-E storm windows showed approximately 15% heating energy savings, whereas clear storm windows were neutral in performance.**

For cooling periods:

- The clear glass storm windows showed cooling energy savings ranging from 1-8%.
- **The low-E storm windows showed a wide range of performance from 2% to over 30% cooling energy savings** (4-16% for the low solar gain low-E storm windows, 2-32% for the high solar gain low-E storm windows).
- While both types of low-E show the potential for larger energy savings than clear glass, it would not be expected for the higher solar gain product to have more cooling energy savings than the lower solar gain product, and there is significant overlap in the results. Due to variability in the data, it is difficult to conclusively say whether one type of low-E performed better than the other.

Detailed results are provided in Appendix B.

Overall, the high variability between the homes made it difficult to draw strong conclusions about the overall energy usage, but the study showed the potential for significantly more energy savings from using low-E glass versus no storm window or clear glass storm windows in warmer mixed climates. **However, it could not be determined whether one type of low-E performed better than the other**.

The team also conducted surveys of the home occupants at the end of both the first and second year of testing. While certainly too small a sample to draw statistically significant conclusions, it was designed to determine what benefits or drawbacks they observed with the storm windows, what factors are most important to them, and any potential issues or problems they might have encountered. The results were consistent over both years:

- In order of ranking, improvements from adding storm windows were noted in the following areas:
    - Appearance
    - Drafts
    - Comfort
    - Noise
    - Energy Bills

  All were rated as "much better" or "somewhat better".

- Other benefits noted by individual respondents included:
    - added security
    - reduced sun glare *(note: this home had the low solar gain low-e glass)*
    - heater and AC running less

- No problems or criticisms were indicated, except one respondent noted it was harder to clean the primary windows with the storm windows attached.

Another question was whether the slightly tinted appearance of the low solar gain low-E glass would be acceptable in a residential setting. Several of the homeowners preferred it, and the others liked both types of low-E glass equally (without knowing which type they had).

Overall, the survey results were very positive, with no major problems identified. One perhaps unexpected result was that **all respondents strongly ranked the improved appearance from adding storm windows as the top benefit**, and several specifically cited improved looks and curb appeal, confirming the enhanced aesthetics of modern technology storm windows. **Increased comfort, reduced drafts, and reduced noise were the other benefits most noted** by individuals.

Figure 9: Office building in Philadelphia upgraded with low-E retrofit panels. Entire building retrofitted, but circled windows indicate perimeter office pairs with detailed side-by-side monitoring.

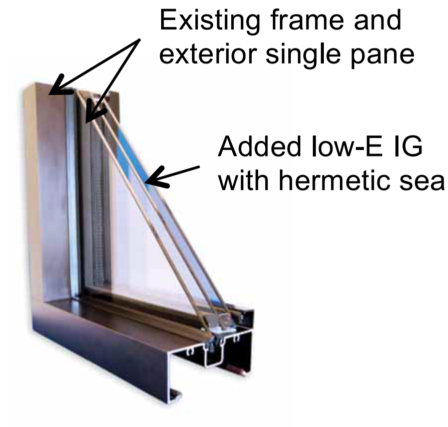


Figure 10: Renovate commercial low-E retrofit system.

5. Commercial Low-E Retrofit Case Studies

Objective: Conduct a case study of low-E retrofit systems on up to three commercial buildings in cold and mixed climates. Determine energy savings and peak load benefits, as well as other ancillary benefits.

5.1. 400 Market Street, Philadelphia PA

In this case study, a 42 year old, 12-story office building in Philadelphia with 18,000 ft^2 of glazing was upgraded with a new commercial low-E retrofit system. 532 windows were retrofitted by adding a low-E double pane insulating glass unit to the existing single pane glazing, to create a triple pane low-E system. (See Figure 9 and Figure 10.) This dramatically improves the insulating performance of the window, lowering the center-of-glass U-factor by 82% from 1.0 to 0.18 Btu/hr·ft2·°F. The center-of-glass SHGC was lowered to 0.44. This type of system can be installed from the interior with minimal disruption to occupants, and at less than half the cost of traditional rip-out-and-replacement of the existing glazing.

The change in overall utility usage for the building was analyzed, but the main technical analysis was a side-by-side comparison from isolating and monitoring energy use in two pairs of unoccupied offices facing two different orientations (north and east). Within each pair, one room was retrofit with low-E glazing, and its twin was left with no renovation (single pane window with a silver window film). Each room was instrumented with temperature controls and an energy monitoring system connected to a specially installed heating and cooling system. The detailed research report is provided in Appendix C, and results summarized here.

A dramatic reduction in energy use in the perimeter offices was observed:

- 39% reduction in total heating energy use in the east-facing office,
- 60% reduction in total heating energy use in the north-facing office,
- 36% reduction in total cooling energy use in the east-facing office, and
- 9% reduction in total cooling energy use in the north-facing office (due to less solar gain on the north).

Additionally, both heating and cooling demand was reduced. (See Figure 11 and Figure 12, which show the heating and cooling demand on the y-axis, ordered from highest to lowest on the x-axis for 15 minute measurement intervals over a one year period.) **Cooling peak demand was reduced by over 10% for over a quarter of the cooling period** in the perimeter offices.

This was the detailed side-by-side comparison for perimeter office energy use, but doesn't include the building core areas. The whole building utility savings was also analyzed, although comparisons are more difficult due to annual variations in weather, and changes in occupancy and use of the building. Nonetheless, we observed a 22 to 31% reduction in total heating energy use (mostly gas, with some supplemental electrical heat). The utility cooling data was less clear, so it is more reliable to use the more precise perimeter office results of 10-35% cooling energy savings depending on orientation. Overall, we estimate that the **total heating and cooling energy use of the building was reduced by over 25% due to the low-E retrofit**.

Interestingly, although there were clear cooling peak demand savings in the detailed perimeter office measurements, this was not evident in the whole building electricity utility bills, indicating that building peak demand is driven by numerous other factors in addition to window loads. Data for heating peak demand for the overall building was not available on the utility bills, but the building operations manager reported the ability to shut off one of three boilers, indicating significant savings.

While the energy savings are significant, equally impressive were the other benefits observed in improving the comfort and usability of the space. One way to assess comfort is the surface temperature of the window, as an occupant sitting next to a less efficient cold or hot window will be uncomfortable, leading to decreased productivity and usability of the space. The retrofit windows had much more constant surface temperatures than the non-retrofit windows. **The retrofit window temperatures were commonly 20 degrees warmer on winter days, and**

10-20 degrees cooler on summer days. The day-night temperature swings were reduced from 50 degrees to 20 degrees for east-facing windows, and from 20 degrees to 4 degrees for north-facing windows. (Also see more detail on this effect in Section 5.2.)

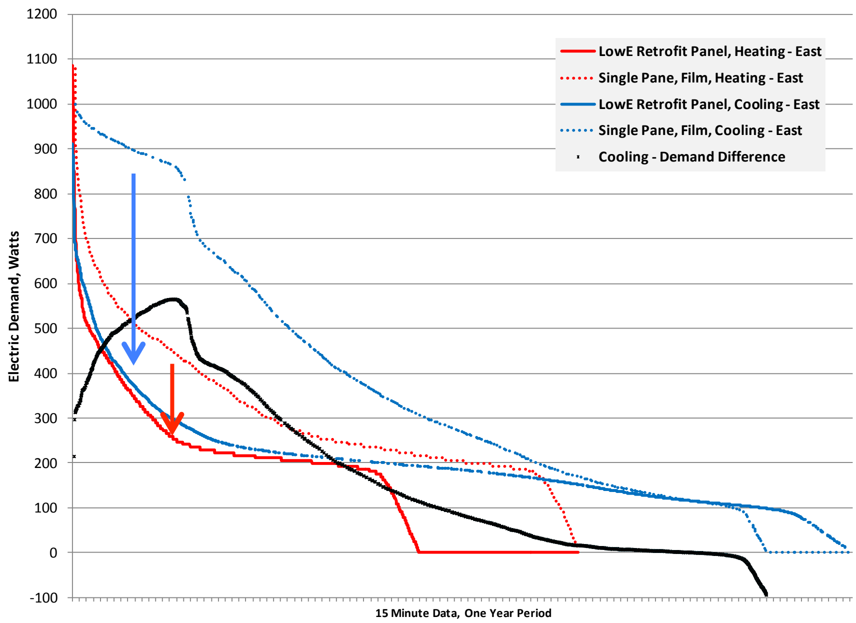


Figure 11: Reduction in heating and cooling demand in east-facing perimeter offices. Black line shows cooling peak demand savings.

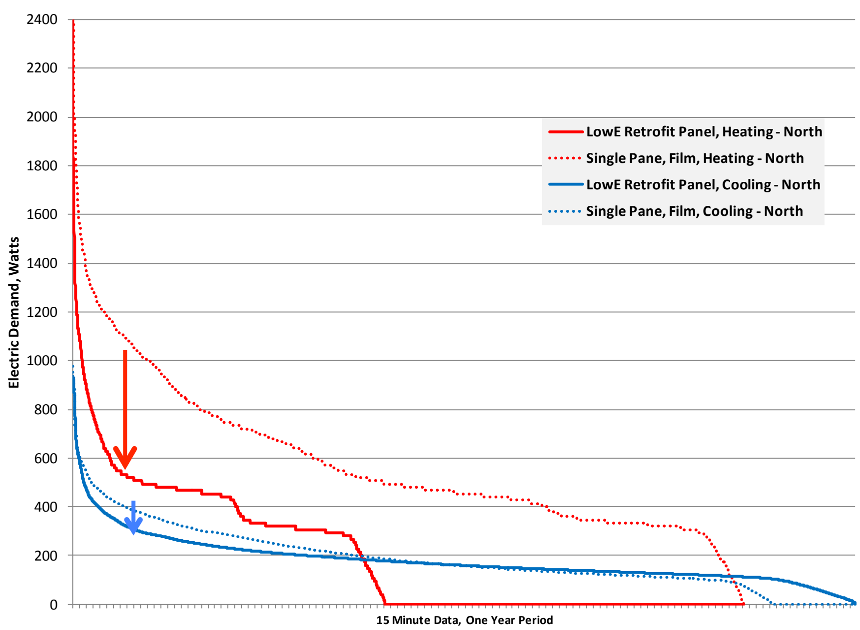


Figure 12: Reduction in heating and cooling demand in north-facing perimeter offices.

Additionally, both the property manager and tenants reported reduced street noise on lower floors and overall improved comfort. Finally, the building operations manager reported that the building was much easier to control, with a shorter morning building warm-up and the ability to shut off one of the boilers. All these will improve the comfort and usability of the space, and the building owner believes this is also leading to improved leasing of the building space.

5.2.   Kevon Office Center, Pennsauken Township NJ

This case study used a lower but larger office building in New Jersey built in 1970 with 100,000 ft^2 of floor area and approximately 19,000 ft^2 of single pane windows. (See Figure 13.) A similar low-E retrofit system was used as in the Philadelphia office building, adding low-E double glazing to existing single glazing to create a triple pane low-E system, but with two low-E coatings (soft coat low-E on the #2 surface and hard coat low-E on the #4 surface of the added insulating glass unit). See Figure 10. The extra low-E coating lowers the final center-of-glass U-factor down to 0.15 Btu/hr·ft2·°F. Two different low-E coating types were tested, providing center-of-glass SHGC values of 0.35 and 0.27.

Figure 13: Office buildings in Pennsauken NJ upgraded with dual low-E retrofit panels.

Figure 14: South-facing test office. Low-E retrofit system on left, original single pane window with silver window film on right.

The purpose of this study was to quantify potential improvements in thermal comfort before and after retrofit, as well as assess whether there is any significant thermal stress on the glazing. The building energy savings due to the retrofit is being measured and reported separately by CDH Energy Corporation as part of a Greater Philadelphia Innovation Cluster (GPIC) and Energy Efficient Buildings Hub project.

The very detailed research report is provided in Appendix D, and results summarized here. Side-by-side comparisons were conducted in two offices, one facing south and one facing north, where one window in each office was retrofitted with the dual low-E glazing, and one window was left with the original single glazing and silver window film. (See Figure 14.) Each window was instrumented with sensors to determine the temperature profile at various positions across the window surface, including on the surfaces and in the air space between the added low-E glazing unit and the original glazing. Additionally, the room air temperature and mean radiant temperature (MRT or "globe" temperature) next to each window were measured. This allowed a detailed assessment of glass temperatures, thermal comfort, and potential glass thermal stress over a six-month period from the winter solstice to the summer solstice.

The low-E retrofit panels greatly reduced daily variations in the interior window surface temperatures, lowering the maximum temperature and raising the minimum temperature by over 20°F compared to the original single pane windows with window film. (See Figure 15 and Figure 16, and also Appendix D.) Not only did the low-E retrofit panel provide a much more narrow swing in surface temperatures, the average surface temperature was much closer to the room air temperature than the original windows. The original single pane windows averaged more than 8°F colder than the air temperature, whereas the low-E retrofitted windows averaged no more than 3°F different than the air temperature. In essence, the low-E retrofit panel system does a superior job of moderating the environmental conditions than the original single pane windows, by reducing heat transfer through both improved insulation (lower U-factor) and reduced solar heat gain. This result was consistent for both orientations.

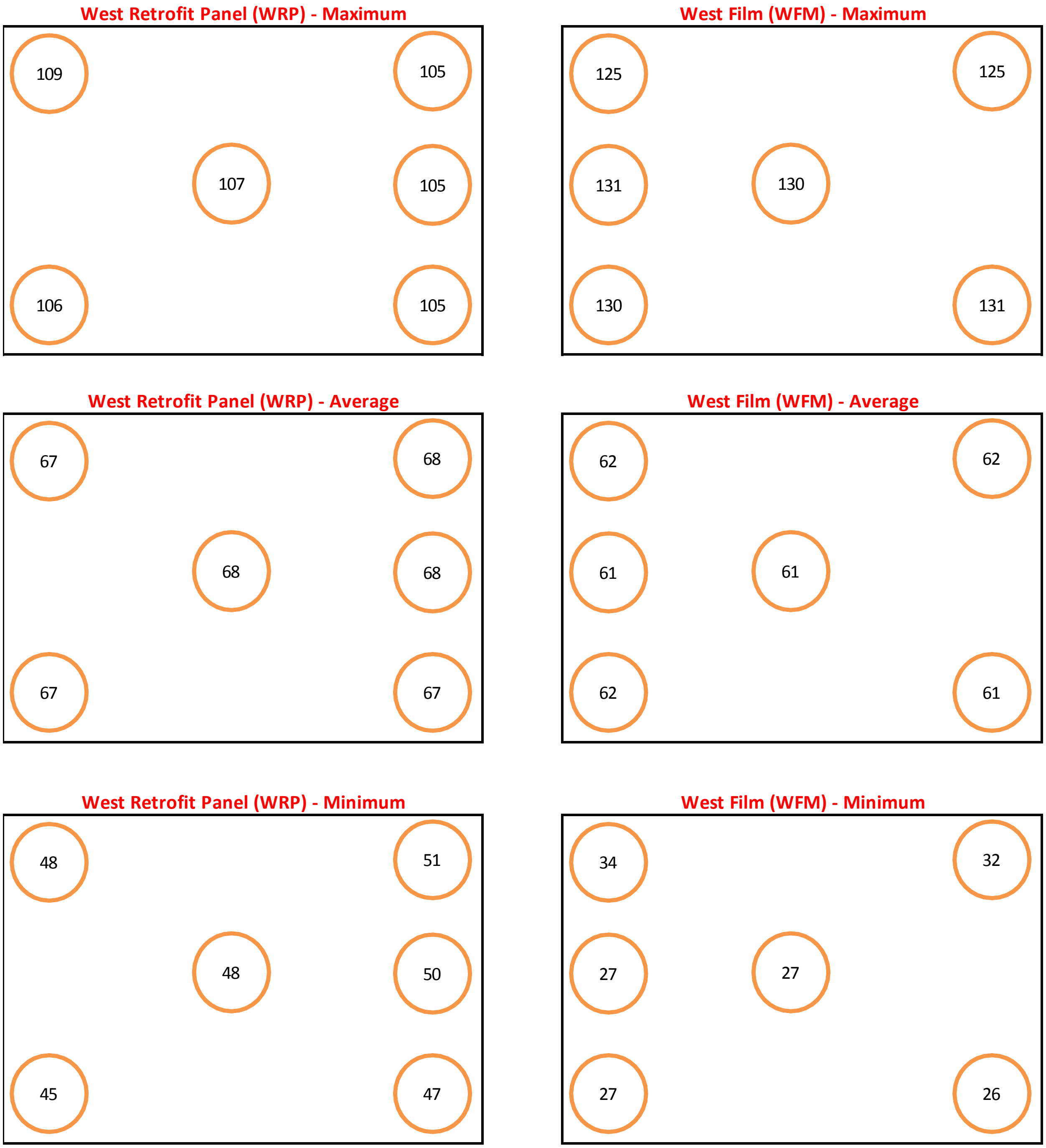


Figure 15: Maximum (top), Average (middle), and Minimum (bottom) glass surface temperatures for the west-facing office. Low-E retrofit system on the left, original single pane window with window film on the right. The different circles indicate the temperature sensor location on the glass. (All temperatures are ^{o}F.)

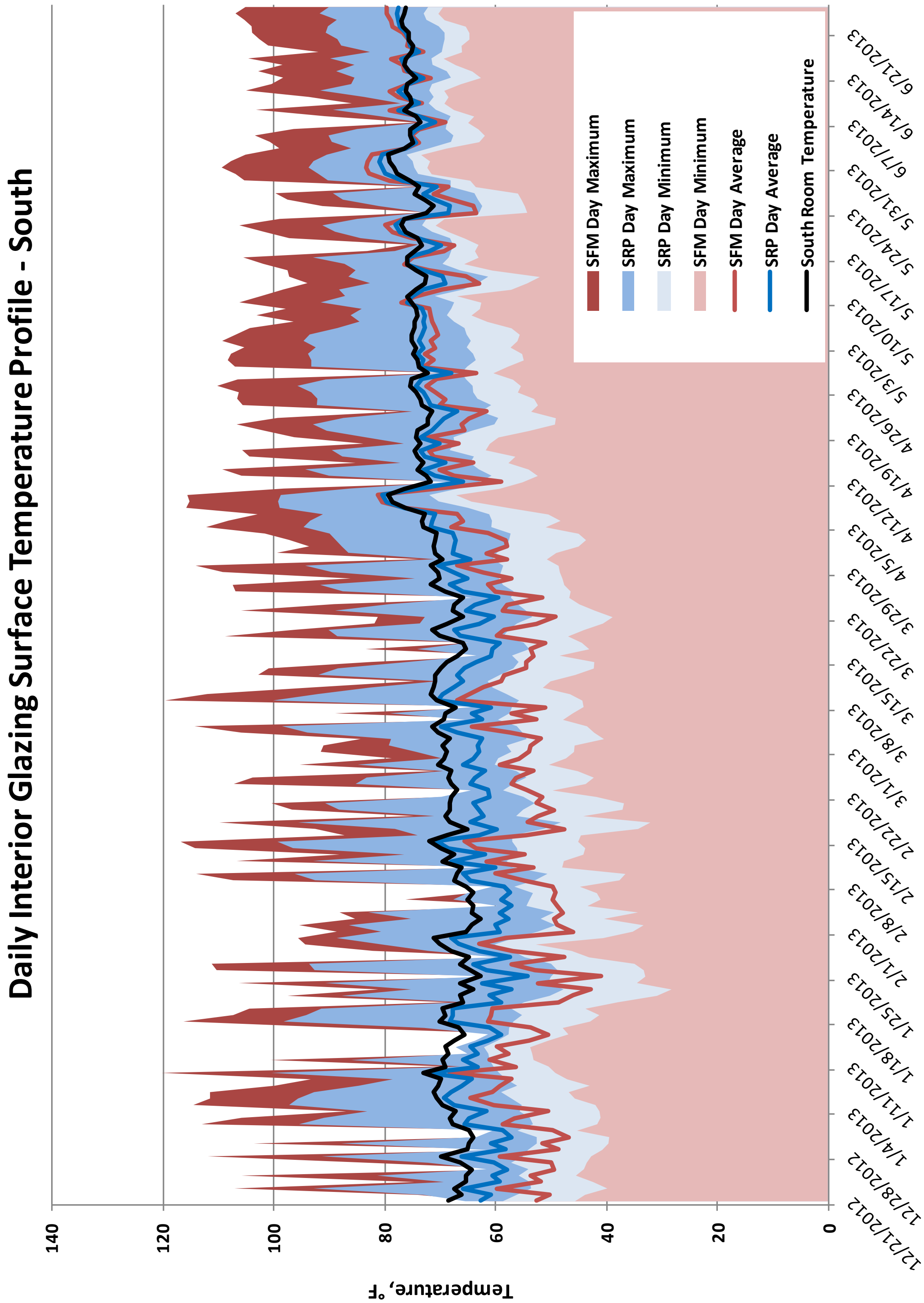


Figure 16: Daily variation in window surface temperature (maximum, average, minimum) for the south-facing office. The low-E retrofit window (shown as the blue regions and line) shows much less deviation and closer adherence to the room air temperature than the original window (shown as the red regions and line). Temperatures are averaged across all sensor positions.

As a result, we would expect occupant comfort to increase if the retrofit window temperature is warmer in the winter and cooler in the summer. One measure of thermal comfort for occupants sitting near windows is the difference between the mean radiant temperature (MRT) and the ambient air temperature. When this diverges, either positive or negative, one side of the body facing the window experiences a mean radiant temperature different than the other side of the body facing the room, leading to temperature asymmetry and discomfort.

Indeed, the window upgrade using low-E window retrofit panels demonstrated significantly improved thermal comfort as compared to the original single pane windows. **The number of hours of potential discomfort with larger temperature excursions exceeding 5°F between the MRT and the indoor air was reduced by 98 percent in the south facing office and over one-third in the west facing office.** Excursions of over 3°F were reduced by 93 percent in the south facing office and over two-thirds in the west facing office. This is shown graphically in Figure 17 and Figure 18, where the data scatter shows much less deviation (both colder and hotter) in the mean radiant temperature from the air temperature for the low-E retrofit window than the original single-pane window. This is consistent for both orientations, and in all seasons, and will lead to **substantially improved occupant comfort with less periods of both overheating and feeling cold**.

Furthermore, **no significant thermal stress was observed when using the low-E retrofit system, as measured by temperature differences across the outer pane of glass over a variety of weather conditions**. The surface temperature difference only exceeded 10°F (500 psi thermal stress) for less than 1.5% of the monitored time, and in all cases, the maximum surface temperature difference never exceeded 35°F, or 1,750 psi. (See Figure 19.) Furthermore, when comparing to similar sensor positions on the original single pane with the solar control film, there were no significant differences in the maximum surface temperature differences, and no reason to expect any significant difference in the potential for thermal stress breakage. While the sensor locations in this study may have missed some corner effects, and each building situation (geometry, exposure, shading, etc.) should be assessed individually, there does not appear to be any significant concern with thermal stress when using the low-E retrofit panel.

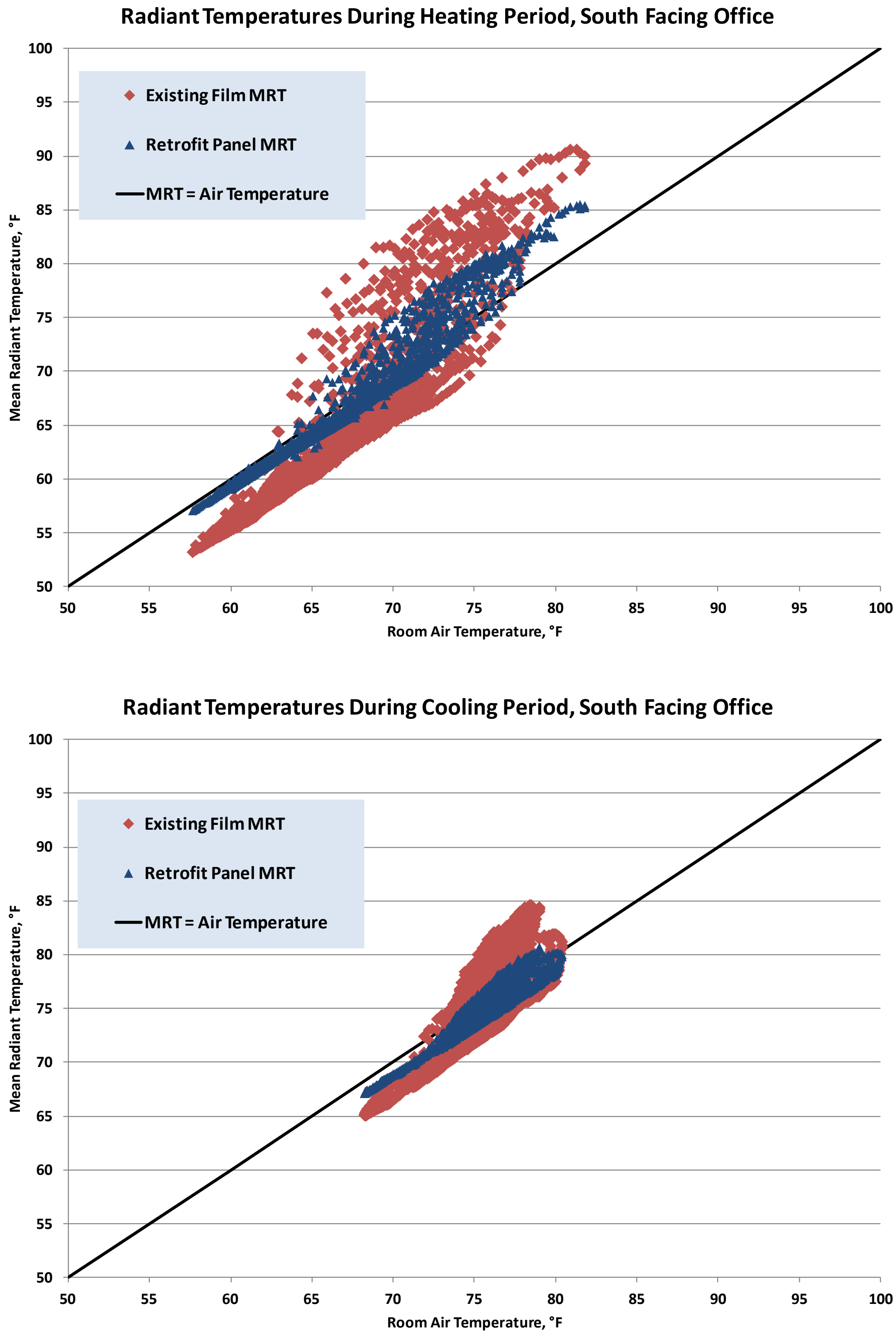
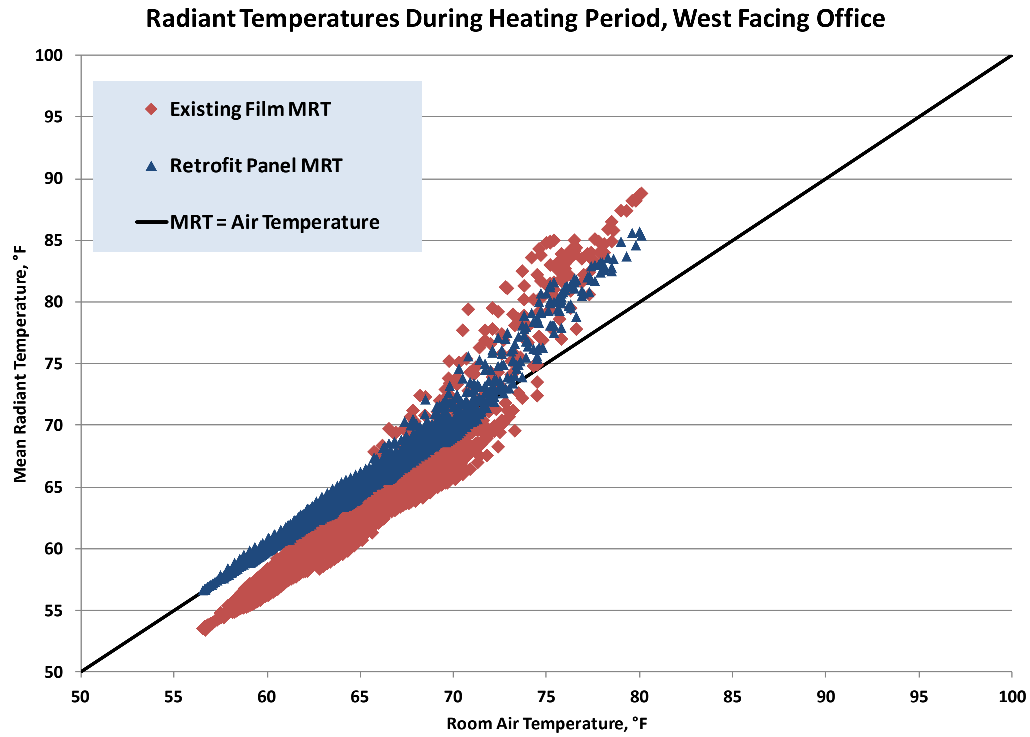


Figure 17: Deviation of mean radiant temperature (MRT) from ambient air temperature during heating periods (top) and cooling periods (bottom) for the south-facing office. The low-E retrofit window (blue) shows much less deviation than the original single-pane window (red).



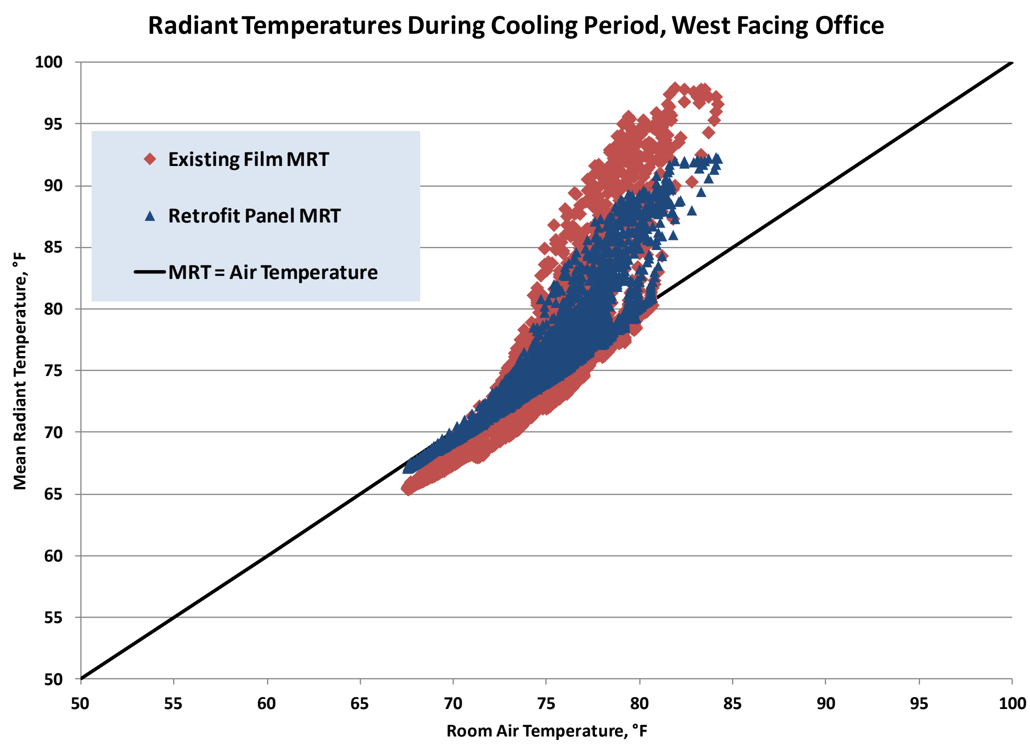


Figure 18: Deviation of mean radiant temperature (MRT) from ambient air temperature during heating periods (top) and cooling periods (bottom) for the west-facing office. The low-E retrofit window (blue) shows much less deviation than the original single-pane window (red).

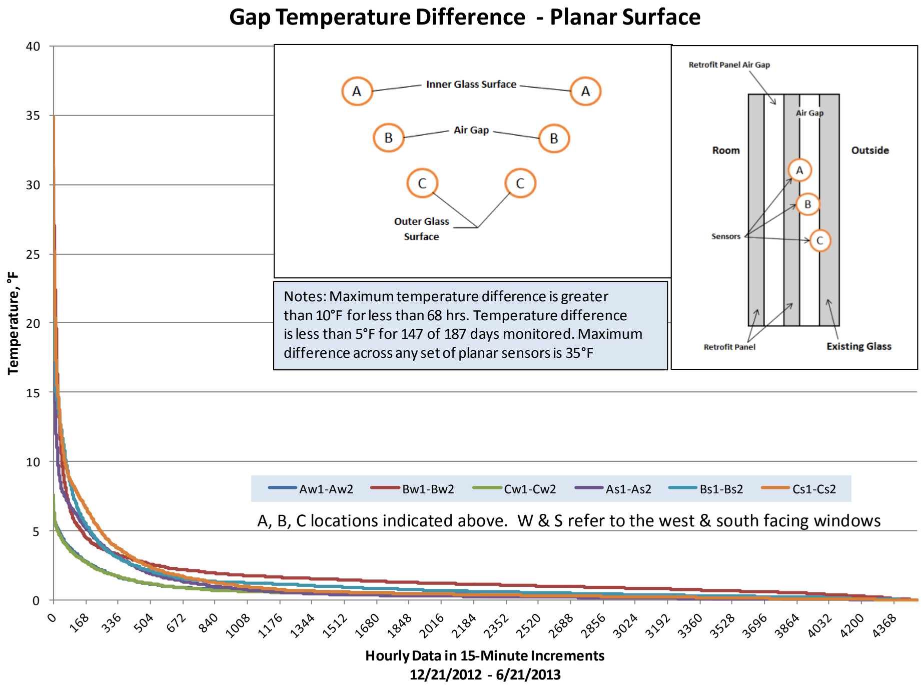


Figure 19: Planar temperature differences across the glass surfaces and air gap between the low-E retrofit panel and original glass. The 15-minute data is sorted to show the largest difference and the duration (in hours, x-axis).

6. Final Observations and Recommendations

Overall, this work confirmed the potential for low-E storm windows, panels, and retrofit systems to provide significant energy savings, reductions in air leakage, and improvements in thermal comfort in both residential and commercial existing buildings.

Over the last 13 years, this technology has moved from initial concept, to lab testing, to field testing, to the start of broader implementation. However, to maximize the potential for widespread energy savings, the project team recommends the following next steps:

1. *Continued educational outreach targeting not just state weatherization programs, but also other utility and energy efficiency programs, home and building improvement contractors, and consumers.*

   Some of this work has already begun within the DOE Building America program activities at Pacific Northwest National Laboratory, such as the addition of low-E storm windows to the Building America Solution Center and the creation of a new educational brochure.

This work should also target development of specific incentives that promote low-E storm windows, such as inclusion of low-E storm windows in utility rebate programs.

2. *Continued refinement of technical information about low-E storm windows and retrofit systems.*

   Again, as part of DOE Building America program activities, PNNL has developed a database of estimated energy savings for low-E storm windows and panels in 22 cities across all U.S. climate zones using NEAT and RESFEN, and further locations could be added as needed for specific utility or efficiency programs. (https://basc.pnnl.gov/resources/database-low-e-storm-window-energy-performance-across-us-climate-zones)

   Furthermore, PNNL has conducted preliminary tests of low-E storm windows and doors in their lab homes facility during heating and cooling periods, and will be doing additional testing. The data from these well-controlled experiments can be used to confirm energy savings estimates from software packages used in various efficiency programs, and provide further insight into the performance of low-E storm windows in warm/mixed climates with both heating and cooling. (http://labhomes.pnnl.gov/experiments/lowE.stm)

3. *Promotion and removal of barriers to use within federal agencies.*

   Development of an Energy Star program for window retrofit technologies such as low-E storm windows and panels could help tremendously in making general consumers aware of this technology. Additionally, the success of the Energy Star program for replacement windows may have inadvertently created a barrier to the use of low-E storm windows, where local personnel in programs such as Home Performance with Energy Star sometimes incorrectly believe that low-E storm windows cannot be used without an Energy Star designation. DOE and EPA can jointly help clear up these misunderstandings, but creation of an Energy Star program for low-E storm windows would immediately remove the barrier.

   Furthermore, there is the opportunity for DOE to promote the use of low-E storm windows, panels, and commercial retrofit systems with other federal agencies and programs that have interest in energy efficient buildings including the U.S. Department of Defense (DOD), General Services Administration (GSA), Department of Housing and Urban Development (HUD), and DOE's own Federal Emergency Management Program (FEMP).

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Appendix A

Performance Comparison of Low-E Storm Windows
in Philadelphia Multifamily Apartment Buildings

Performance Comparison of Low-E Storm Windows in a Philadelphia Multifamily Apartment Building

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Contents

Tables and Figures

Background

Controlling rising energy costs in older multistory, multifamily buildings can take various pathways such as envelope or equipment improvements. Equipment upgrades, such as the use of high efficiency motors or boilers can result in reduced energy costs. However, for older building envelopes with low wall insulation levels and window technologies with high U-factors, the efficiency gains from equipment improvements may be hindered. While the equipment may be more efficient, the discomfort of the occupants in inefficient buildings often leads to increased energy use (e.g., supplemental heaters). Furthermore, the equipment upgrades in older buildings must be sized to service the same loads whereas in more efficient envelopes, the equipment upgrades can be sized smaller thus saving upfront costs as well as ongoing fuel costs.

Envelope upgrades; however, can be very expensive for building owners. Envelope upgrade costs may include not only the installation of new materials, but also include removal and disposal of old materials and displacement of occupants during renovations.

Addressing these concerns for envelope upgrades, an innovative storm replacement window technology has been installed to decrease the window U-factor, add a low-E coating, and reduce air infiltration. The storm window retrofit was performed on two large three-story residential multifamily apartment buildings located in downtown Philadelphia, Pennsylvania on West Girard Avenue (Figure 1). The buildings were constructed in 1962 with 101 apartment units using 4,720 ft^2 of single-pane, metal-framed windows with attached single-pane, triple track, clear glass storm windows. During this retrofit, it was noted that many of the existing storm windows were not functioning properly, broken, or missing.

The purpose of the window upgrade was to reduce operating energy costs, increase the comfort of the occupants, and provide a more uniform interior temperature that does not rely on use of supplemental heating units. The window upgrade technology selected is a new low-E storm window. The storm window retrofits are performed from the exterior; therefore, the occupants are not displaced during the renovation process.

Modern low-E exterior storm windows were provided for the window upgrades by Quanta Technologies Inc. Upgrading the existing metal frame single-pane windows with the low-E storm window; the new combined window system is estimated to have an approximate U-factor of 0.44[1] and a solar heat gain coefficient (SHGC) of 0.48. The original single-pane windows are estimated to have a U-factor of 1.12 and SHGC of 0.61, and a U-factor of approximately 0.58 and a SHGC of 0.56 with the old clear glass exterior storms. As a result, the new low-E storm windows lower the U-factor by 61 percent compared to the single-pane primary window, and 24 percent compared to the single-pane window with the older traditional storm window. In both cases, the storm windows were attached to surrounding wood trim to ensure a thermal break with no direct metal-to-metal contact. Additionally, the new low-E storm windows were expected to reduce air infiltration compared to the older leakier windows. This effect was measured as described below.

[1] All U-factors are in $Btu/hr{\cdot}°F{\cdot}ft^2$

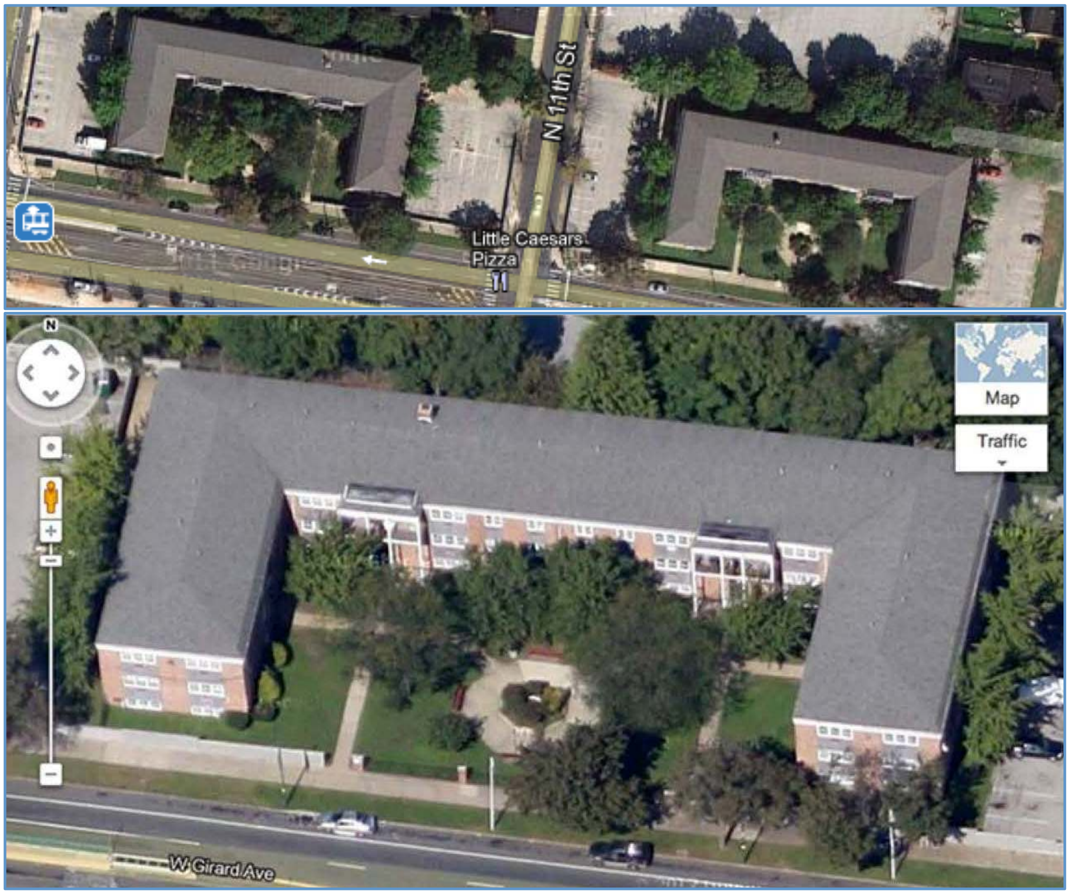

Figure 1. Multifamily Apartment Buildings Upgraded with Low-E Window Retrofit Panels

Test and Analysis Methodology

Improvements in the energy performance were assessed in two ways: blower door tests on representative apartment units to measure air infiltration reductions; and analysis of the utility bills for one of the two buildings.

For the blower door tests, 15 percent of the dwelling units were chosen for the study (15 units). For the best diversification they were located on any of the three floors, and also included studio, one, and two bedroom layouts.

Each of the units was tested for infiltration leakage with the existing storms both open and closed. After the new storms were installed, the infiltration tests were performed again to quantify the leakage reduction attributed to the new low-E storm windows. The testing was performed at 50 Pa air pressure difference.

To better approximate the whole building performance, the building's utility bills for the preceding year and the year following the window retrofit were analyzed to calculate actual savings. However, the analysis is limited by changing building occupancy and weather patterns from year to year and thus serves only as a marker of energy savings. The benefit of the utility bill analysis is to generally confirm the savings based on the test study and to generally estimate a magnitude of the savings that can be realistically expected from the window retrofits.

Monitoring Results

Infiltration Testing

Infiltration testing on individual apartments was performed at multiple points in the project. Perhaps surprisingly, initial infiltration data indicates that the reduction in air leakage from the existing storms was not measurable – the older triple-track storm windows showed no significant improvement in air leakage between when they were closed and open. Following the installation of the new low-E storm windows, infiltration measurements were again taken with the storm windows open and with the storm windows closed. The main windows were closed and latched in both cases (where latching was feasible). Figure 2 compares the result of the infiltration testing for each unit. The infiltration testing was performed at 50 Pa of pressure difference from the apartment to the outside using a depressurization methodology. The test metric is cubic feet per minute at the test pressure (CFM50) and is the total leakage from the apartment.[2]

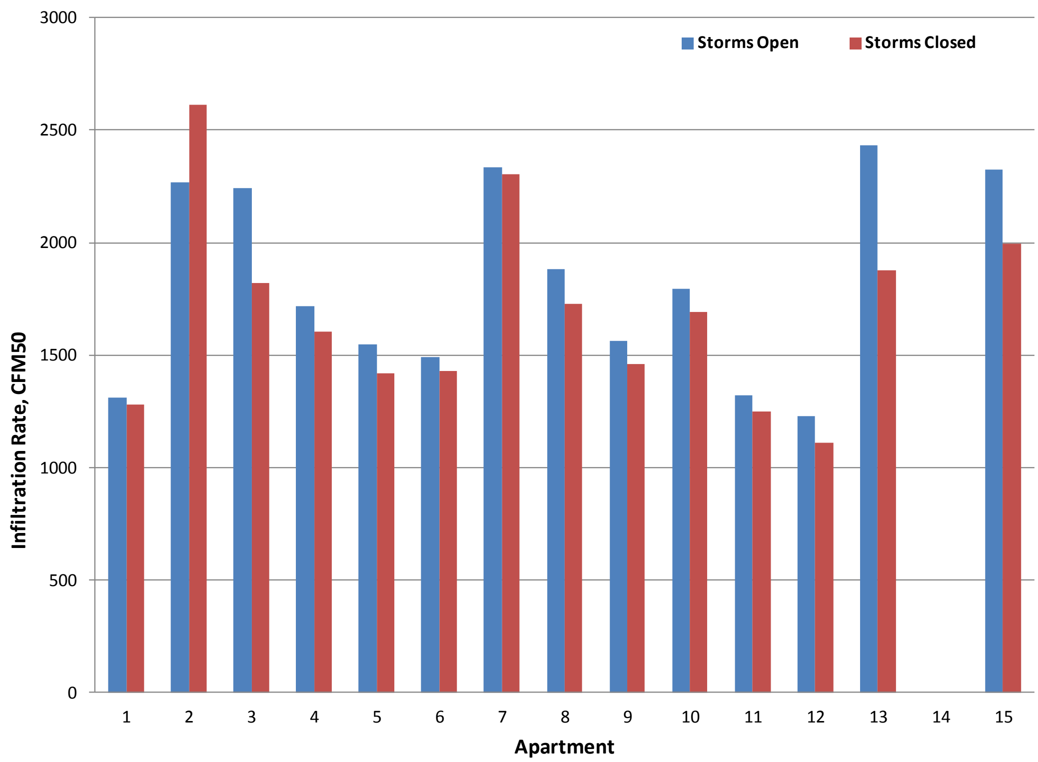

Figure 2. Post Retrofit Air Leakage Measurements with Low-E Storms Opened and Closed

When evaluating the change in the air exchange rate and the change resulting from the installation of the storm windows, unit 2 data is excluded due to the anomaly of an increasing level with the storms closed.[3] Unit 14 is also excluded as it was not available for testing on the appointed test date. The remaining units show a 10 percent reduction overall in the overall apartment air infiltration rate with a range of 1 percent to 23 percent reduction across all units. This is an average reduction of 3.2 CFM50 per square foot of window area. It is important to note that this 10 percent reduction in air infiltration for the overall apartment test units was solely from adding the new low-E storm windows; no other air sealing measures were applied.

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[2] Total leakage includes leakage to the outside and to adjacent units. Isolation of one apartment to determine solely leakage from the unit to the exterior was not feasible in the occupied building.

[3] It is unknown at this time the cause of the anomalous result for unit #2.

Whole Building Gas Utility Usage

The primary metric to quantify the benefit of the retrofit storm windows is energy consumption. Analysis of the monthly utility bills for fuel use for pre- and post-retrofit conditions assumes that the window upgrades are the primary change in the building operation that accounts for the energy consumption differences across the two heating seasons. Changes in outdoor temperature, the primary driver for heating energy use, are accounted for through a normalization of the consumption data of the heating degree days for the same month period. Temperature set points, occupancy levels, and window operation during heating periods are important factors but are not available in sufficient detail to qualify the summary results.

Heating energy was estimated for a period from October through April. The heating period was selected where there would be the least crossover between heating and window use or cooling system operation. Figure 3 shows the total monthly estimated gas use for heating plotted with the heating degree days for the month.

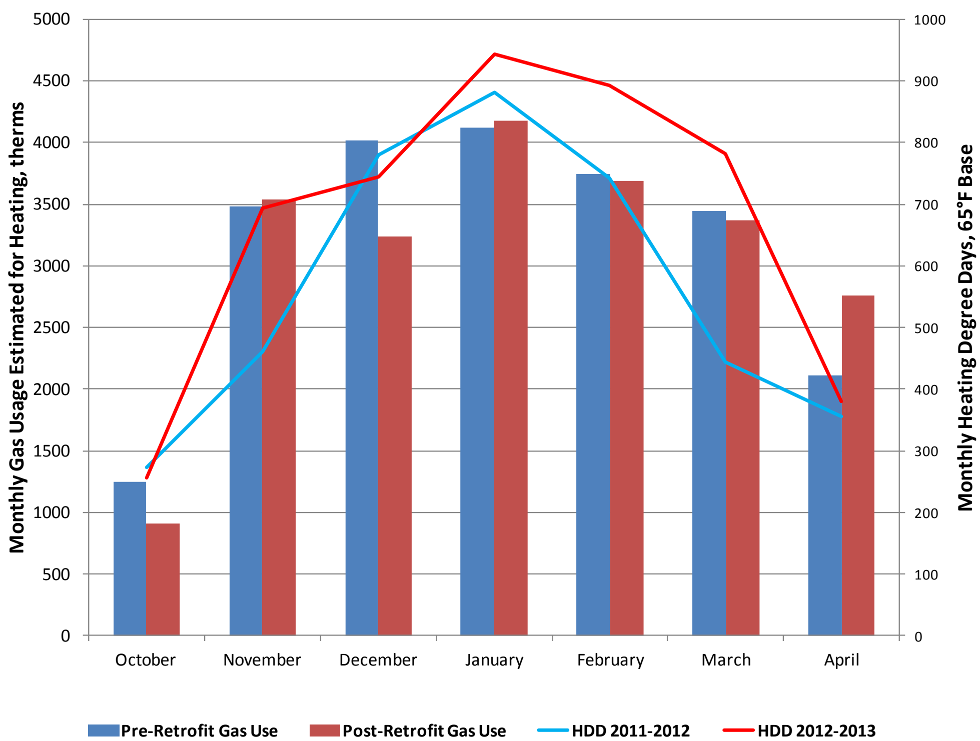

Figure 3. Monthly Estimated Heating Gas Use and Heating Degree Days

The heating energy was estimated by subtracting the estimated gas use for water heating from the June and September monthly billing periods. These periods were selected based on the few heating degree days and the slightly cooler incoming water temperatures that may better represent the energy used for water heating.

Based on the estimated fuel use for heating and the heating degree days, the fuel use is normalized to the heating degree days. This approach is considered valid if the interior temperature is assumed fairly consistent for each apartment over the analysis period. Figure 4 shows the normalized use for comparison of the pre- to post-retrofit heating periods.

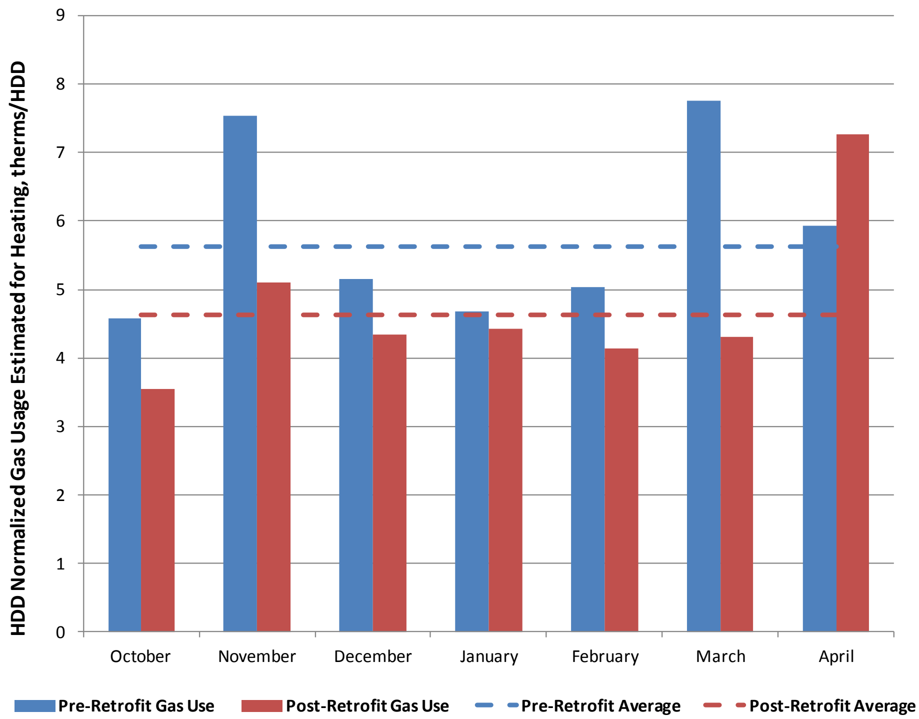

Figure 4. Monthly Normalized Heating Gas Use for Low-E Storm Window Pre- and Post-Retrofit

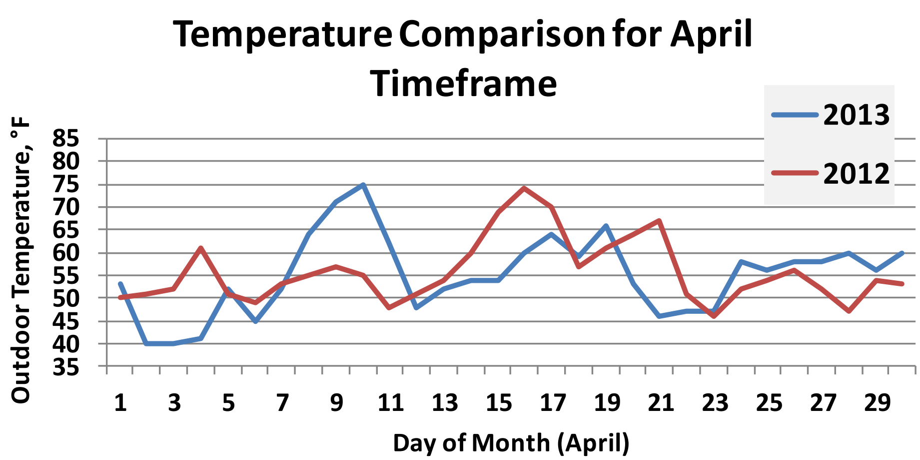

Figure 5. Temperature Comparison for April

Heating energy was reduced by about 1 therm per heating degree day over the seven-month period, or about an 18 percent reduction. If a narrower window for heating is used from November through March, then the energy use is reduced by about 1.25 therms per heating degree day or approximately 22 percent energy savings. It is not specifically known the cause of the April energy use to be higher after the storm windows were installed; however, one indicator is that a warm spell occurred earlier in the month 2013 (see Figure 5) where many residents may have opened the windows (including the storms) and then left the storms opened when the weather turned colder later in the month.

The gas use for heating is affected by both the imprecise temperature control for each apartment and the occupant operation of the windows. It is expected that with changing outdoor temperatures and an imprecise control over the heating supply to the apartment, that the windows might be used to help control large temperature extremes. If this is the case, then the full benefit of the storm windows may be dampened. Table 1 shows the overall energy use and estimated savings based solely on utility bill data.

Table 1. Energy Use Comparison Based on Monthly Utility Billing

Heating	October 2011 to April 2012 [A]	October 2012 to April 2013 [B]
Heating Degree-Days, HDD	3,938	4,693
Heating Gas Use [C], therms	22,167	21,692
Normalized Gas Use, therms/HDD	5.63	4.62
Heating Savings Over Base		18%
Heating	**November 2011 to March 2012 [A]**	**November 2012 to March 2013 [B]**
Heating Degree-Days, HDD	3,309	4,058
Heating Gas Use [C], therms	18,808	18,023
Normalized Gas Use, therms/HDD	5.68	4.44
Heating Savings Over Base		22%

[A] Pre-window retrofit
[B] Post-window retrofit.
[C] Heating Gas Use estimated by subtracting estimated hot water gas use in non-heating swing months.

Individual Unit Electric Utility Usage

Many of the apartments have through the wall air conditioning units. It is not known how often the units are employed or the interior set point temperature for the A/C units. Given the uncertainty of the data, an estimate of cooling energy use is made by comparing the summertime energy use with a swing season electricity energy use. This methodology assumes that the electric energy use for lighting, appliances, and miscellaneous use in the summer months is no more than that in the swing seasons. Figure 6 charts the average electricity use for the test apartments and the estimate for cooling energy for the pre- and post-retrofit low-E storm windows. It appears that with a similar cooling demand (based on cooling degree days) for each year, there is a distinct reduction in electricity use (the darker bars represents the total electricity use and the lighter shaded overlay column is the estimated electricity used for cooling).

Normalizing the cooling electricity to cooling degree days attempts to adjust the electricity use for air conditioning based on the weather conditions. Figure 7 graphically shows this analysis.

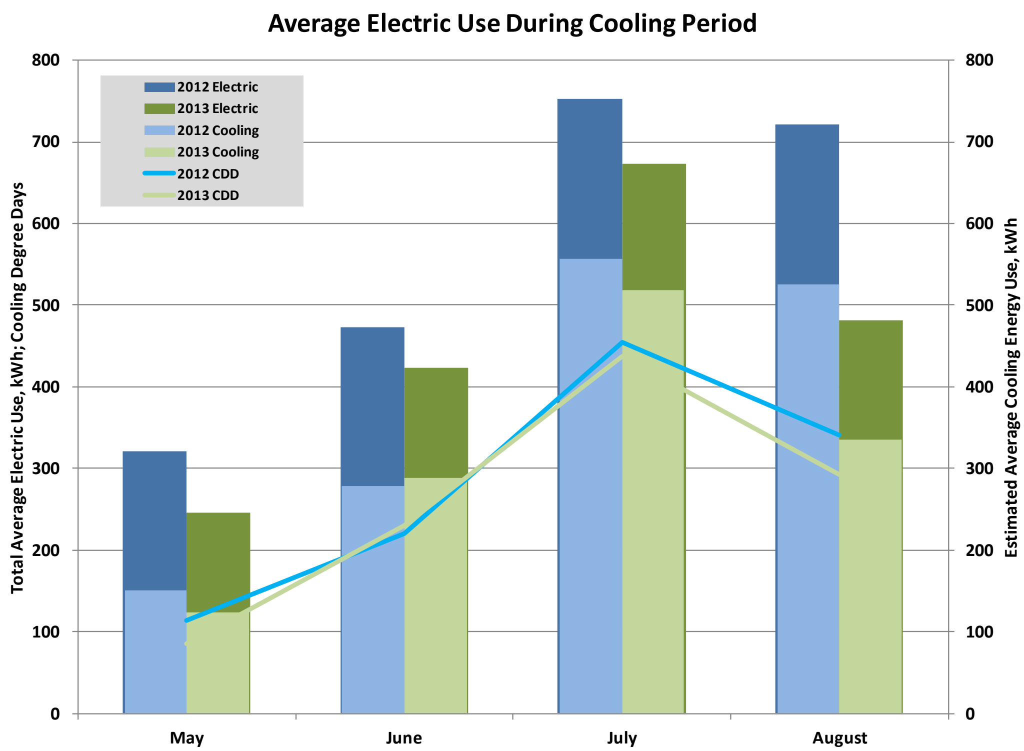

Figure 6. Average Unit Electricity and Estimated Cooling Electricity Use for Summer Months

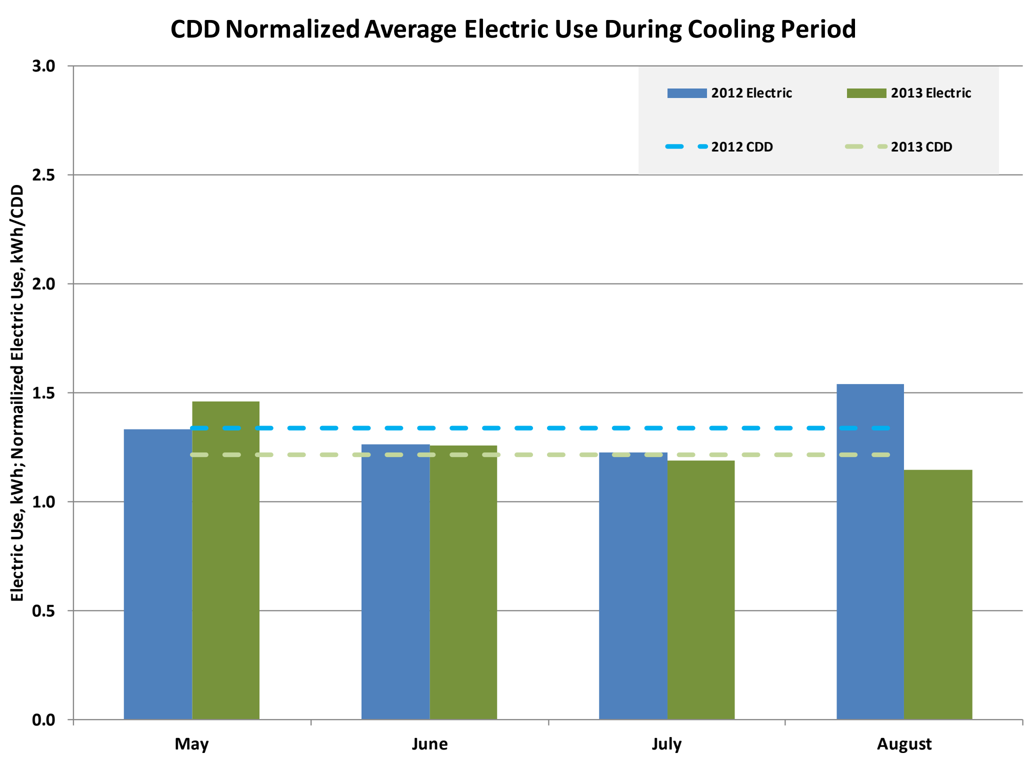

Figure 7. CDD Normalized Estimated Average Cooling Electricity Use

Summarized in tabular form (Table 2), the summertime electricity use for four cooling months shows just over 9 percent electricity savings on average.

Table 2. Cooling Electricity Use Estimates

Cooling Month	Apartment Average Electric Use[A], kWh		Estimated Cooling Electric Use, kWh		CDD[B] Normalized, kWh/CDD		Post- to Pre-Retrofit Savings[C]
	2012	2013	2012	2013	2012	2013	
May	322	245	151	124	1.33	1.09	18.0%
June	474	424	278	289	2.45	2.54	-3.8%
July	752	673	557	519	4.90	4.57	6.7%
August	721	482	526	335	4.63	2.95	36.3%
Month Average Total	2,269	1,824	1,512	1,267	1.34	1.21	9.3%

[A] Only non-zero meter values (occupied apartments) included.
[B] CDD = Cooling Degree Days, 65°F base.
[C] Savings based on normalized energy use.

Whole Building Simulation Estimates

An initial software analysis was used to translate the performance results of upgrading the storm windows in 10 to 15 apartments to the larger building complex of 100 units. Due to the relatively minimal amount of information available for each of the apartments, the analysis utilized a software tool that is commonly applied to existing homes, including multifamily buildings, that has internal defaults for energy use of non-space conditioning loads. The software, REM/Rate version 14.2[4], was used to model the whole building using an average size for all of the apartments.

The software analysis focused on two improvements afforded by the upgrade to the low-E storm windows. One is the reduced infiltration outlined above, and the second is the improved (lower) U-factor and lower solar heat gain coefficient based on estimated values (refer to the Background section above). The purpose of the analysis is to estimate the annual energy savings resulting from using the upgraded storm windows.

As the software analysis relies on a number of estimated factors, the model was calibrated using actual whole building meter data for gas (the only meter data available for this purpose). Following the calibration to within about 4 percent (higher predicted than measured), the air infiltration rate was decreased by 10 percent consistent with the reported average reduction following the storm window installation. The overall window characteristics, including the existing window and the existing storm baseline was 0.64 U-factor and 0.54 solar heat gain coefficient (SHGC). Following the low-E storm window upgrade these values were modified to 0.44 U-factor and 0.48 SHGC.

Assuming that the average energy use of all apartment gas and electric loads is somewhat represented by the software estimates, the heating energy is extracted for comparison since the low-E storm window upgrades will reduce this end load consumption. The results are outlined in Table 3 and are reported to compare the energy savings individually for the change in infiltration rates and window characteristics.

[4] www.archenergy.com/products/remrate

Table 3. Heating Energy Software Analysis

	Heating Energy, therms	Percent Savings over Base
Baseline	7,990	-
Infiltration Improvement	7,055	11.7%
Low-E Storm Window Improvement	7,296	8.7%
Combined Infiltration and storm window improvements	6,639	20.3%

Given the much larger uncertainty for cooling energy and the lack of interior temperatures during the cooling season, only a rough estimate of the cooling energy savings can be provided based on simulation results. These savings are only representative of general trends and should not be used as firm estimates of cooling energy savings unless it is known that the apartment is fully conditioned for cooling throughout the season. The summary results similar to the heating results are shown in Table 4.

Table 4. Cooling Energy Software Analysis

	Cooling Energy, kWh	Percent Savings over Base
Baseline	157,562	
Infiltration Improvement	158,224	-0.4%
Low-E Storm Window Improvement	130,854	17.0%
Combined Infiltration and storm window improvements	132,084	16.2%

The software simulation results align with the measured heating savings and therefore a reduction in fuel use for heating of at least 20 percent may be expected. However, this result is dependent on the control of the heating supply to individual apartments and the consistent use of the storm windows – both factors that are considered highly variable in this building.

The software results for cooling energy use are less definitive to predict actual energy savings; however, should the storm windows be consistently employed and with a somewhat consistent use of the cooling equipment, electric energy savings of over 15 percent may be expected.

Conclusions

Replacement of the existing storm windows in two large multifamily buildings with 101 units was evaluated for improvements in air leakage and heating gas and electric consumption. The existing clear single-glazed metal windows and clear single-glazed storm windows were upgraded to remove the existing storms and replaced with new low-E storm windows. The improvement in the combined window U-value is estimated to be approximately 0.14 U-factor lower than the original windows (0.58 to 0.44 $Btu/hr \cdot ft^2 \cdot °F$). The solar heat gain coefficient was estimated to be reduced by about 0.08 (0.56 to 0.48).

As a result of the storm window upgrades, the air infiltration analysis shows a 10 percent reduction in overall apartment air infiltration on average across the units. The improved air tightness of the windows along with the low-E glazing is expected to improve the comfort of the occupants, especially near the windows on cold winter days.

An initial utility bill analysis, which includes all units in the building and the common areas, indicates that an 18 percent gas use reduction for the heating season (which includes the transition months of October and April). When evaluating the specific heating period of November through March, the more focused analysis shows a 22 percent reduction in energy use. A software analysis shows an approximate 20 percent heating energy savings over a full typical heating season. It can be expected that based on the first winter following the storm window upgrade, the heating system operation may be further optimized in the swing seasons when the system is being activated or deactivated.

Cooling energy savings was estimated to be approximately 9 percent when normalized to the cooling degree days for each test period. However, the software analysis shows a slightly higher savings of approximately 15 percent over the full cooling season. This difference between the model and real life is expected due to the expected inconsistent use of individual cooling equipment and indoor temperature set points for cooling.

Analysis of ongoing utility costs and a review of the heating (and cooling) equipment operation with building engineers are recommended to fully understand the benefits of the window upgrades.

Further support to the occupants providing direction on the use of the storm windows, the control of the heating supply to the apartment, and for a modified control of the central heating system by the plant manager, would all contribute to further increased energy savings afforded by the low-E storm window replacement.

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Appendix B

Residential Low-E Storm Window Retrofit Study
in a Warm / Mixed Climate

Residential Low-E Storm Window Retrofit Study in a Warm / Mixed Climate

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Funded by U.S. Department of Energy
project #DE-EE0004015

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Home Innovation RESEARCH LABS™

NOVEMBER 2013

Report # 3323.001RES_11152013

Disclaimer

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Tables

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Background

Controlling rising energy costs in older single-family dwellings can take various pathways such as envelope or equipment improvements. In particular, poor performing windows are often a weak link in an older home's energy performance, yet the cost of new replacement windows can be out of reach for many homeowners, especially when considering the extra cost for removal and disposal of the existing windows. This study evaluates the opportunity for cost effectively improving energy efficiency and occupant comfort in homes through retrofit of exterior wall glazing by installing low-E storm windows over the existing single-pane wood frame windows. A previous study for older weatherization homes in Chicago showed that adding low-E storm windows to single glazed primary windows reduced the overall heating load of a home by as much as 21 percent, with a simple payback of under five years.[1] The State of Pennsylvania also conducted an analysis to determine that low-E storm windows were consistently cost effective across a wide range of home types, and subsequently added low-E storm windows to its weatherization measure selection priority list for single-family homes in 2010.[2] However, there have not been any studies of the performance of low-E storm windows in a warmer, mixed climate, where both summer cooling and winter heating are important. Therefore, the goal of this study is to quantify the potential for energy savings based on the use of storm windows over a set of single-family homes in a warmer geographic area with mixed heating and cooling. This information is helpful to homeowners making informed decisions on selecting energy efficiency upgrades and when considering house performance improvement options.

Three types of storm window technologies were considered for this study. One storm window technology is a standard approach that uses clear glass. Two other innovative storm replacement window technologies were tested; one has a standard low-E coating with high solar heat gain properties and another has a low-E coating with a lower solar heat gain properties. Both low-E coatings are pyrolytic or "hard coat" low-E with a durable ceramic metal oxide coating that can be used in a storm window application, unlike other low-E coating types that must be protected in a sealed insulating glass unit. All technologies improve the insulating performance and decrease the window U-factor; however, the low-E coating further decreases the U-factor and provides an added measure of comfort. Additionally, modern storm windows can provide additional benefits in reducing air infiltration for the existing window and the overall home. Because the storm window retrofits are performed from the exterior, there is minimal or no disruption to home owners during the window installation – a significant benefit of this technology.

The storm window retrofit was performed on ten single-family homes located in the suburbs of Atlanta, Georgia. The homes varied in age from 35-86 years old and all had single-pane windows. A total of 136 storm windows were provided by Larson Manufacturing Company and Quanta Technologies, Inc., using low-E glass provided by AGC Flat Glass North America and Pilkington North America (NSG Group). The storm windows were installed to the exterior of the existing single-pane wood windows. Based on window characteristics provided by the window manufacturers for the specific products, the U-factor and Solar Heat Gain Coefficient for the installed windows are shown in Table 1.

[1] Drumheller, S.C., C. Kohler, S. Minen. 2007. "Field Evaluation of Low-E Storm Windows," LBNL-1940E, NAHB Research Center and Lawrence Berkeley National Laboratory, presented in *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings X International Conference*, Dec. 2-7, 2007.)

[2] Zalis, W. et al. 2010. *Evaluation of Low-E Storm and R-5 Windows for Inclusion in Pennsylvania's Weatherization Priority List*, Prepared by W. Zalis, Energetics Incorporated; T. Culp, Birch Point Consulting; C. Kohler, LBNL; and P.M. LaFrance, U.S. DOE; for the Pennsylvania Department of Community and Economic Development, May 2010, unpublished.

Table 1. Window Ratings with Exterior Storm Windows

Window Configuration	U-Value [A]	SHGC [B]
Existing, single-pane, double hung, wood	0.88	0.61
With exterior storm, clear glass	0.47	0.54
With exterior storm, Low-E, Low SHGC	0.36	0.34
With exterior storm, Low-E, High SHGC	0.36	0.46

[A] U-factor in Btu/hr·ft^2·°F
[B] SHGC (Solar Heat Gain Coefficient)

Test and Analysis Methodology

Atlanta, Georgia was chosen to qualify the energy savings and evaluate the feasibility of using low-E retrofit storm windows in a mixed climate with both heating and significant cooling (Climate Zone 3). All 10 homes were over 35 years old with many energy efficiency features substandard relative to current building practices and standards. The selected homes all had single glazing, ranged from 35-86 years old in mature neighborhoods, were single story (except one split level), and had an average living space just over 1,300 ft^2. The average window area per home was 143 ft^2. The selected homes had central air conditioning rather than individual window units to simplify measurement of cooling energy use. All homes were located in a suburban setting that included shading typical for that type of housing stock.

Exterior storm windows with three types of glass with different glazing characteristics were evaluated in an attempt to quantify the incremental savings and to identify the option that is most appropriate for the climate and the application. The glazing characteristics for the different storm windows included:

- Type 1 – clear glass;
- Type 2 – Solar control low-E (pyrolytic low-E coating with low solar heat gain); and
- Type 3 – Standard low-E (pyrolytic low-E coating with high solar heat gain).

The homes were divided into three groups and a schedule was established to compare the three storm window types. The first year focused on comparing the energy use when storm windows were used relative to the original single-pane windows. This was done by alternating each month with and without storm windows mounted while monitoring the heating and cooling energy use. The intent is that the monthly alternation of storm use and no storms installed would reduce the seasonal and occupant variability, in addition to help normalize for weather. The storm windows were labeled in such a way that neither the homeowner nor the window installer knew which glass type was being tested.

In the second year of testing, Year 2, the performance of two different glass types was directly compared in each home by leaving the storm windows up all year, but alternating sashes with different glass types each month within each home. For example:

- one set of homes alternated monthly between high and low solar gain low-E (Test house set 2);
- one set of homes alternated monthly between clear glass and high solar gain low-E (Test house set 3); and
- one set of homes alternated monthly between clear glass and low solar gain low-E (Test house set 1).

It was hoped that this intrahome approach would reduce the variability of comparing glass types between homes. For each home, one of the Year 2 storm window types was the same storm window type used in Year 1. Table 2 shows the Year 1 and Year 2 storm window test configuration for each Test Site.

Table 2. Storm Window Configuration for Each Test Site

Test Site [B]	Storm Window Type [A] Year 1 Testing Alternate Month		Year 2 Testing Alternate Month	
A	3	None	3	1
B	1	None	1	2
C	2	None	2	3
D	1	None	1	2
E	2	None	2	3
F	2	None	2	3
G	3	None	3	1
H	2	None	2	3
I	1	None	1	2
J	3	None	3	1

[A] Storm windows alternated on a monthly basis during each Year of testing.
[B] Similarly highlighted Test Sites use the same storm window configuration for testing each Year.
Green highlight = (Test house set 1)
Red highlight = (Test house set 2)
Purple highlight = (Test house set 3)

Each home was tested for air leakage both before and after the storm windows installation to measure the impact of the windows retrofit on the overall air tightness of the house for that age of housing stock.

In order to perform an evaluation of the storm windows compared with either no storm window installed or with another type of storm window, specific comparison periods were selected for a more detailed analysis. These comparison periods are specific climatic periods of sequential months when either heating or cooling operation was somewhat consistent. Figure 1 shows the selected comparison periods underlayed with the sequence of storm window installation.

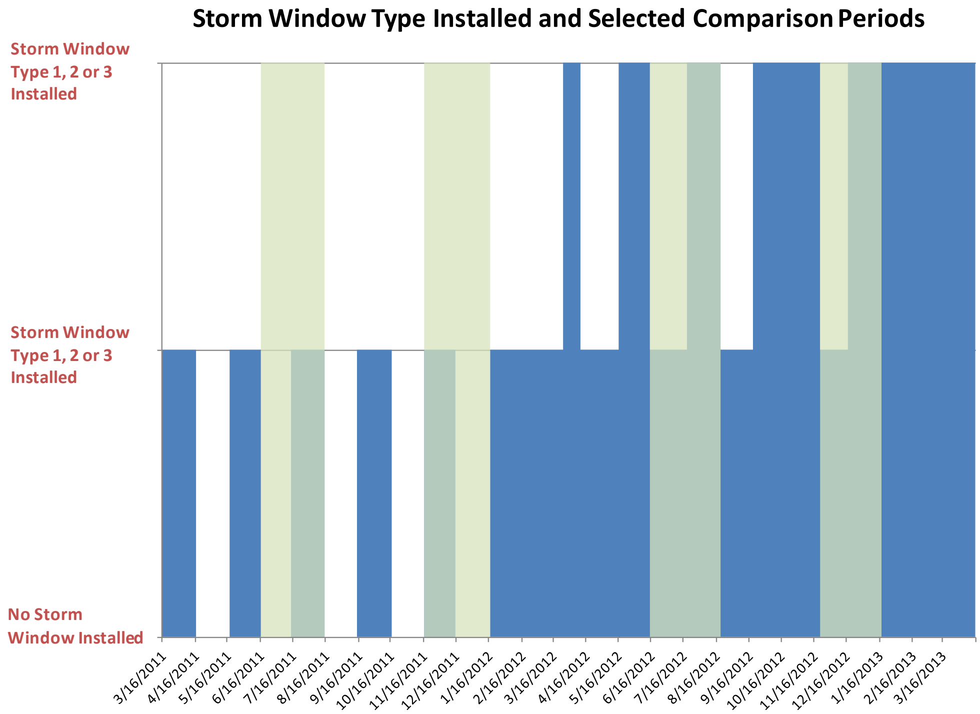

Figure 1. Storm Window Installation Sequence and Analysis Periods)
(The shaded areas indicate the periods selected for more detailed analysis)

Measured energy use for heating and cooling was normalized based on the outdoor temperatures to facilitate a more direct evaluation of the energy savings from installation of the storm windows. This analysis did not account for changing building occupancy (if any). Other weather patterns such as direct solar gains, shading, or wind effects are not directly accounted in the analysis and may influence the results, especially in the cooling season.

Instrumentation and Monitoring

Each home was outfitted with energy and temperature monitoring equipment. All of the data logging devices required a manual download of the data on a periodic basis. In a few cases, the monitoring hardware had been disconnected when furnace or air handler repairs were made resulting in a loss of data.

The following monitoring equipment and parameters were included in each home:

- Interior temperature and relative humidity were measured at the thermostat with a MadgeTech RHTemp101A sensor and recorded in 30-minute intervals;
- Furnace usage readings were through a MadgeTech State110 and recorded when the furnace turned on and off, to create duration of gas usage; and
- Air conditioning usage was measured through a WattNode Pulse meter installed on the AC components with pulse data stored in a MadgeTech Pulse 101A.

Measured data was processed on a daily basis to provide overall trends for energy use during the specific periods of interest in heating and cooling.

Test Homes

Ten homes were selected for the study. Each is briefly described with a photo and pertinent aspects that influence the energy use:

- Test Home Site G - Douglasville, GA
- 35 years old
- 1,400 sq. ft.
- 3 occupants
- Gas furnace (5 years); Air Conditioner (5 years) 2-ton
- 16 wood-frame windows

- Test Home Site B - Mableton, GA
- 51 years old
- 1,200 sq. ft.
- 4 occupants
- Gas furnace (8 years); Air Conditioner 2.5-ton
- 16 wood-frame windows

- Test Home Site E - Mableton, GA
- 53 years old
- 1,200 sq. ft.
- 5 occupants
- Gas furnace (1 years); Air Conditioner (5 years) 2-ton
- 15 wood-frame windows

- Test Home Site F - Mableton, GA
- 53 years old
- 1,000 sq. ft.
- 4 occupants
- Gas furnace (fair condition); Air Conditioner 2-ton (fair condition)
- 15 wood-frame windows

- Test Home Site C - Mableton, GA
- 51 years old
- 1,000 sq. ft.
- 3 occupants
- Electric furnace (6 years); Air Conditioner (6 years)
- 11 wood-frame windows

- Test Home Site D - Mableton, GA
- 86 years old
- 1,300 sq. ft.
- 4 occupants
- Gas furnace (15 years moderate condition); Air Conditioner (2-ton)
- 12 wood-frame windows

- Test Home Site A - Austell, GA
- 38 years old
- 1,800 sq. ft.
- 2 occupants
- Gas furnace (4 years); Air Conditioner (2-ton, 10 years)
- 13 wood-frame windows

- Test Home Site J - Winston, GA
- 36 years old
- 1,200 sq. ft.
- 2 occupants
- Gas (Propane) furnace (1 year); Air Conditioner (2.5-ton, 5 year)
- 15 wood-frame windows

- Test Home Site H - Mableton, GA
- 52 years old
- 2,000 sq. ft.
- 2 occupants
- Gas furnace (1 year); Air Conditioner (2.5-ton, 1 year)
- 22 wood-frame windows

- Test Home Site I - Mableton, GA
- 47 years old
- 1,600 sq. ft.
- 3 occupants
- Gas furnace (1 year); Air Conditioner (2.5-ton, 7 year)
- 15 wood-frame windows

Monitoring and Test Results

Infiltration Testing

Infiltration testing on each home was performed at two points in the project using blower door tests. A baseline was created for each home prior to storm window installation and a comparison test following the installation. Table 3 depicts the air infiltration reduction in each home. The infiltration testing was performed at 50 Pa of pressure difference to the exterior using a depressurization methodology. The test metric is cubic feet per minute at the test pressure (CFM50).

Table 3. Air Infiltration Reduction

Test House	Built	Age	Size (sf)	Infiltration Reduction
A	1973	38	1,805	1%
B	1960	51	1,198	24%
C	1960	51	964	2%
D	1925	86	1,271	21%
E	1958	53	1,200	5%
F	1958	53	932	44%
G	1976	35	1,479	3%
H	1959	52	1,404	10%
I	1964	47	1,627	13%
J	1975	36	1,197	11%
Averages		**50**		**17%**

The baseline measurements show these older homes to be very leaky with noticeable leakage around the existing windows (total home air leakage ranged from 12-57 ACH50 before installation of the storm windows), representing a source of large energy loss. For comparison, the national average for homes of these vintage is approximately 22 ACH50, whereas modern newly constructed homes are often under 5-7 ACH50.

After installation of the storm windows, the average reduction in air infiltration was 17 percent, or 3.7 ACH50. Note that this is the reduction in air leakage for the entire home just by adding storm windows – no other air sealing or changes were made. However, the standard deviation was also approximately 13 percent indicating a large discrepancy between test sites such that a general conclusion may be difficult to extract. For comparison, the improvement observed in the similar case study conducted in Chicago ranged from 5.7 to 8.6 percent [Drumheller, et al]. The results here show a larger average reduction, but also with more variation. This is not unexpected given the variability within the set of homes, and the different type of home construction between the two data sets. This overall level of infiltration reduction should yield an annual energy savings, but will be affected by occupant lifestyle, habits, exterior weather, or exterior vegetation.

Performance Data Summary and Analysis

Refer to Figure 1 above for the selected periods when the storm window installation evaluation was made. Summaries of the total monitoring period will be provided along with a specific analysis of four two-month periods:

- One 2-month period comparing heating performance of the base single-pane window with the first type of storm window assigned to each home;
- One 2-month period comparing cooling performance of the base single-pane window with the second type of storm window assigned to each home;
- One 2-month period comparing cooling performance of the first type of storm window to the second type of storm window within each home; and
- One 2-month period comparing heating performance of the first type of storm window to the second type of storm window within each home.

The analysis of the indoor temperatures and energy use is made for each of the 10 test sites (A through J) and as an average across all sites. Test site D has been excluded from most of the analysis since the monitoring equipment was inadvertently disconnected during a portion of the test period. For some sites, the second year heating data was not available due to logger malfunctions. For sites E and F, cooling data was lost in the second year. Data from test site J is of limited use since it was heated by propane fuel which could not be accurately monitored for consumption.

Indoor Temperature Summary

The indoor temperature measurements over the monitoring period (Figure 2) show a range across the test homes of over 10°F in the heating period and slightly less than 10°F in cooling (ignoring outlier sites), likely due to differences in occupant behavior and thermostat settings. This wide range in indoor temperatures will lead to more mixed energy performance results based on the storm window improvements. Less critical to heating energy but important for cooling energy use, the indoor relative humidity (Figure 3) also shows a wide range over the full monitoring period. Calculating the dew point temperature (Figure 4) over the period, the range narrows indicating relatively similar moisture levels in the homes despite the temperature and humidity differences.

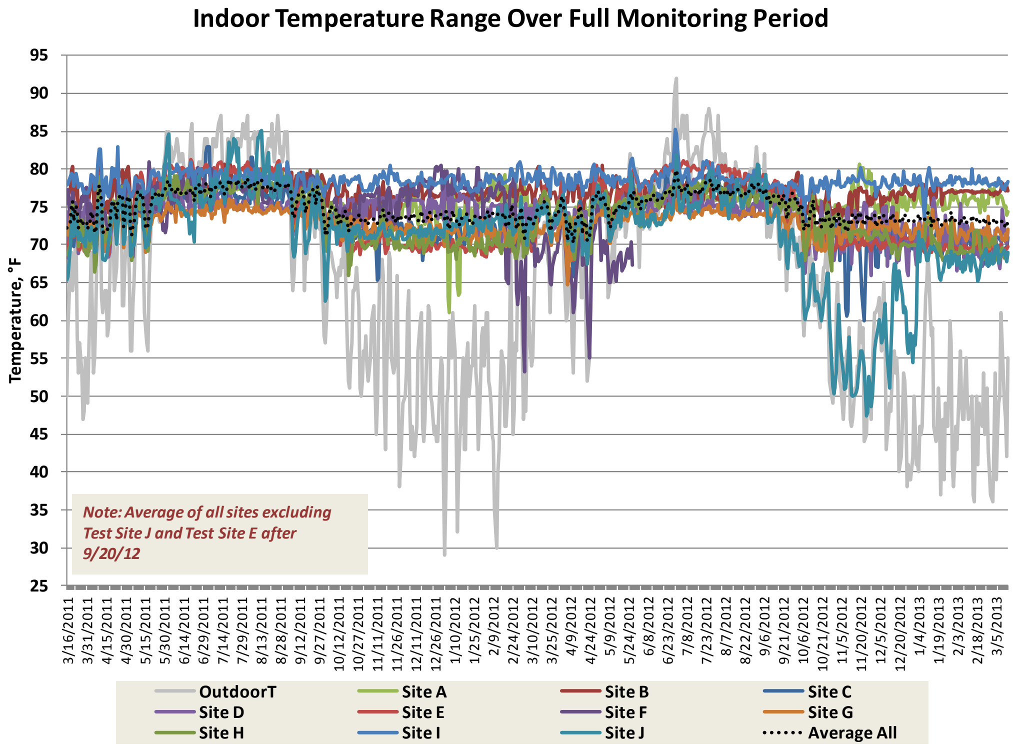

Figure 2. Monitoring Period Indoor Temperatures

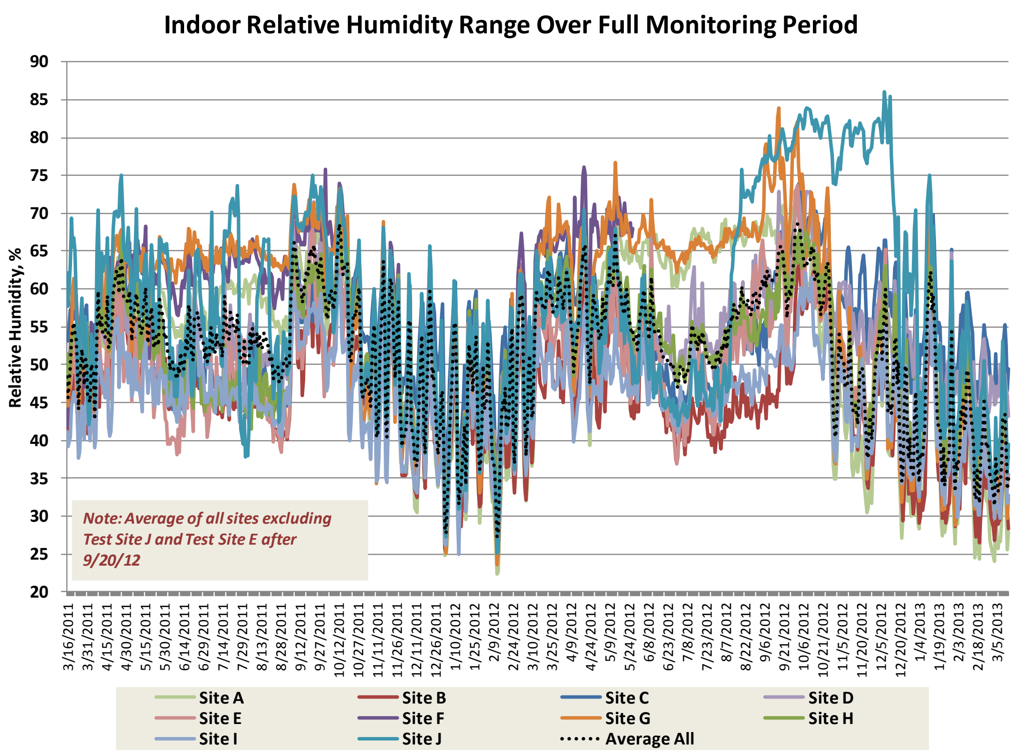

Figure 3. Monitoring Period Indoor Relative Humidity

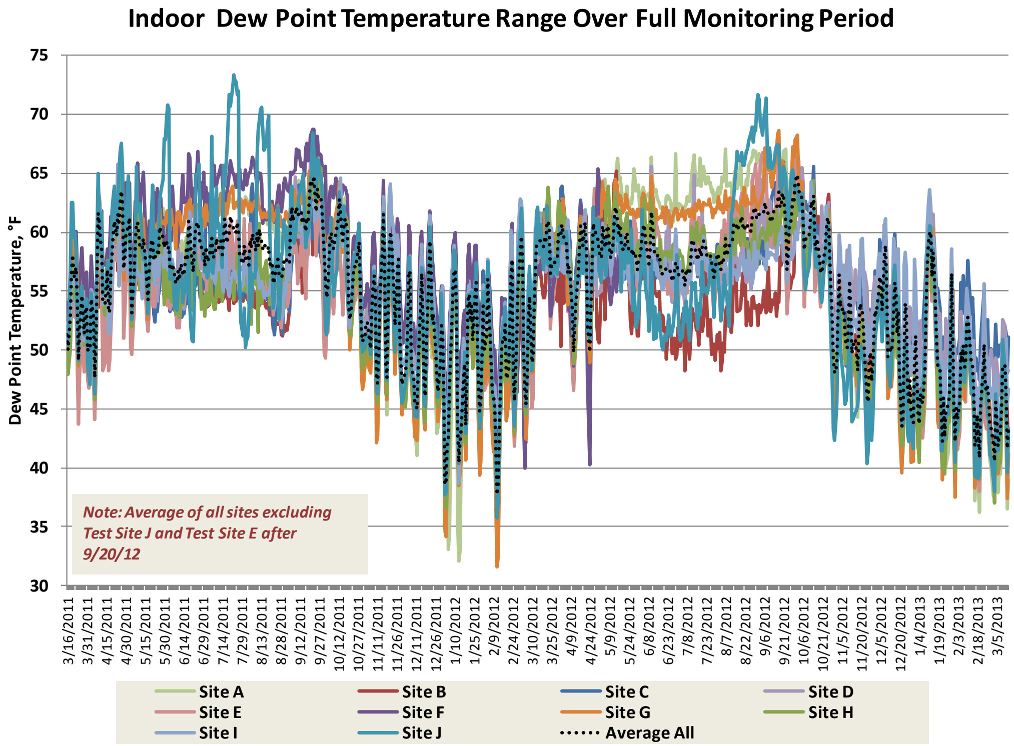

Figure 4. Monitoring Period Dew Point Temperature

For each of the specific two-month comparison periods outlined above and highlighted in Figure 1, the indoor temperatures are charted in Figure 5, Figure 6, Figure 7, and Figure 8. These more narrow comparison periods highlight the approximately 10 degree temperature difference range across the test sites during the heating period and approximately five degree temperature difference in the cooling periods. The temperature ranges across the test homes will affect the energy use for heating and cooling and including the comparison analysis for the storm windows.

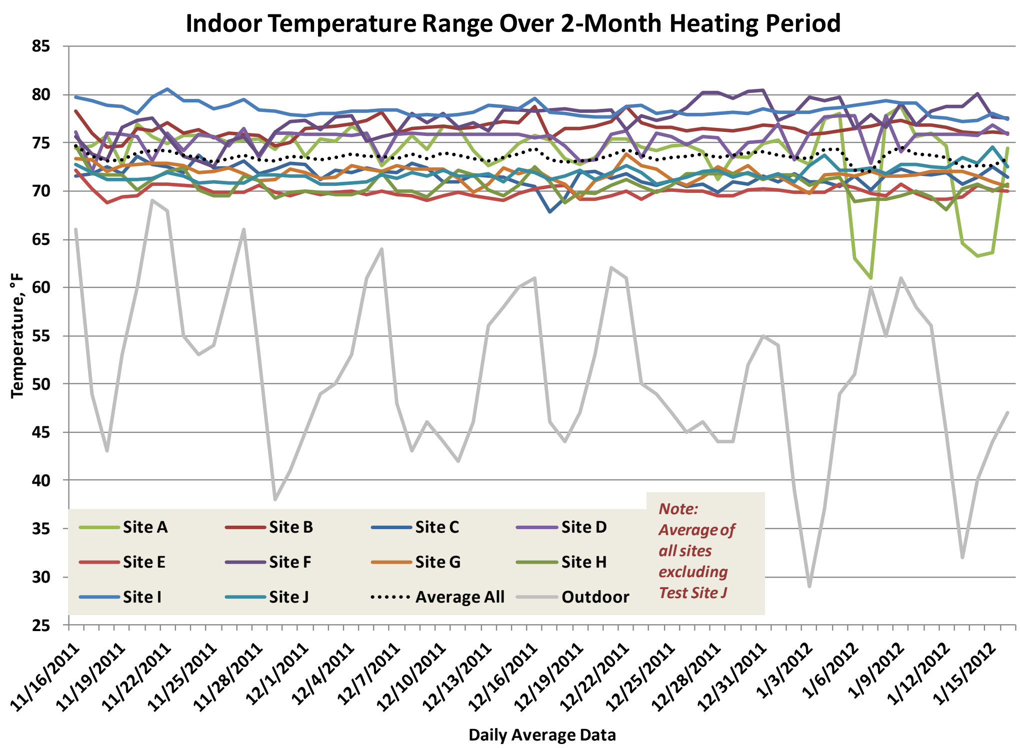

Figure 5. Temperatures During 2-Month Heating Period Comparison

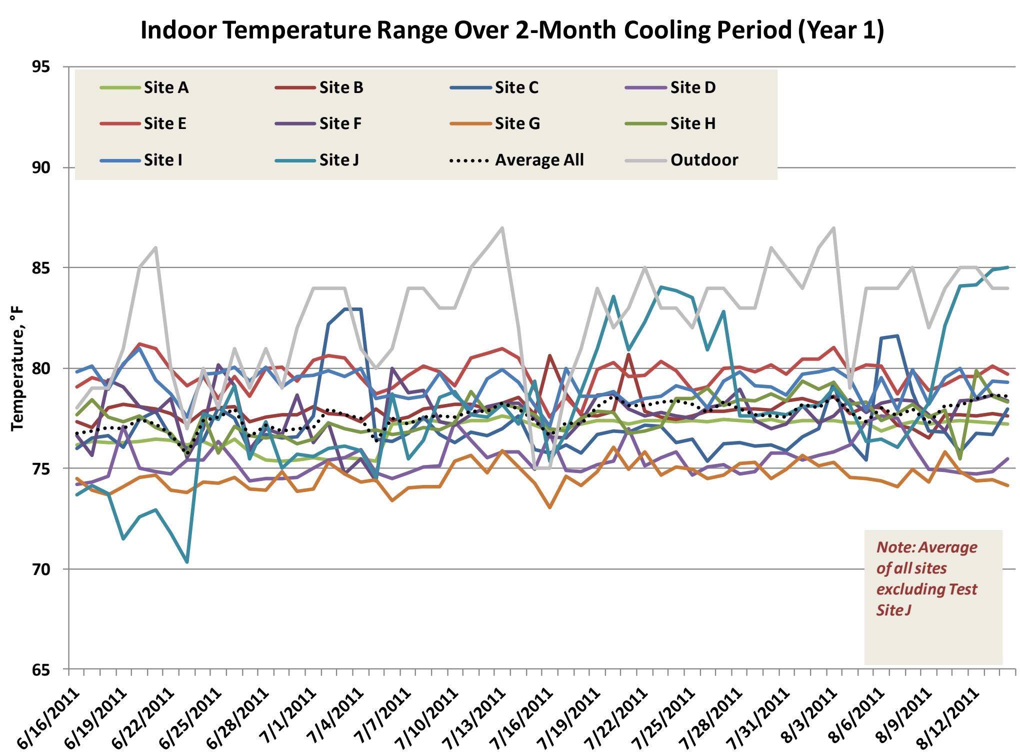

Figure 6. Temperatures During the First 2-Month Cooling Period Comparison

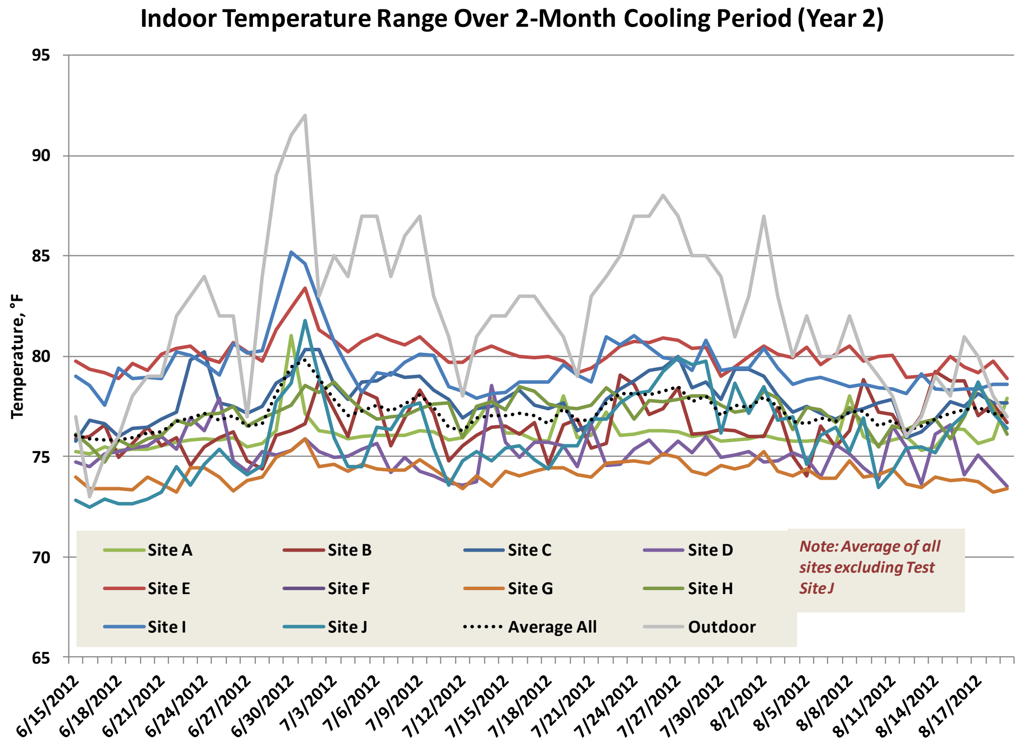

Figure 7. Temperatures During the Second 2-Month Cooling Period Comparison

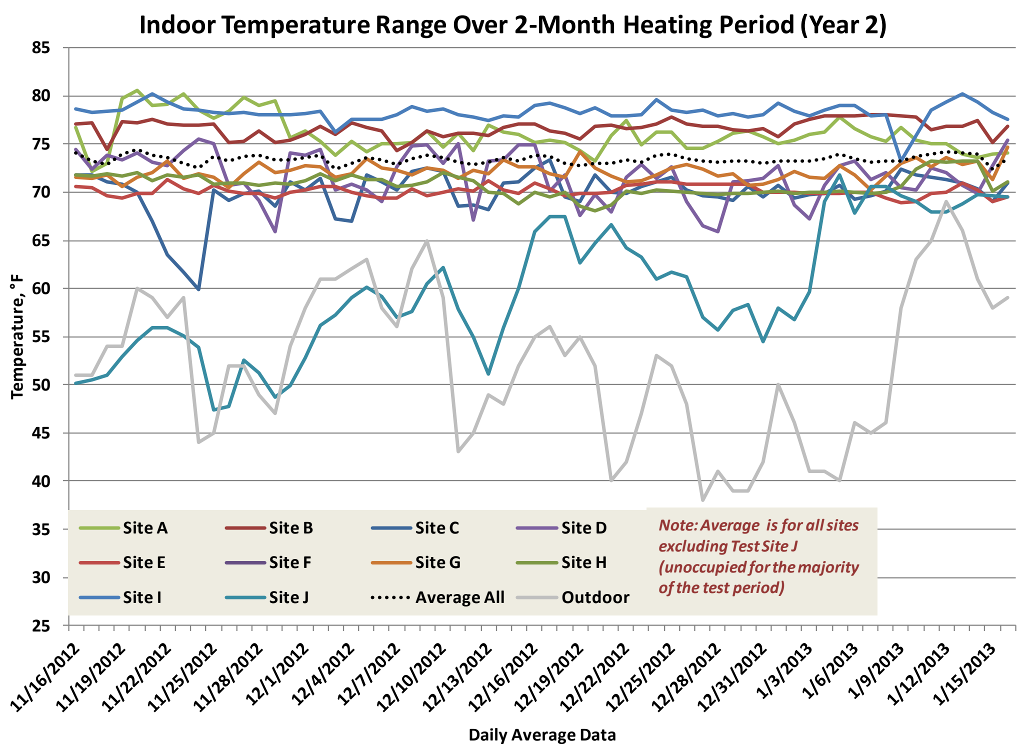

Figure 8. Temperatures During the Second 2-Month Heating Period Comparison

Cumulative Energy Use over Heating and Cooling Periods

For each of the 10 test sites, a simple plot of the cumulative energy use (solid lines) is plotted with the cumulative heating and cooling degree days from March 2011 through December 2012 (Figure 9 through Figure 19). Representing the data as cumulative for the variables allows a comparison of the slope of the heating and cooling degree days with the slope of the heating and cooling energy use rather than a simpler, but less informative, daily total of these same parameters.

For example, in Figure 9 the dotted lines show the cumulative degree days for the heating and cooling seasons (cooling, blue; heating, red). The cumulative total is reset to zero at the start of the season. Across all 10 test sites, the number of heating and cooling degree days were assumed identical and based on local weather station data. Specific periods selected for comparison of the storm windows is shown in the shaded highlight.

The same methodology is used for the heating and cooling energy. When the heating and cooling energy flatten, that is indicative of when the system was turned off for the season. The black line/marker is read on the right axis and indicates when and what types of storm windows were installed. A black marker at "0" indicates only the original single-pane windows are in place.

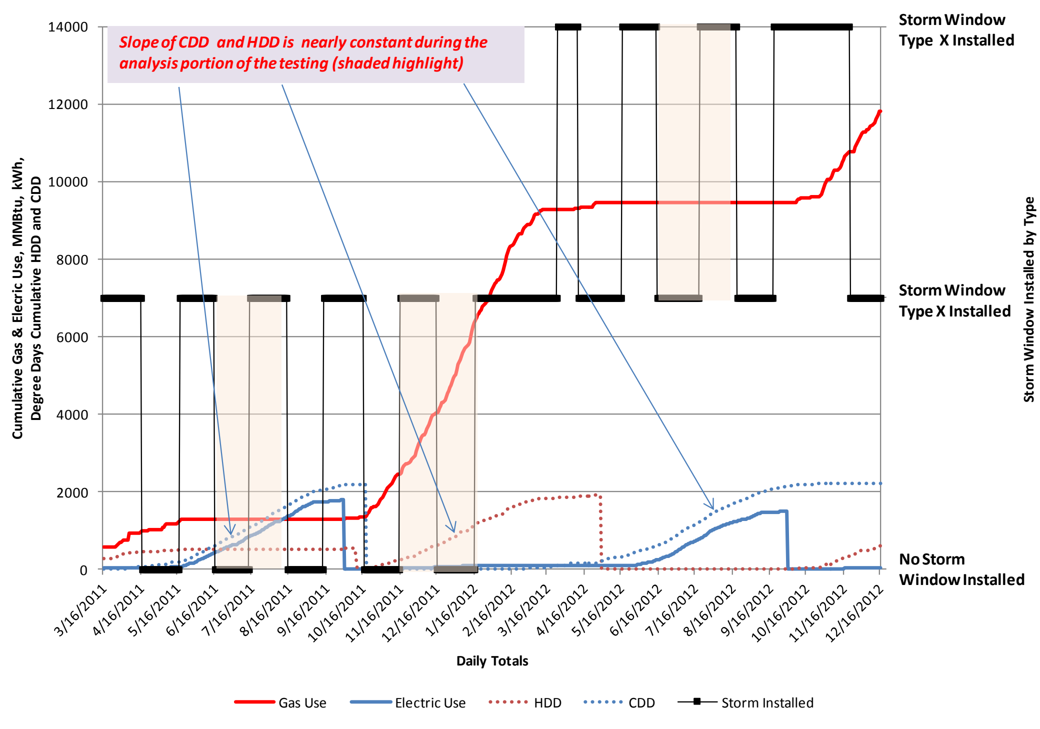

Figure 9. Cumulative Degree Day and Energy Use, Example

For each test site, the cumulative heating and cooling energy is shown in relation to the heating and cooling degree days, Figure 10 through Figure 19. For readability, the magnitude of the left axis is adjusted for the maximum cumulative energy use. The total cumulative gas and electric energy use for each home over each year is also listed in Appendix A for each window configuration (no storm window vs. the first storm window type in Year 1; two different storm window types in Year 2). In the original test plan, it was initially hoped that the intrahome approach in Year 2 would reduce the home and occupant variability to give a clear comparison of the different glass types. However, there remains significant uncertainty in the cumulative results, and additionally, heating data towards the end of the period for some of the test sites was not collected due to malfunctioning and disconnected sensors. Therefore, the main analysis described in the next section focused more narrowly on two analysis periods where more consistent demand in heating and cooling was observed.

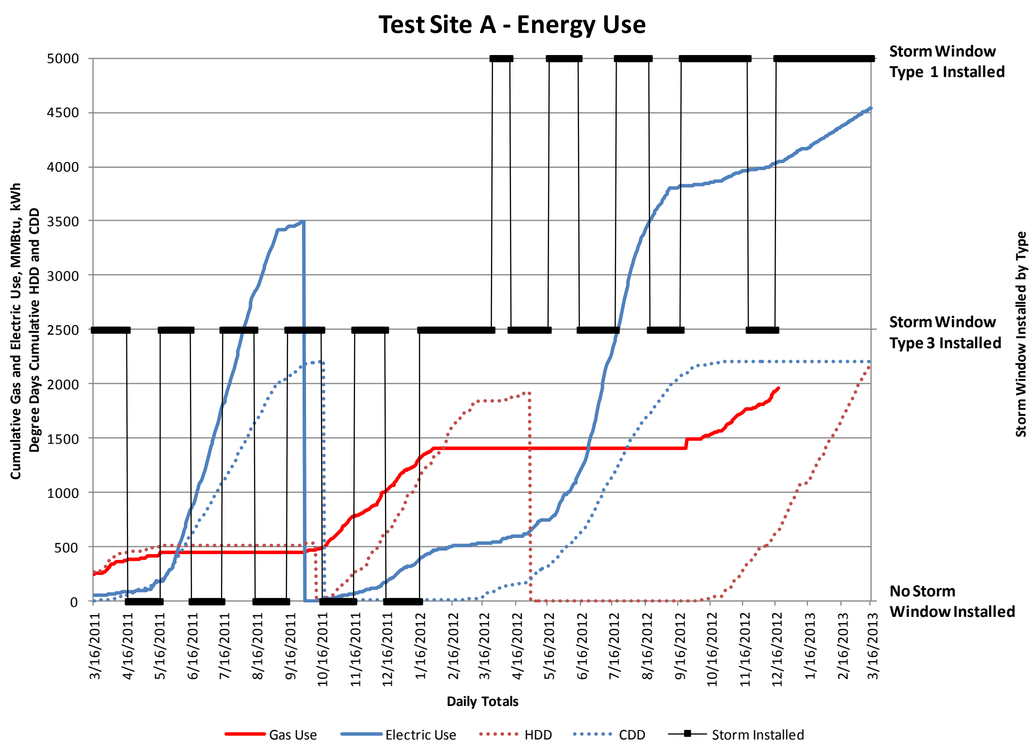

Figure 10. Cumulative Degree Day and Energy Use, Site A

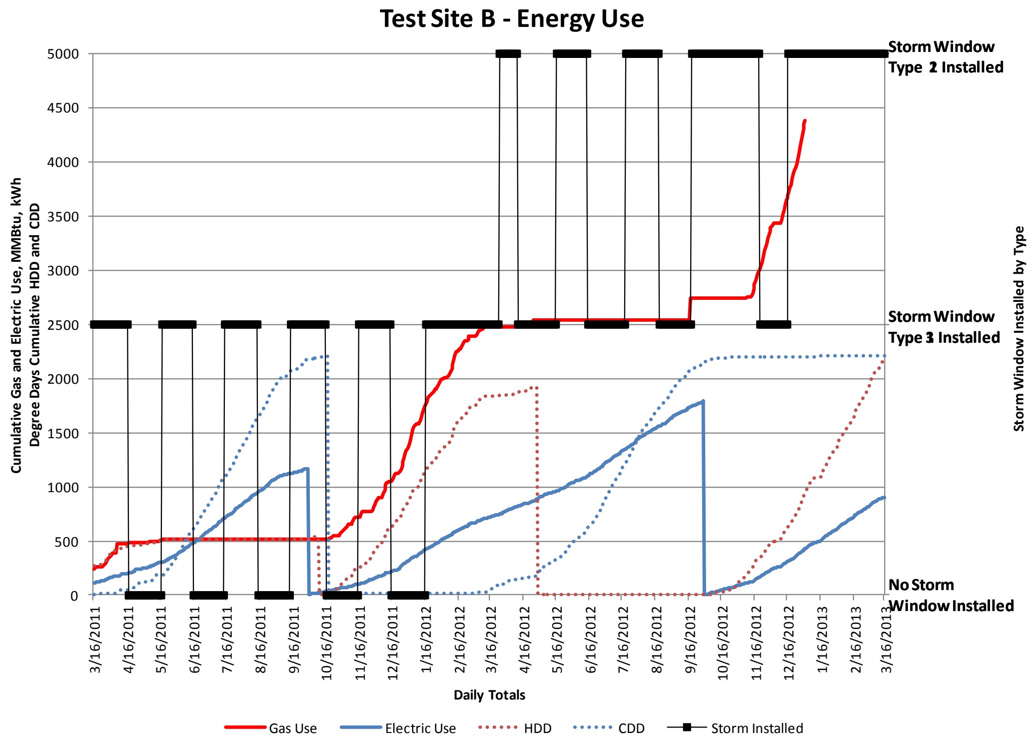

Figure 11. Cumulative Degree Day and Energy Use, Site B

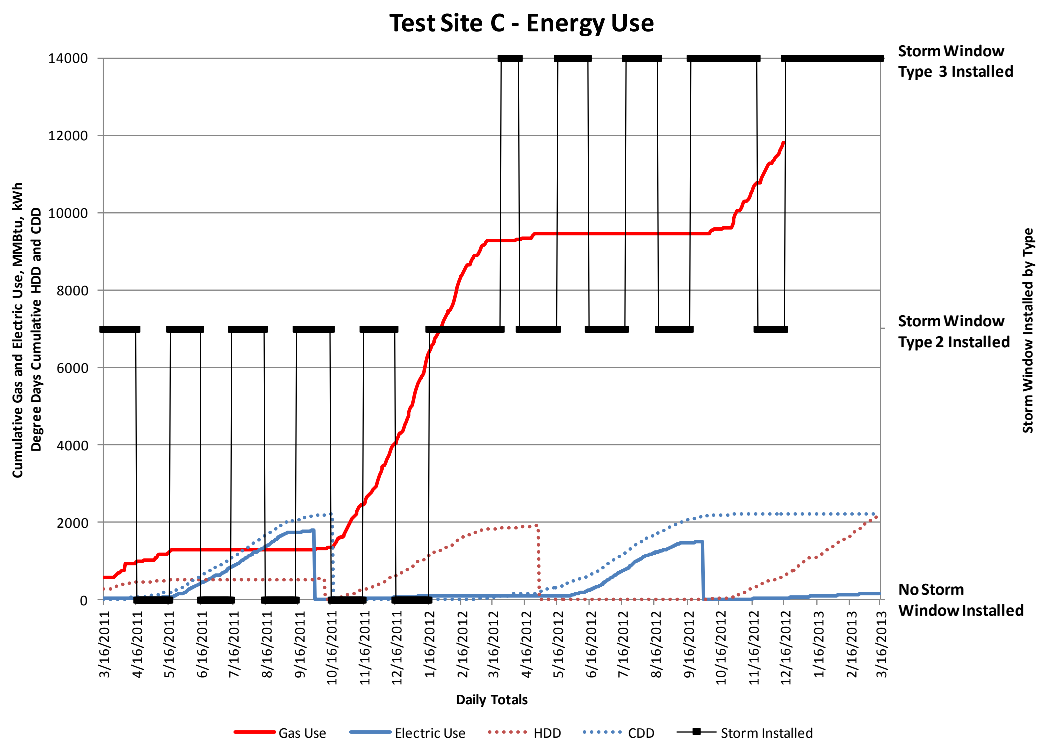

Figure 12. Cumulative Degree Day and Energy Use, Site C

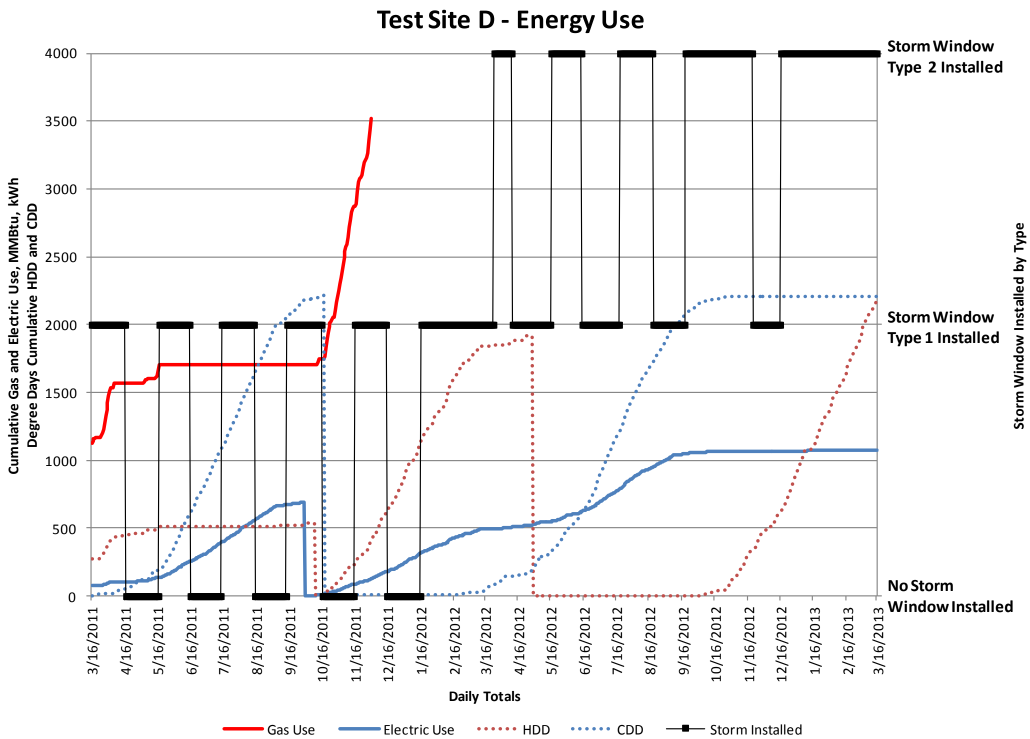

Figure 13. Cumulative Degree Day and Energy Use, Site D

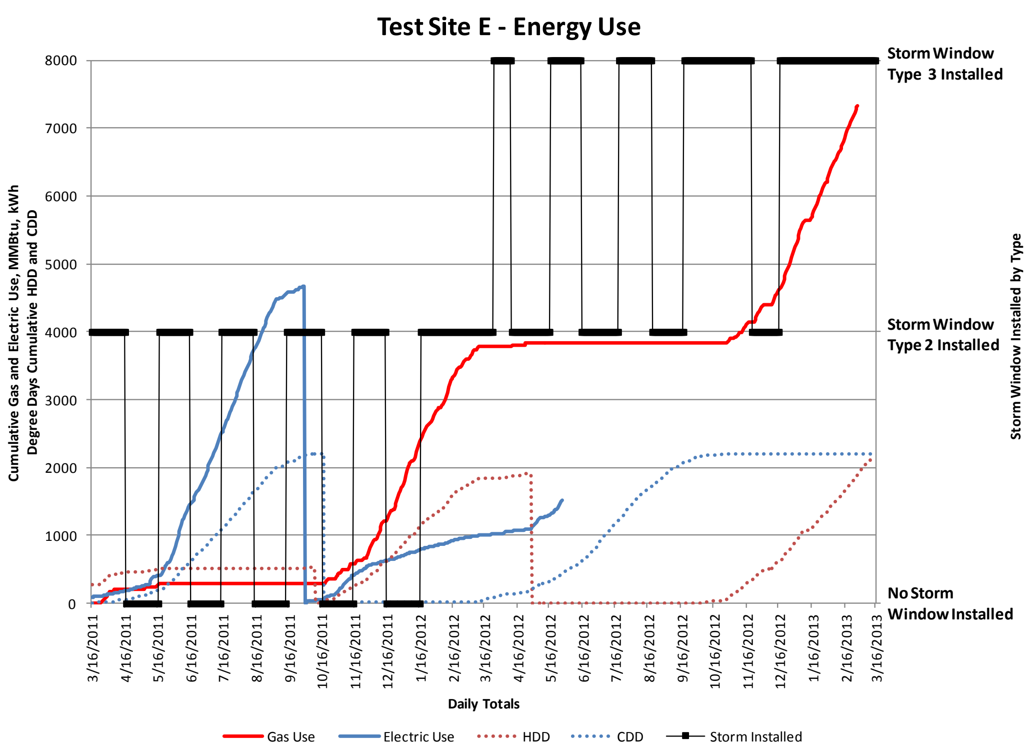

Figure 14. Cumulative Degree Day and Energy Use, Site E

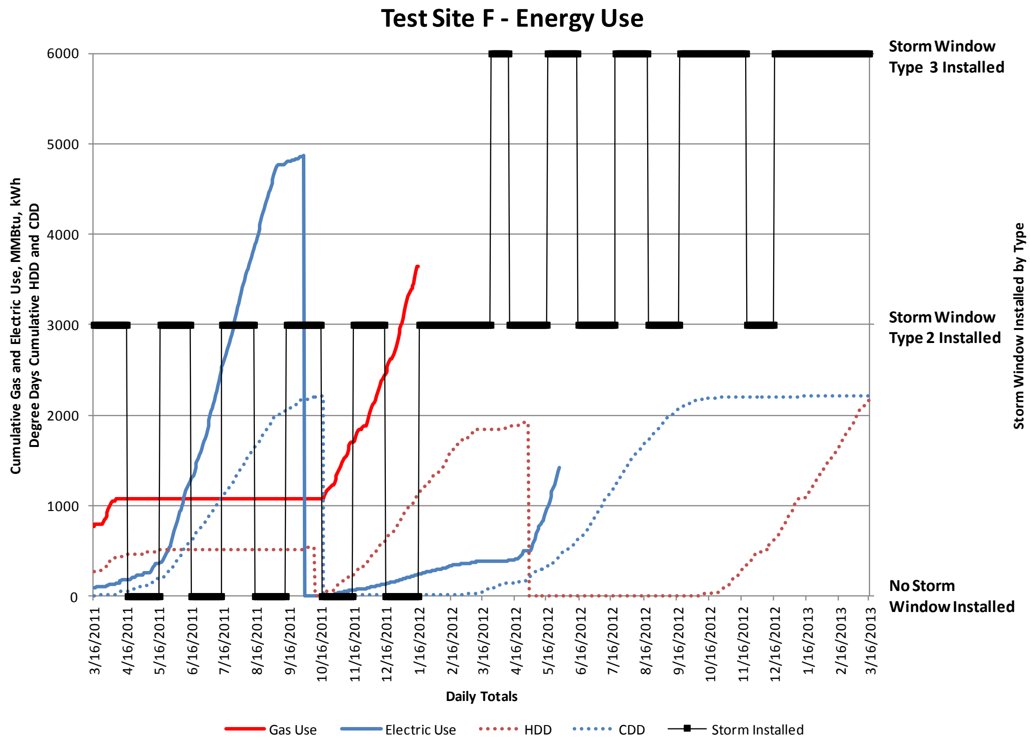

Figure 15. Cumulative Degree Day and Energy Use, Site F

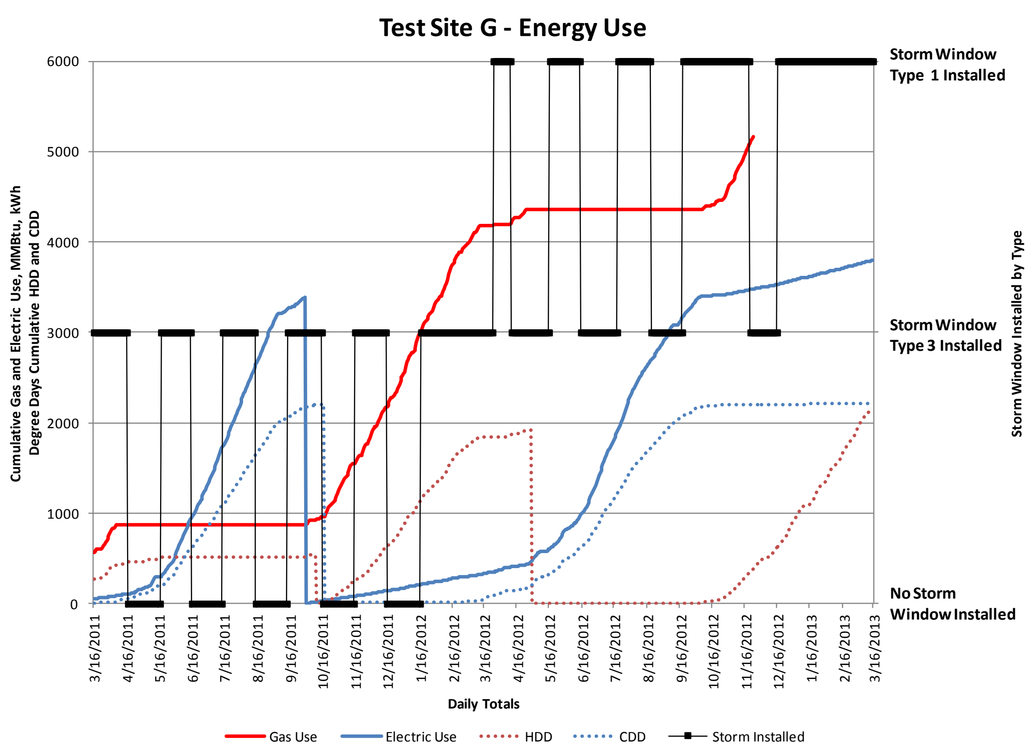

Figure 16. Cumulative Degree Day and Energy Use, Site G

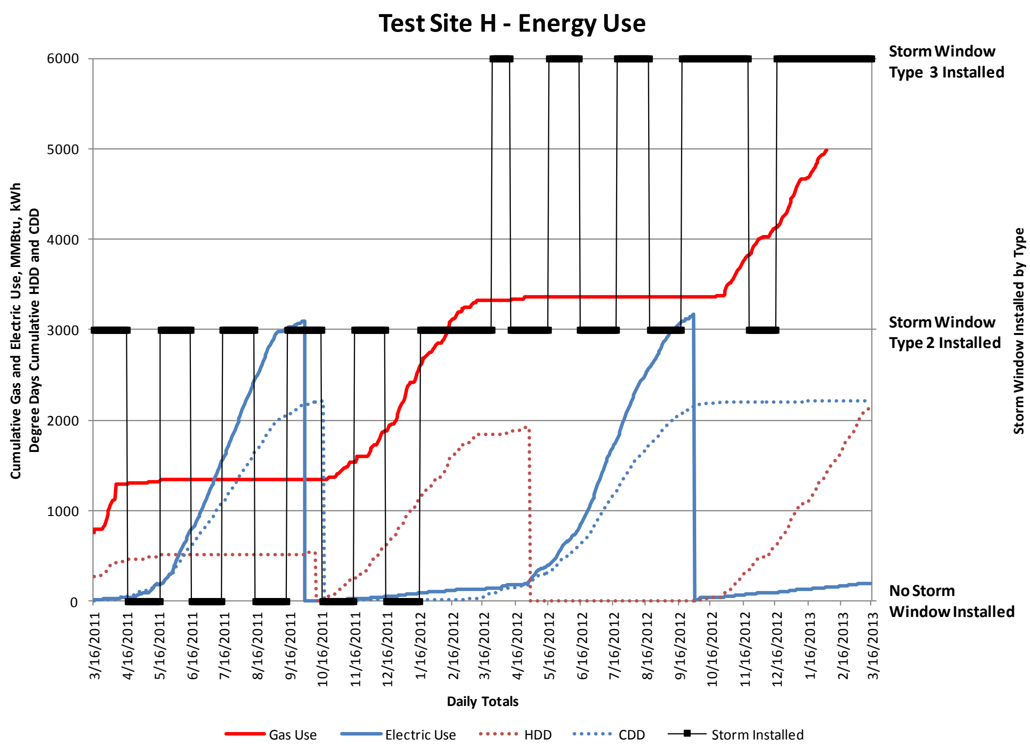

Figure 17. Cumulative Degree Day and Energy Use, Site H

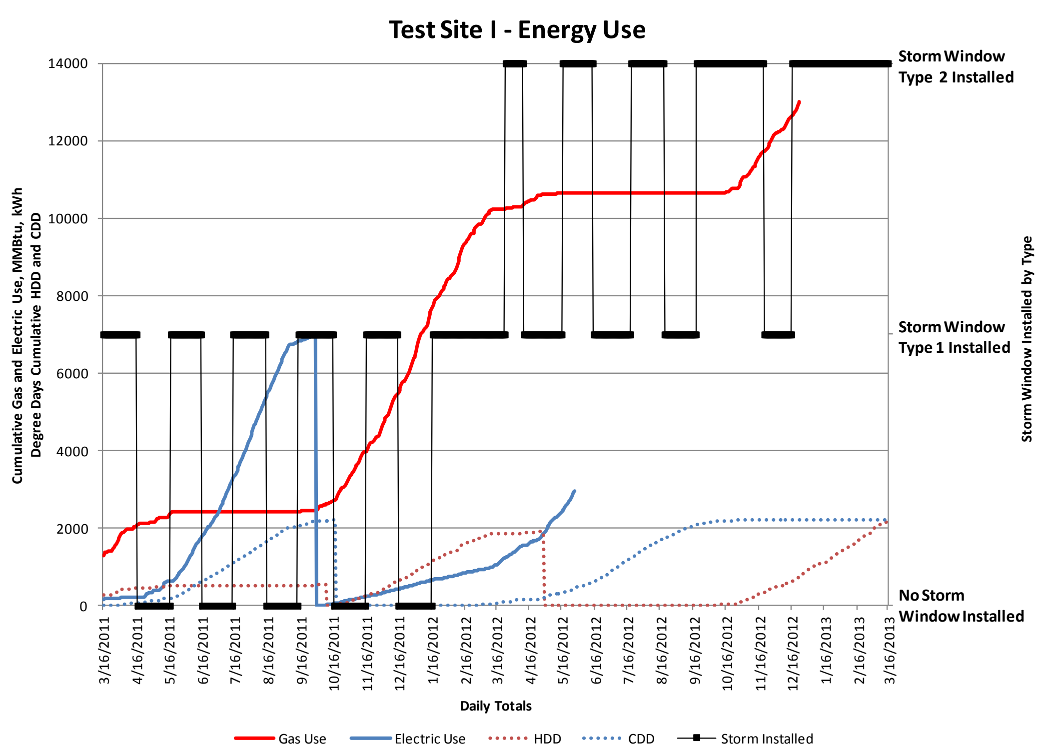

Figure 18. Cumulative Degree Day and Energy Use, Site I

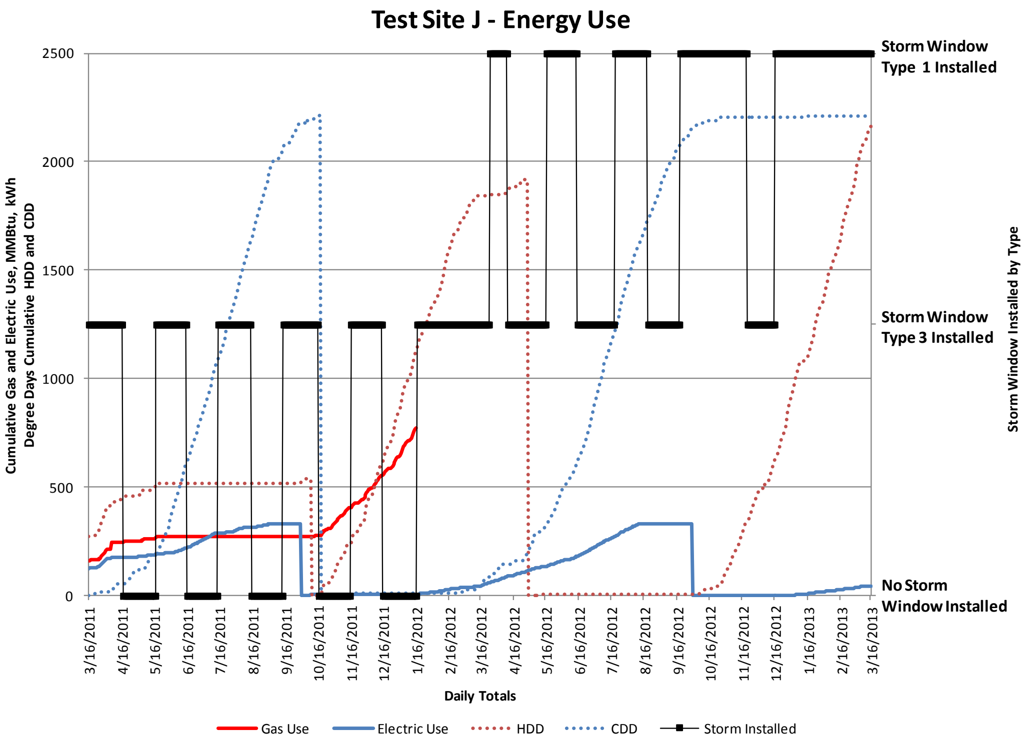

Figure 19. Cumulative Degree Day and Energy Use, Site J

Average Energy Use during Comparison Periods

Heating Periods

The heating comparison periods selected were from November 16, 2011 through January 16, 2012 and November 21, 2012 through January 16, 2013 (refer to Figure 1). These periods were selected based on a more consistent demand for heating across the analysis period. The analysis plots the daily average temperature difference between the indoor and outdoor temperatures against the daily total energy use for heating. The plot for each individual test site is shown in Appendix B.

The first year of testing compared three different storm window types against the original condition of single-pane windows without storm windows. Either three or four homes comprise the data set for each storm window type (refer to Table 2). Figure 20, Figure 21, and Figure 22 plot the house to ambient temperature difference for heating periods. The storm window performance is compared to the condition without storm windows installed (the original windows). For the first year data, Figure 20 shows the data for the standard clear storm window (Type 1), Figure 21 for the low solar gain low-E (Type 2), and Figure 22 for the high solar gain low-E (Type 3).

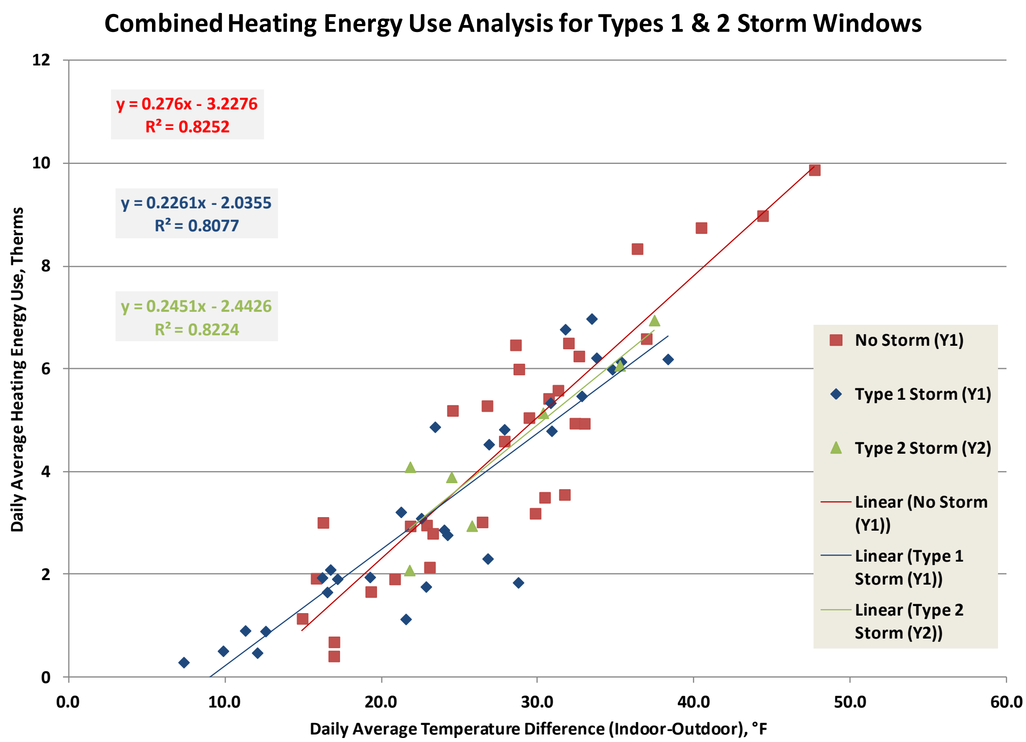

Figure 20. Type 1 and Type 2 Storm Window Compared to No Storm Installed – Heating

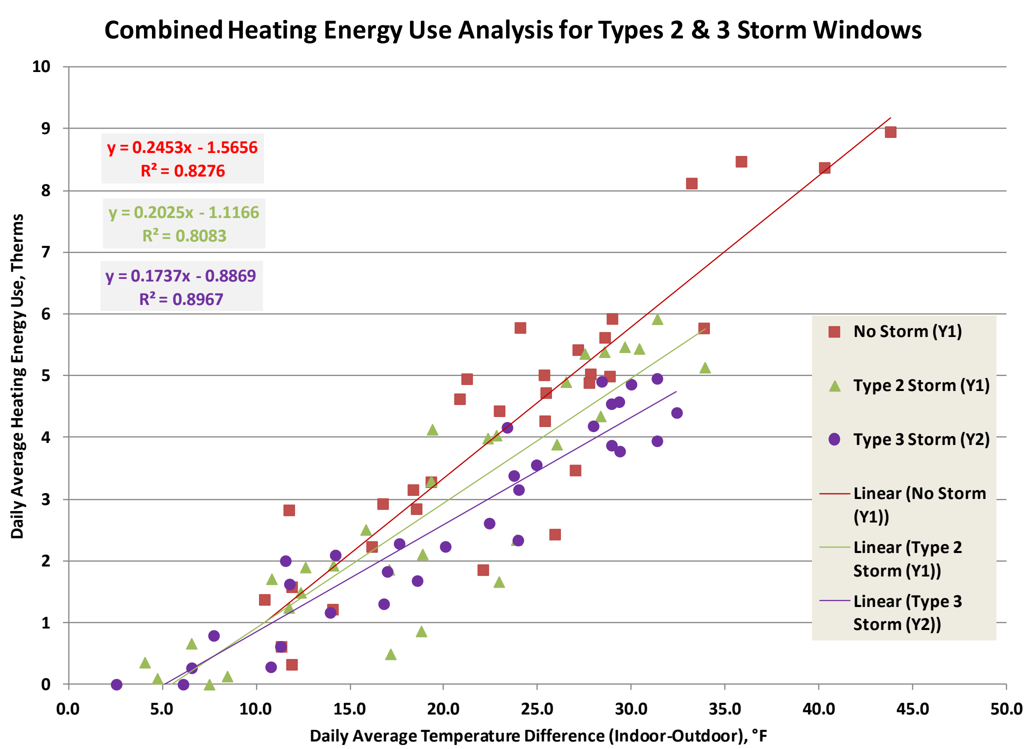

Figure 21. Type 2 and Type 3 Storm Window Compared to No Storm Installed – Heating

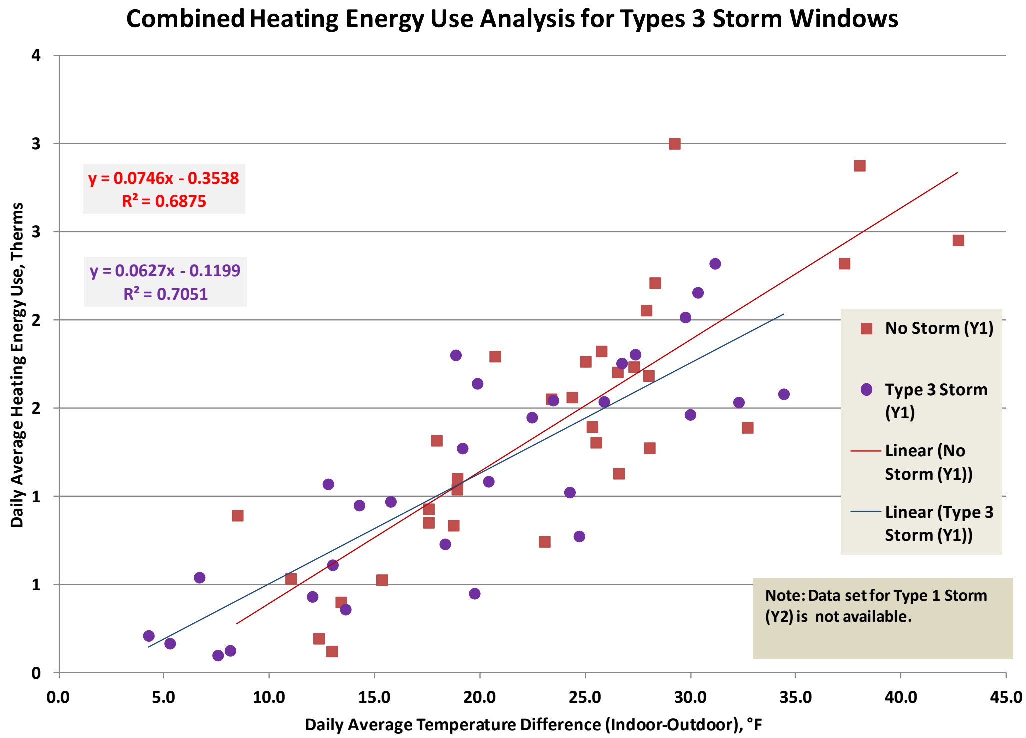

Figure 22. Type 3 Storm Window Compared to No Storm Installed – Heating

All of the data plots demonstrate a significant amount of scatter with R-squared values less than 0.9. Given the limited data set and the somewhat mild heating season (between approximately 500 and 600 heating degree-days per month), the confidence in predicting energy savings is somewhat limited. The total heating degree days over the 2011-12 winter were about 16 percent lower than the historical average. The resulting low inside-outside temperature difference makes it difficult to highly correlate temperature to energy usage, and the variability in factors such as wind speed and solar intensity become of the same magnitude as the conductive losses.

When averaging across all test sites (excluding test site D), the plot in Figure 23 shows the first heating period when the storm windows (3 types) were installed (blue diamond) and the first heating period when no storm windows were installed (red square). In addition, a limited amount of data is available for a second heating period when storm windows were installed (green triangle).

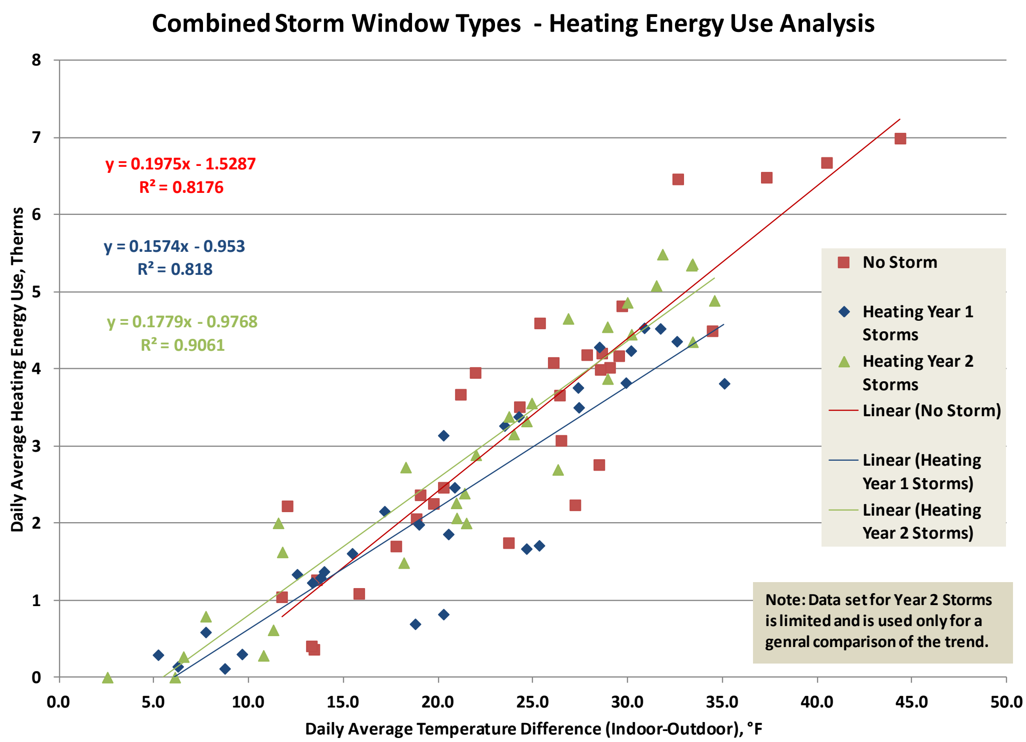

Figure 23. Heating Period Analysis Averaging All Test Sites

While the correlations shown in Figure 23 demonstrate a fairly large amount of scatter, the slope of the trend line for each window configuration is clear. The larger the temperature differences between the homes and ambient, the lower the demand for heating energy when the storm windows are installed. In a broad comparison of energy use, normalized to heating degree days across two heating periods, there is a 10 percent energy savings with storm windows installed in the first year testing and an 8 percent in the second year testing. These results are based on the comparison with the Year 1 no storms installed condition.

However, when looking at the clear storm windows compared with the low-E storm windows, there is a neutral energy savings for the clear storms and approximately 15 percent energy savings for the combined average of the Type 2 and Type 3 storm windows. The results reflect significant variability in the data and can only be used as general trends.

Cooling Periods

The cooling comparison periods selected were from June 16, 2011 through August 14, 2011 and June 15, 2012 through August 19, 2012 (refer to Figure 1). For the first cooling period, the window comparison is between the existing single-pane windows and the first type of storm window assigned to each home. Energy data for cooling plotted relative to the temperature difference between the indoor and outdoor conditions results in a much larger uncertainty based on the wide range of scatter. This is somewhat expected for the cooling season where the drivers for cooling are much more varied than just indoor-outdoor temperature difference, for example including humidity, direct solar gains, and the settings by the homeowner. Results for each individual test site are shown in Appendix C.

Similar to the heating season analysis, the same storm window set is used in the cooling season. When evaluating the same storm window types in a set of test homes (refer to Table 2), the results for the cooling seasons Year 1 and Year 2 are plotted to analyze the outdoor-indoor temperature difference against the energy use, on a daily basis. The storm window performance is compared to the condition without storm windows installed (the original windows). Figure 24 shows the data for the standard clear storm window (Type 1), Figure 25 for the low solar gain low-E (Type 2), and Figure 26 for the high solar gain low-E (Type 3).

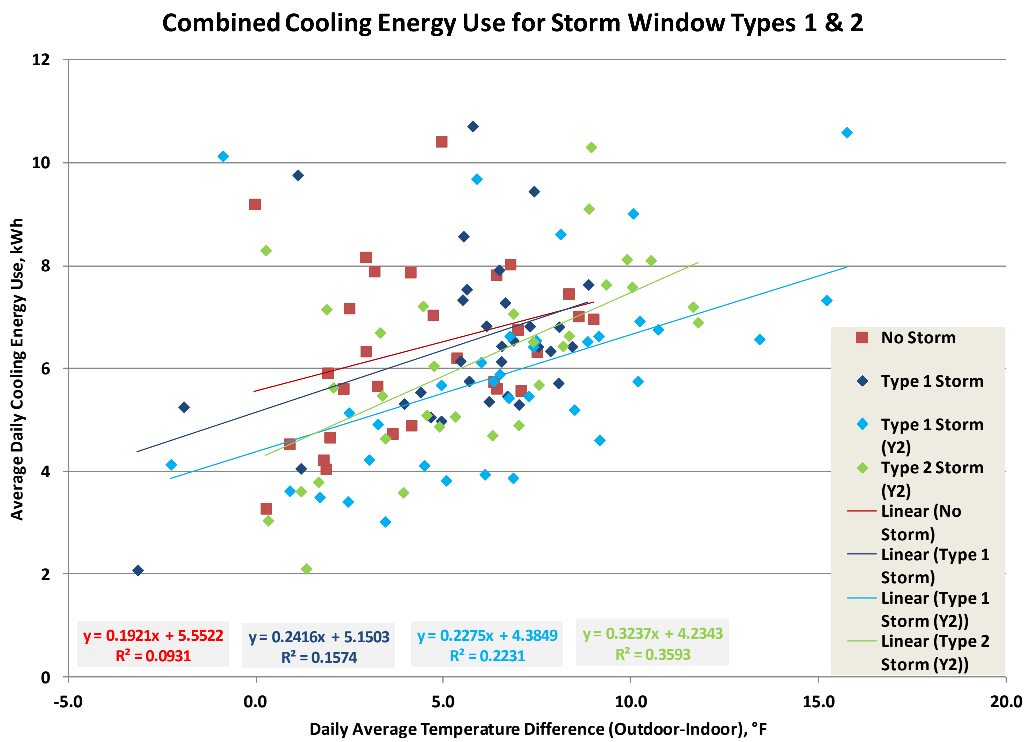

Figure 24. Type 1 Storm Window Compared to No Storm Installed and Type 2 Storm – Cooling

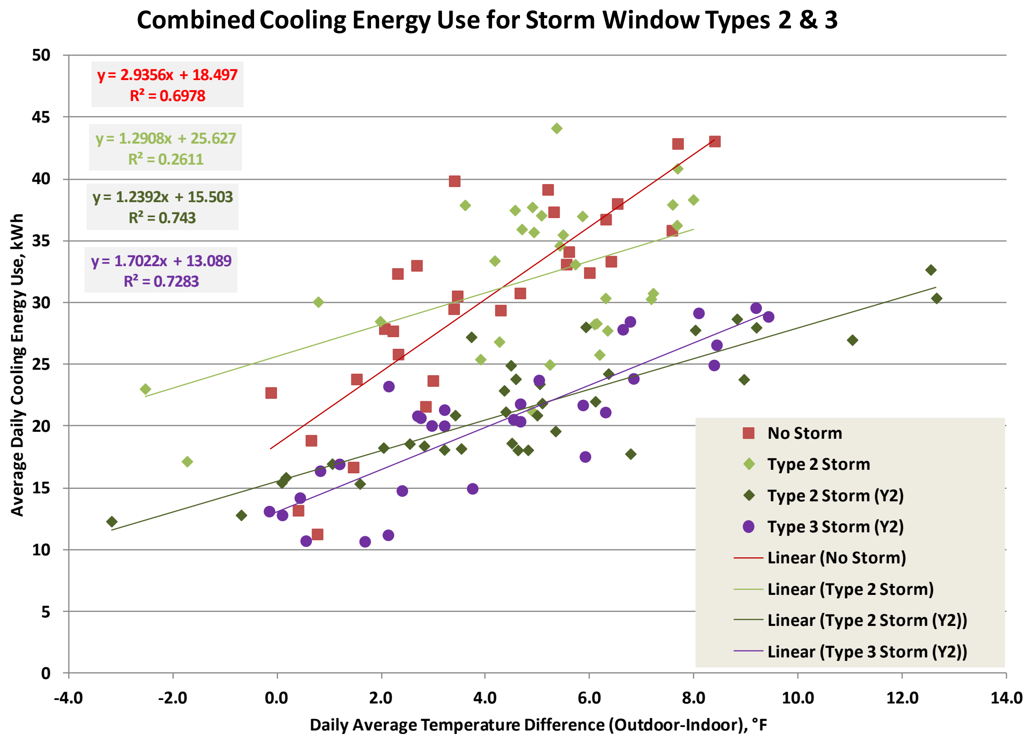

Figure 25. Type 2 Storm Window Compared to No Storm Installed and Type 3 Storm – Cooling

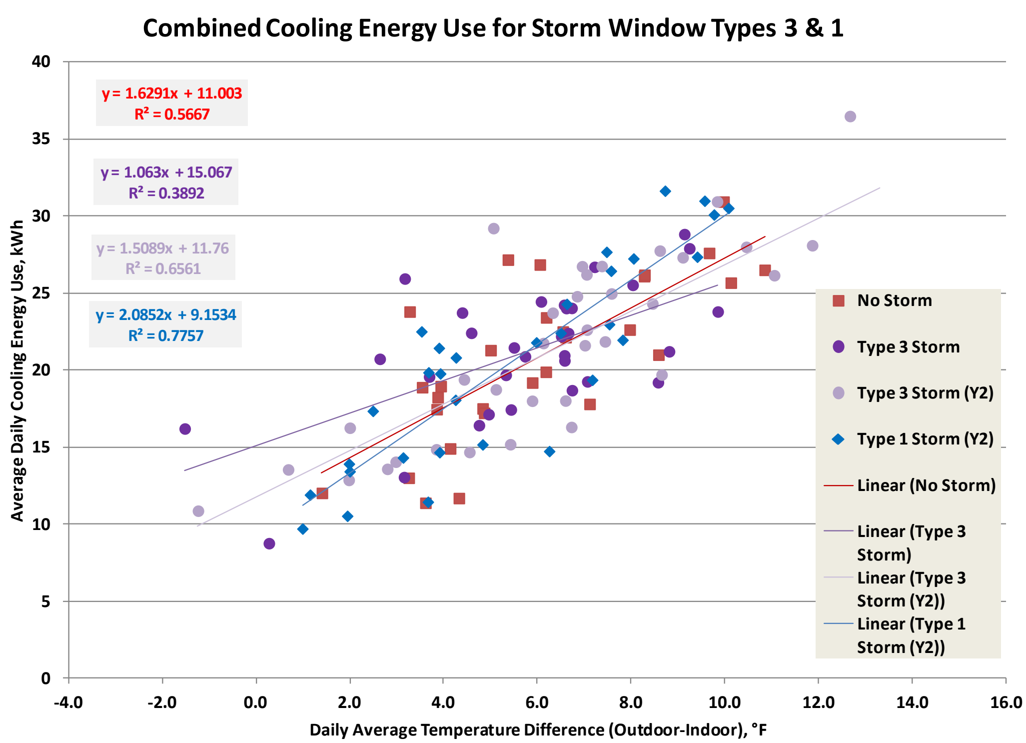

Figure 26. Type 3 Storm Window Compared to No Storm Installed and Type 1 Storm – Cooling

Results from the cooling analysis show considerable variability between the indoor and outdoor temperature difference and the cooling energy. This is due in part to the smaller temperature difference and variations in direct solar gains across the homes.

Taken together, the storm windows can be averaged to provide an overall picture of storm window performance relative to the original windows without storms installed; shown in Figure 27.

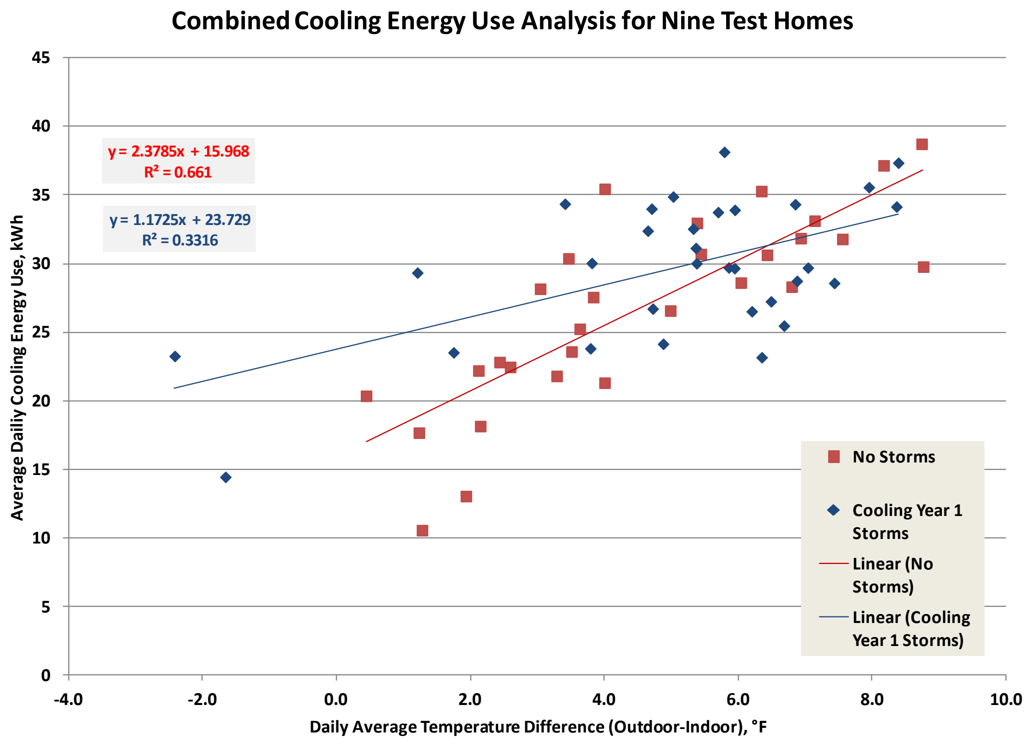

Figure 27. Average Cooling Energy Relative to the Temperature Difference for Nine Test Homes

The data shown in Figure 27 demonstrates a mixed picture of cooling energy use. The straight line fit indicates that when the temperature difference is more severe in cooling, the benefit of the storm window is seen. However, at milder temperature differences, it appears that the storm windows are of minimal or even negative benefit. This result can be understood as the storm windows would decrease the nighttime benefit of less insulated windows when the outdoor temperature falls below the indoor set point, thereby reducing nighttime cooling. These effects are very difficult to extract from a limited data set and when lacking more detailed indoor conditions such as temperatures in each room. It is also difficult to draw conclusions from Figure 26 in that it combines three glass types with very different solar heat gain coefficients, which is one of the important factors for determining cooling energy use.

Similarly, when averaging all of the storm window types together but using only those homes where data is available in two cooling periods, the results tend towards higher confidence levels. Figure 28 shows results for the average performance of six test homes and include samples of all three storm window types. The results are slightly more consistent. This data averages 1-Type 1 storm, 2-Type 2 storms, and 3-Type 3 storms in Year 1, and 3-Type 1 storms, 1-Type 2 storms, and 2-Type 3 storms in Year 2. When normalizing the data to the cooling degree days, there is a small energy savings with the Year 1 storms of about 2.5 percent but the same storm set in Year 2 shows neutral performance. The Year 2 storm window set shows about a 2 percent savings over the no storm window condition.

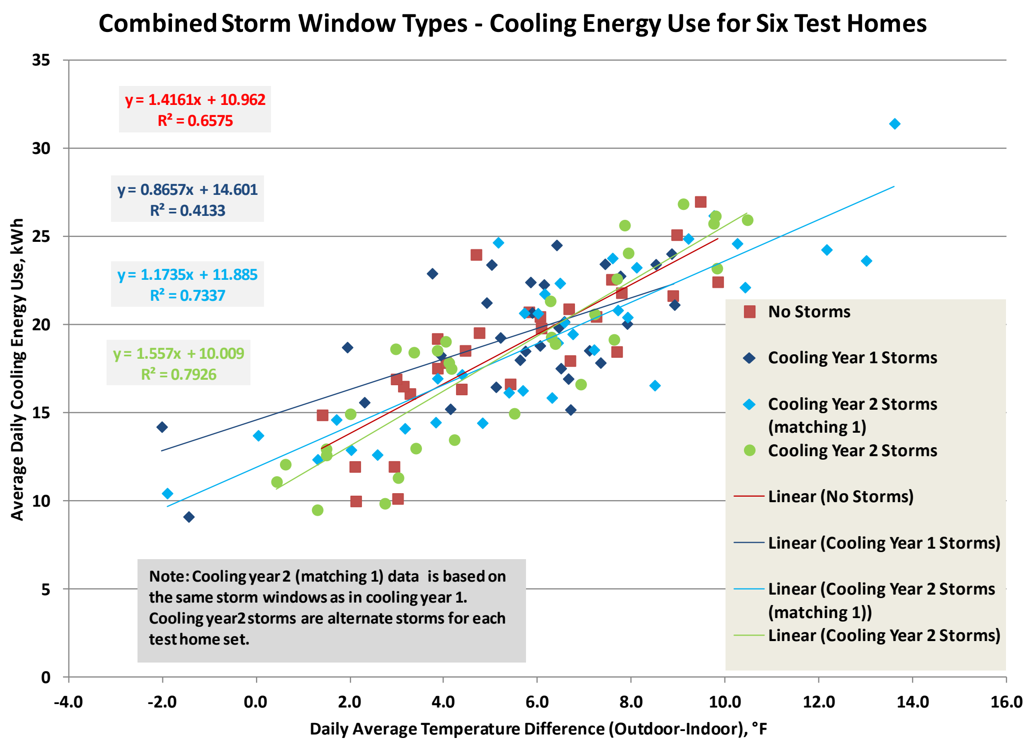

Figure 28. Average Cooling Energy Relative to the Temperature Difference for Three Different Windows and Six Test Homes

Summary

Based on the heating analysis periods, the summary comparison of the various low-E storm windows is shown in Table 4. Normalizing the energy use to the heating degree days for the period, the results show the energy use for each storm window type and overall for all storm windows together.

Table 4. Summary Heating Energy for Storm Window Types

		Heating Degree Day Normalized Heating Energy, (Therms/HDD)			
		No Storms	Type 1 Storms	Type 2 Storms	Type 3 Storms
Test House Set 1	(Year 1)	0.274	0.267		
	(Year 2)		0.282	0.275	
Average Savings Over Original Window			0.1%	-0.2%	
Test House Set 2	(Year 1)	0.259		0.222	
	(Year 2)			0.140	0.170
Average Savings Over Original Window				27.8%	34.3%
Test House Set 3	(Year 1)	0.085			0.090
	(Year 2)				0.074
Average Savings Over Original Window					2.2%
All Test Houses		0.204		0.184	
Average Savings Over Original Window				9.5%	

Summarizing the heating energy use measured for the analysis periods for each storm window type in a set of test homes and comparing to the original windows without storm windows, the results trend as follows:

- The Type 1 storm window (clear glass) results indicate a small heating energy benefit with the storm window installed, approximately 2.5 percent on a normalized Heating Degree Day basis over the original single-pane window in Year 1, and 3 percent less in Year 2 resulting in an overall neutral performance (0.1 percent).
- The Type 2 storm window (low solar gain low-E) shows a large reduction in heating energy use in the test homes, over 25 percent in test house set 2 but a neutral result for test home set 1.
- Type 3 storm window (high solar gain low-E) testing demonstrates a mixed result showing a modest heating energy savings of about 2 percent in test home set 3 but a much larger savings in test home set 2 of approximately 34 percent.

Furthermore, when aggregating all or a subset of the different storm window types, the results show:

- When data for all three storm window types are combined over all homes over both heating analysis periods, the use of storm windows in general provided a 9.5 percent heating energy savings compared to the original single-pane windows.
- When data for both low-E storm window types are combined, there is approximately 15 percent heating energy savings from the use of low-E storm windows, whereas clear storm windows are neutral in performance.

While there is significant variability in the results that makes it difficult to draw strong conclusions, it appears that there is the potential for significantly more energy savings when low-E glass is used versus no storm window or clear glass storm windows. However, due to variability in the data, it is difficult to conclusively say whether one type of low-E performed better than the other.

Summarizing the cooling energy use measured for the analysis periods for each storm window type in a set of test homes and comparing to the original windows without storm windows, the cooling energy results trend as shown in Table 5.

Table 5. Summary Cooling Energy for Storm Window Types

	Cooling Degree Day Normalized Cooling Energy, (kWh/CDD)			
	No Storms	Type 1 Storms	Type 2 Storms	Type 3 Storms
Test House Set 1 (Year 1)	0.385	0.366		
(Year 2)		0.344	0.370	
Average Savings Over Original Window		8.0%	3.9%	
Test House Set 2 (Year 1)	1.800		1.803	
(Year 2)			1.256	1.229
Average Savings Over Original Window			15.6%	31.7%
Test House Set 3 (Year 1)	1.253			1.195
(Year 2)		1.241		1.269
Average Savings Over Original Window		0.9%		1.5%
All Test Houses	1.616		1.398	
Average Savings Over Original Window			13.5%	

However, when normalizing to the cooling degree days for the periods under investigation, the results trend well toward energy savings with the low-E storm windows:

- The Type 1 storm window (clear glass) shows a cooling energy reduction of 8 percent for one set of homes and 1 percent for another set of homes, compared to the original single-pane windows.
- Type 2 storm windows (low solar gain low-E) demonstrated a wide range of performance with cooling energy savings of 4 percent for one set of homes and nearly 16 percent for another set of homes.
- Similarly Type 3 storm windows (high solar gain low-E) result in anywhere from a 1.5 percent cooling energy savings in one set of homes to over 30 percent energy savings in another set of homes.

These highly variable results provide little confidence in predicting energy savings; however, the general trend is that energy savings can be expected with the use of the storm windows in this climate, and potentially larger savings using low-E glass. While both types of low-E show the potential for larger energy savings, it would not be expected for the higher solar gain product to have more cooling energy savings than the lower solar gain product, and indeed, there is significant overlap in the results (2-32 percent cooling energy savings vs. 4-16 percent, respectively). Therefore, due to variability in the data, it is difficult to conclusively say whether one type of low-E performed better than the other.

Appendix A:
Summary Total Energy Use for Test Sites

The total energy use for heating and cooling and including the heating and cooling degree days for the respective periods is shown in Table A1. The grouping by test site (refer to Table 2 above) is shown in Table A2. Note that these totals are for the available data in each period for each test site.

Table A1. Total Energy for Heating and Cooling

Test Site	Year 1				Year 2			
	No Storm	Storm X	No Storm	Storm X	Storm X	Storm Y	Storm X	Storm Y
	Gas, therms		Electric, kWh		Gas, therms		Electric, kWh	
	814 HDD	602 HDD	1052 CDD	1175 CDD	601 HDD	810 HDD	1199 CDD	992 CDD
A	64	42	1,904	1,927	16	40	1,862	1,793
B	93	58	776	698	118	96	870	813
C	371	212	904	966	215	133	810	662
D	122	121	498	432	-	-	382	264
E	152	87	2,627	2,745	100	133	336	259
F	182	108	2,521	2,494	-	-	615	479
G	141	104	1,741	1,801	70	72	1,742	1,589
H	94	92	1,550	1,612	57	100	1,736	1,441
I	377	262	3,789	3,738	212	156	1,264	844
J	37	25	100	117	-	-	172	138
All	163	111	1,641	1,653	113	104	979	828
		32%		-1%		8%		15%

Table A1. Average Energy Use in Test Site Groupings

	Gas, therms		Electric, kWh		Gas, therms		Electric, kWh	
Sites A,G, J	No Storm	Storm Type 3	No Storm	Storm Type 3	Storm Type 3	Storm Type 1	Storm Type 3	Storm Type 1
	81	57	1,248	1,282	29	37	1,259	1,173
		29%		-3%		-30%		7%
Sites B,D,I	No Storm	Storm Type 1	No Storm	Storm Type 1	Storm Type 1	Storm Type 2	Storm Type 1	Storm Type 2
	197	147	1,688	1,623	110	84	839	640
		25%		4%		24%		24%
Sites C,E,F,H	No Storm	Storm Type 2	No Storm	Storm Type 2	Storm Type 2	Storm Type 3	Storm Type 2	Storm Type 3
	200	125	1,901	1,954	93	91	874	710
		38%		-3%		2%		19%

The roll-up results in Tables A1 and A2 are used as a reference point only due to the high variability of the measurement results. Note that the reported savings has not been adjusted for heating or cooling degree days.

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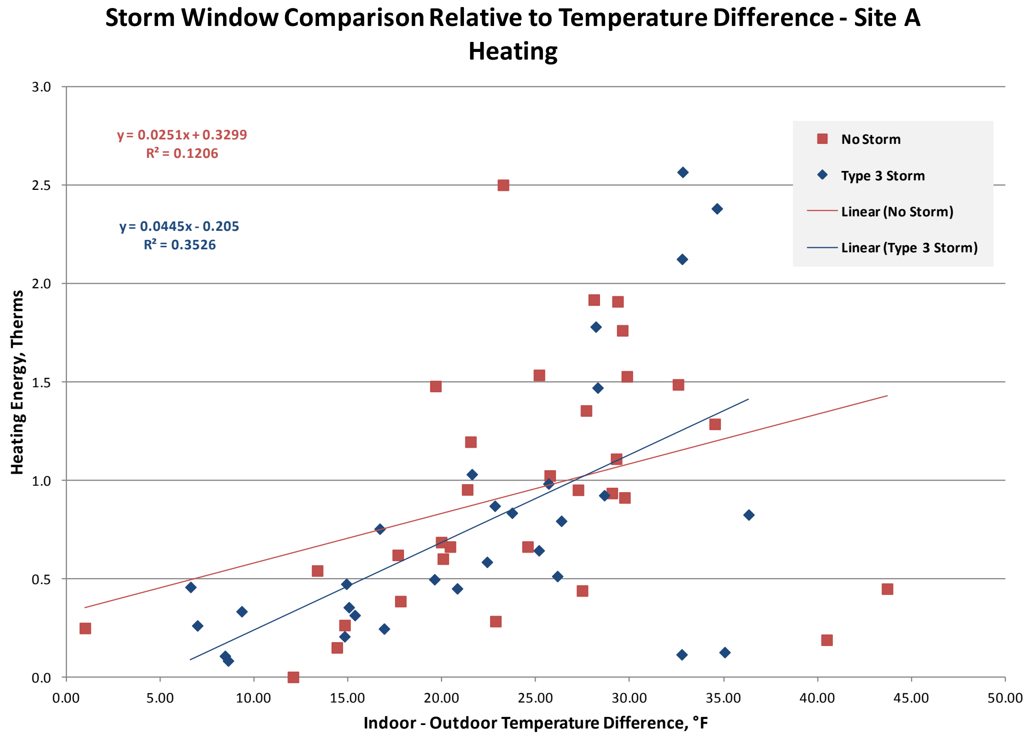
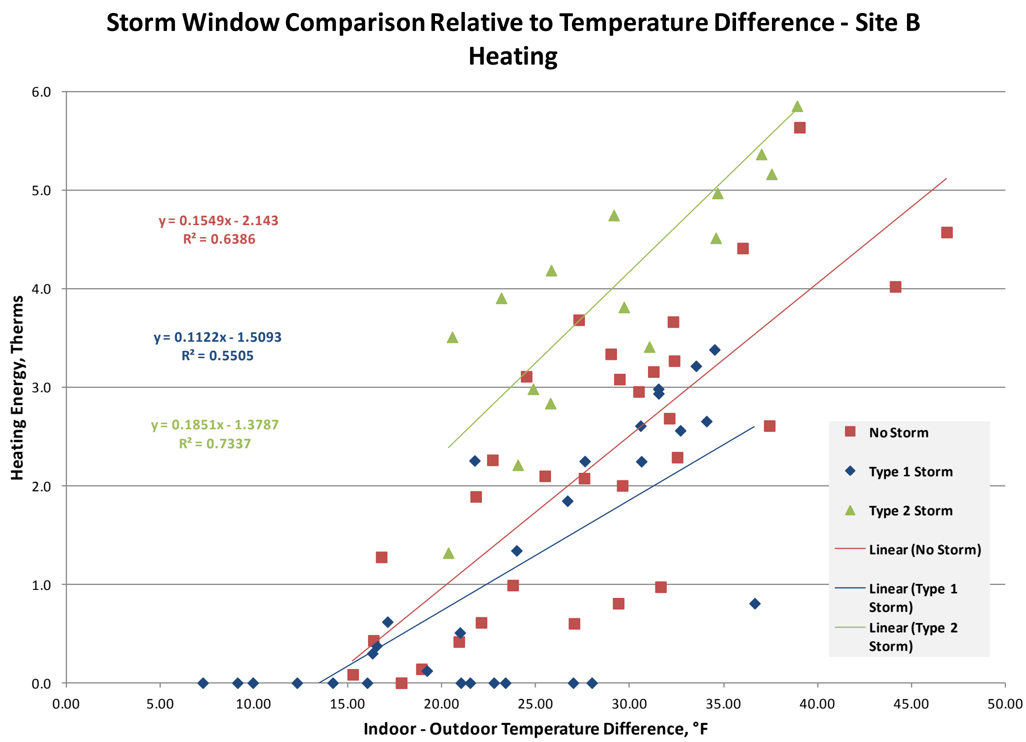
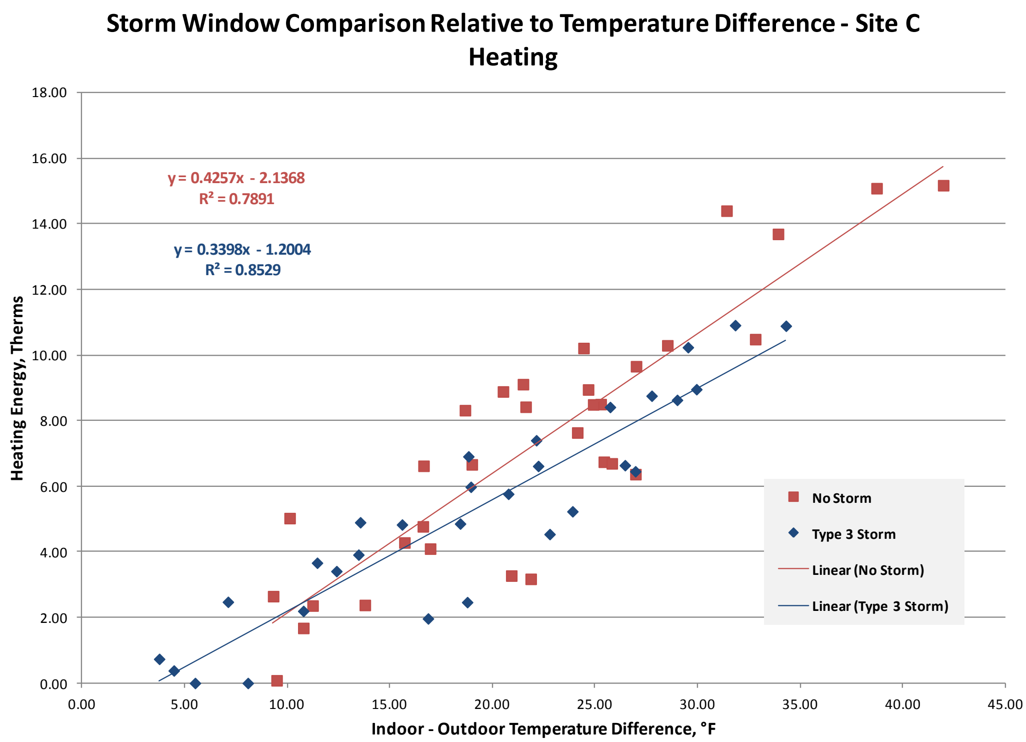
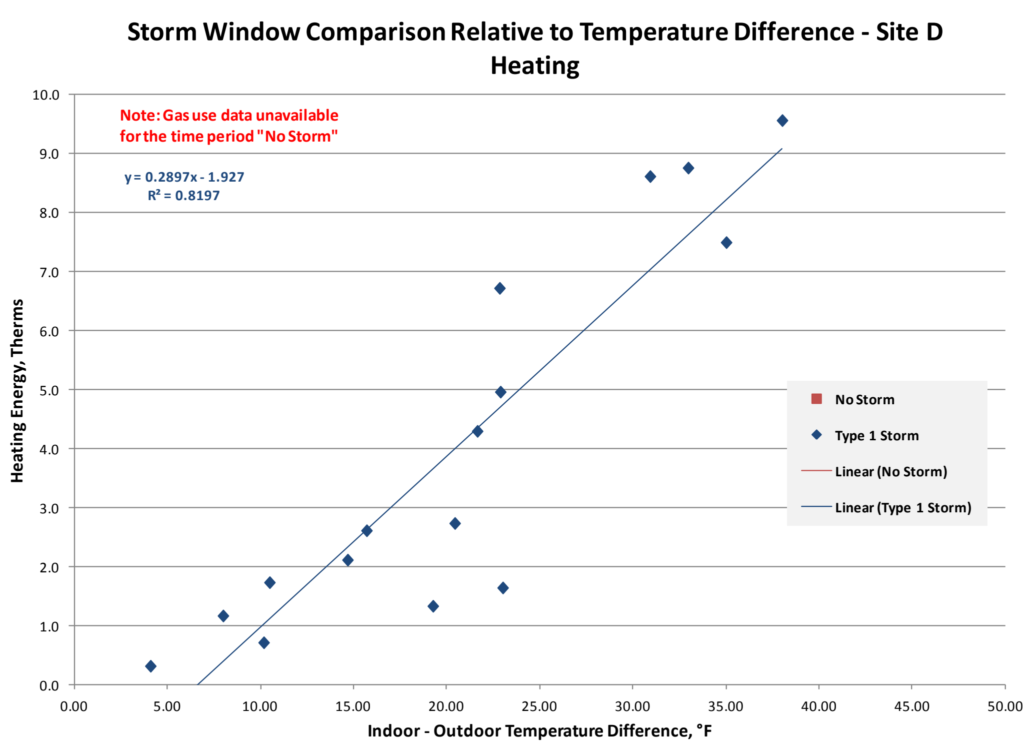
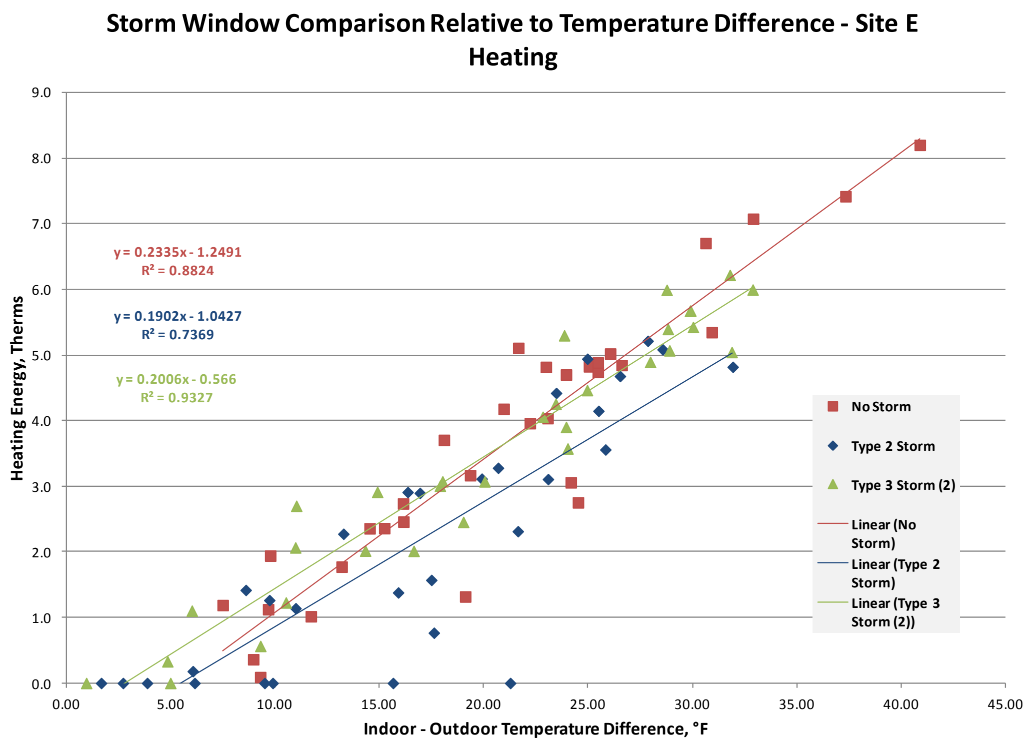
Appendix B:
Heating Energy for Each Test Home



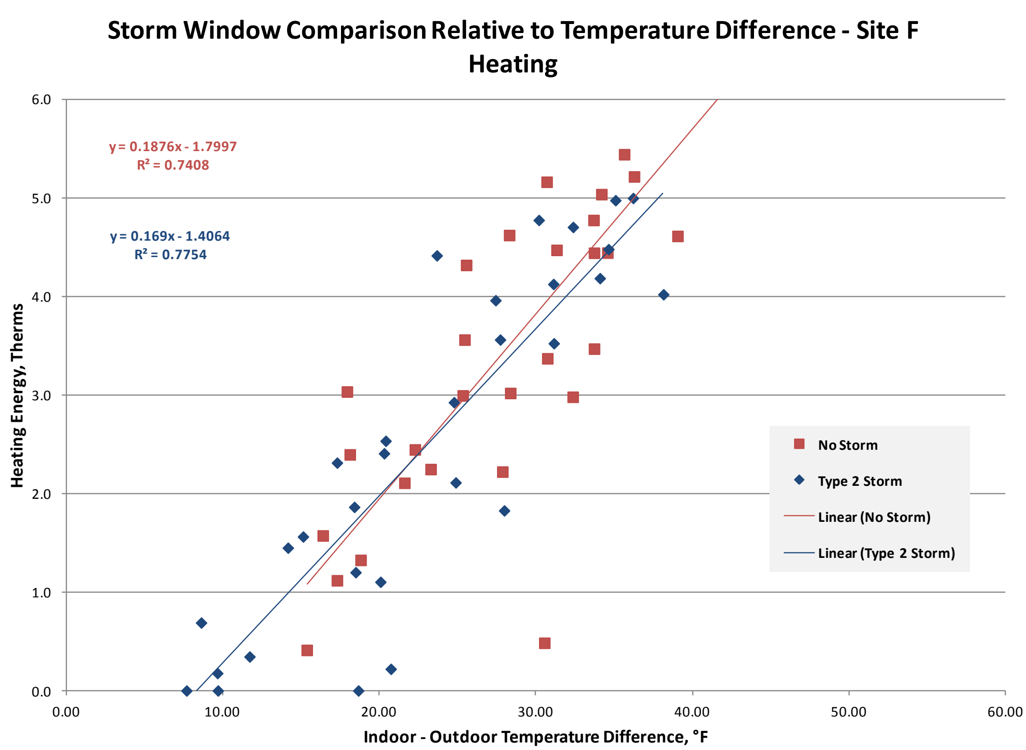



Storm Window Comparison Relative to Temperature Difference - Site C
Heating
y = 0.4257x - 2.1368
R² = 0.7891
y = 0.3398x - 1.2004
R² = 0.8529
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 3 Storm
Linear (No Storm)
Linear (Type 3 Storm)

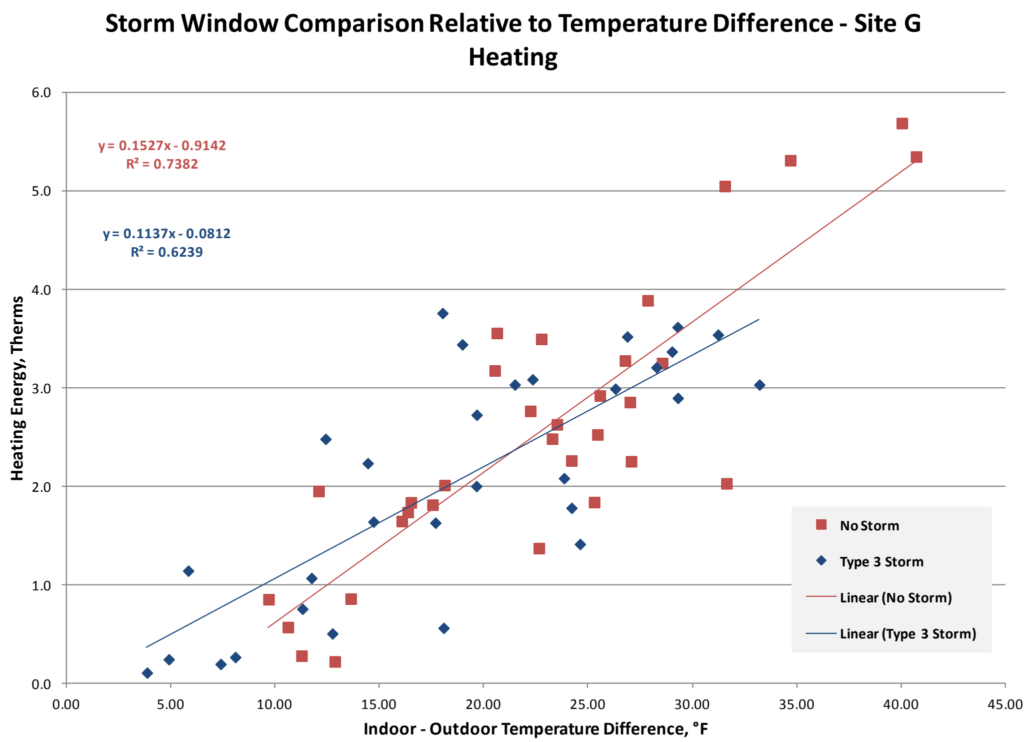

Storm Window Comparison Relative to Temperature Difference - Site D
Heating
Note: Gas use data unavailable for the time period "No Storm"
y = 0.2897x - 1.927
R² = 0.8197
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 1 Storm
Linear (No Storm)
Linear (Type 1 Storm)

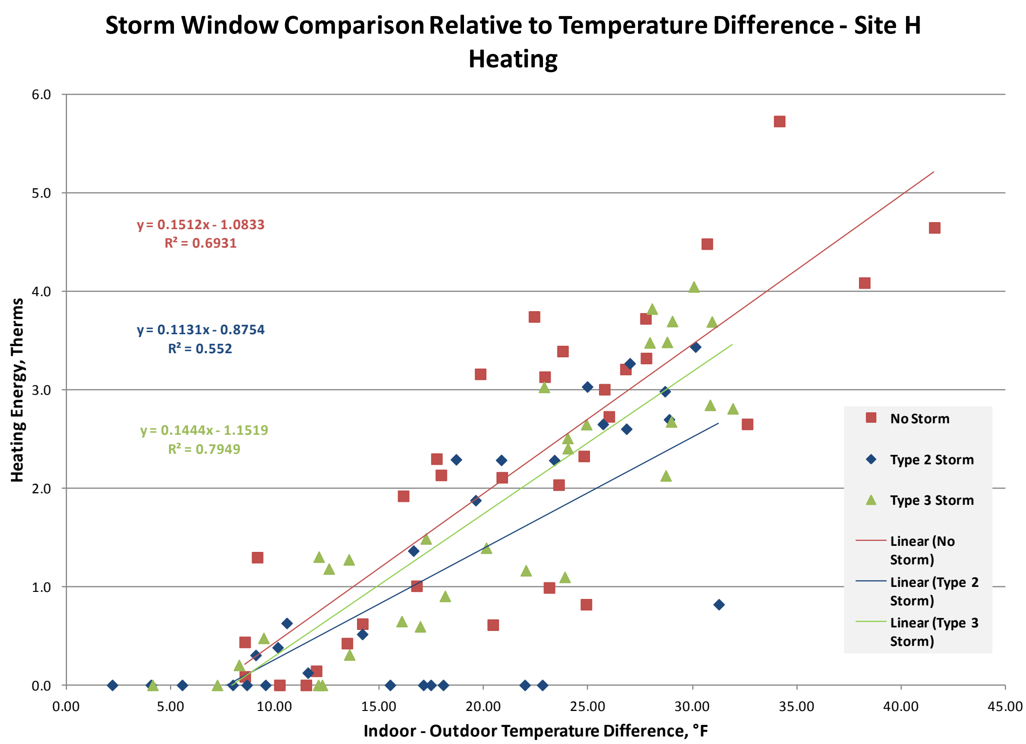


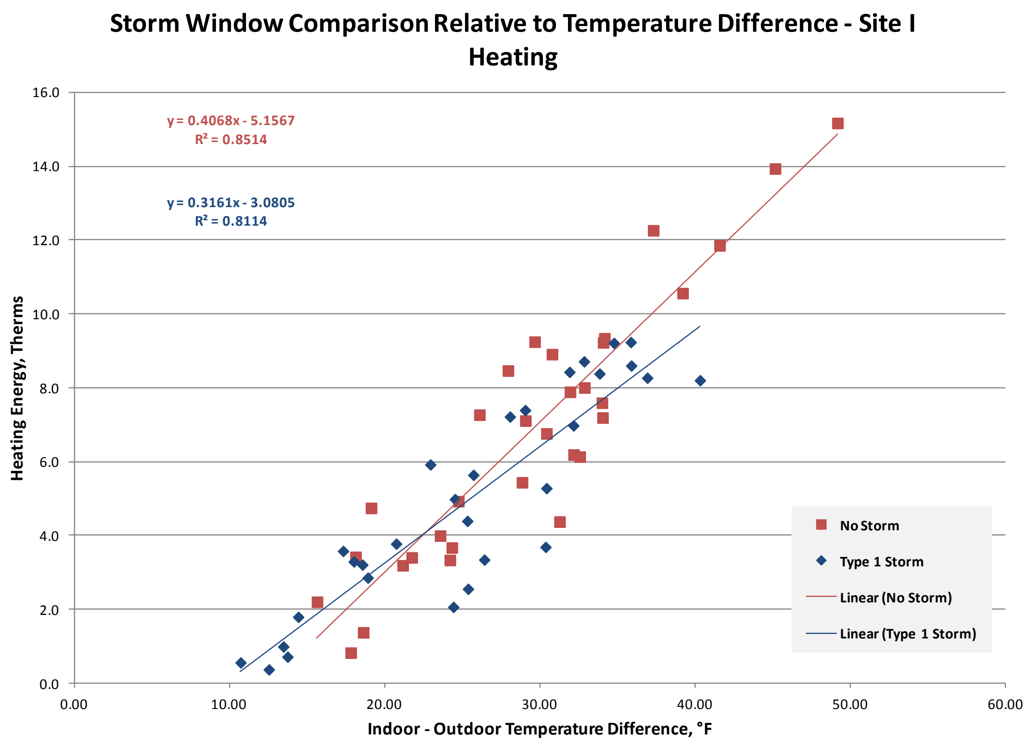
Storm Window Comparison Relative to Temperature Difference - Site E
Heating
y = 0.2335x - 1.2491
R² = 0.8824
y = 0.1902x - 1.0427
R² = 0.7369
y = 0.2006x - 0.566
R² = 0.9327
No Storm
Type 2 Storm
Type 3 Storm (2)
Linear (No Storm)
Linear (Type 2 Storm)
Linear (Type 3 Storm (2))
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F

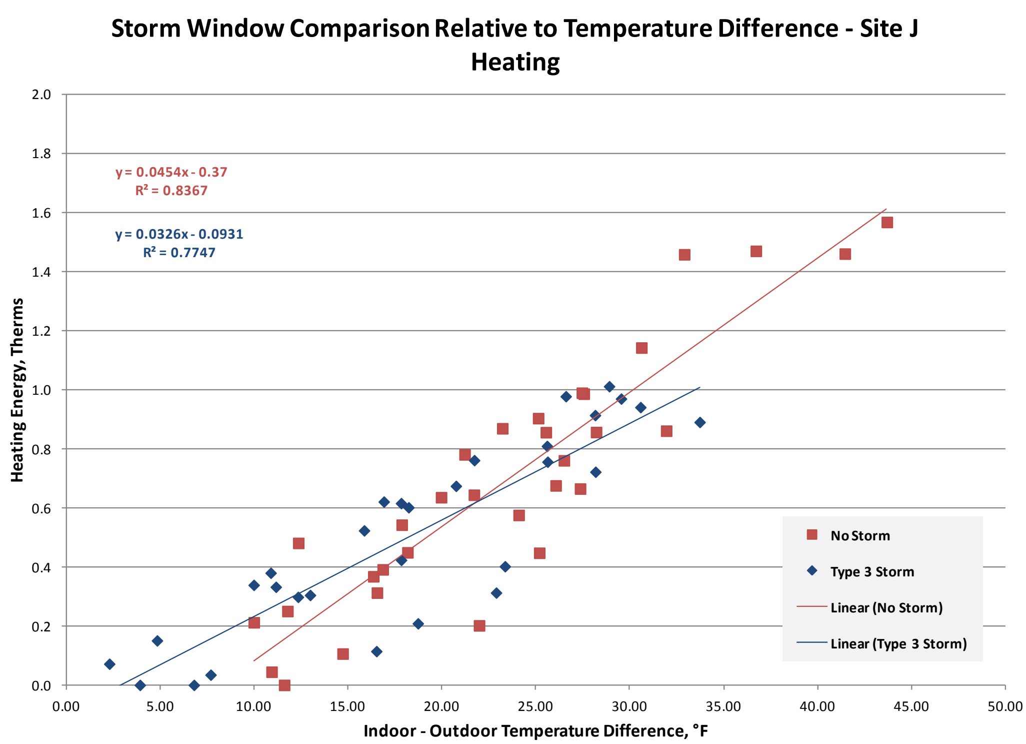


Storm Window Comparison Relative to Temperature Difference - Site F
Heating
y = 0.1876x - 1.7997
R² = 0.7408
y = 0.169x - 1.4064
R² = 0.7754
No Storm
Type 2 Storm
Linear (No Storm)
Linear (Type 2 Storm)
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F


Storm Window Comparison Relative to Temperature Difference - Site G
Heating
y = 0.1527x - 0.9142
R² = 0.7382
y = 0.1137x - 0.0812
R² = 0.6239
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 3 Storm
Linear (No Storm)
Linear (Type 3 Storm)


Storm Window Comparison Relative to Temperature Difference - Site H
Heating
y = 0.1512x - 1.0833
R² = 0.6931
y = 0.1131x - 0.8754
R² = 0.552
y = 0.1444x - 1.1519
R² = 0.7949
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 2 Storm
Type 3 Storm
Linear (No Storm)
Linear (Type 2 Storm)
Linear (Type 3 Storm)


Storm Window Comparison Relative to Temperature Difference - Site I
Heating
y = 0.4068x - 5.1567
R² = 0.8514
y = 0.3161x - 3.0805
R² = 0.8114
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 1 Storm
Linear (No Storm)
Linear (Type 1 Storm)


Storm Window Comparison Relative to Temperature Difference - Site J
Heating
y = 0.0454x - 0.37
R² = 0.8367
y = 0.0326x - 0.0931
R² = 0.7747
Heating Energy, Therms
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 3 Storm
Linear (No Storm)
Linear (Type 3 Storm)

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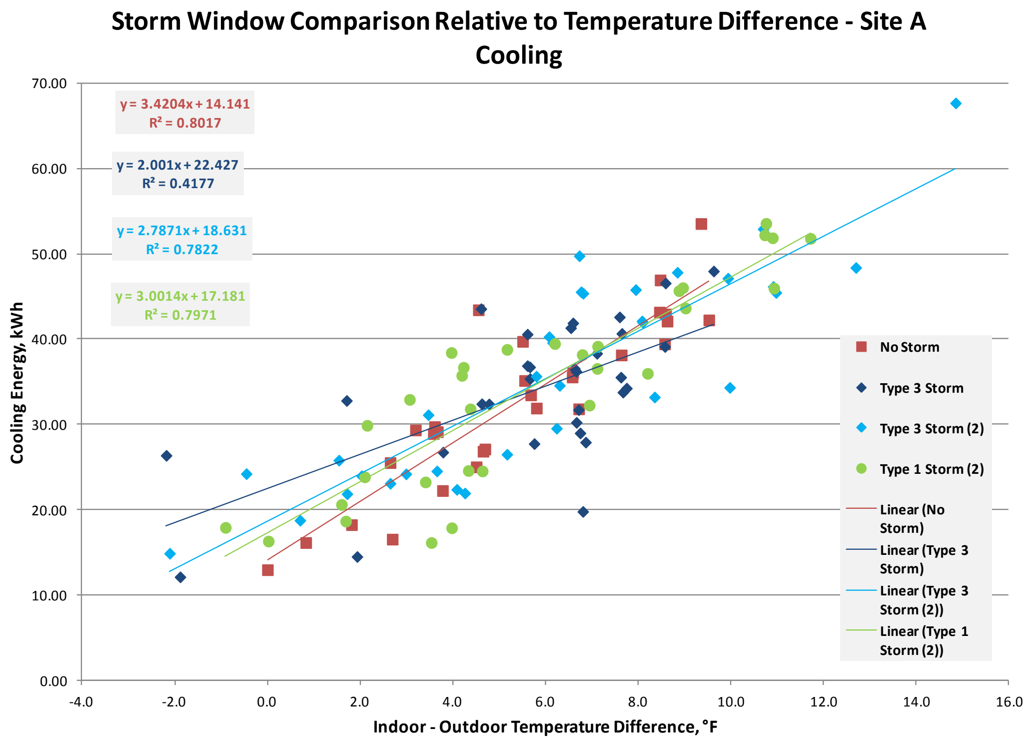
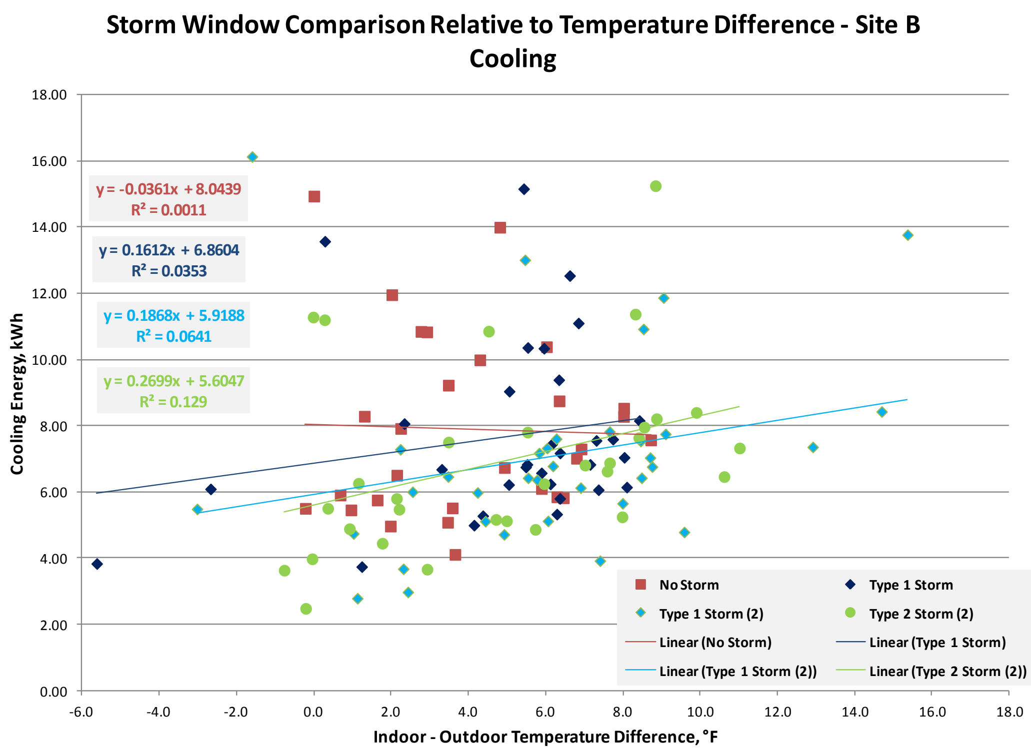
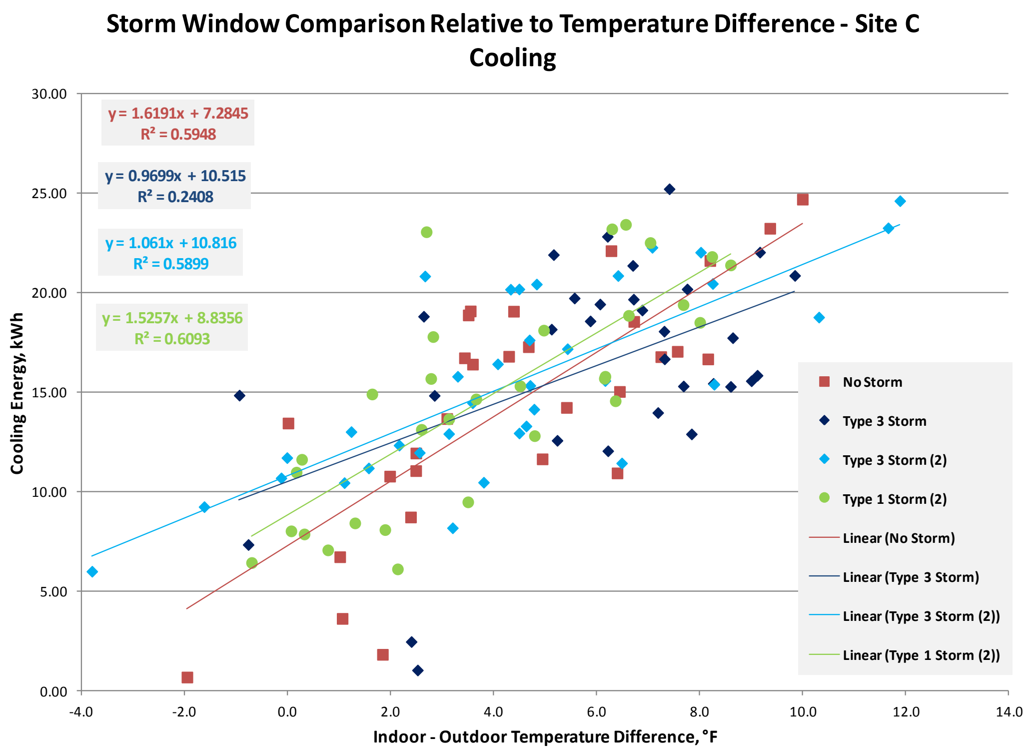
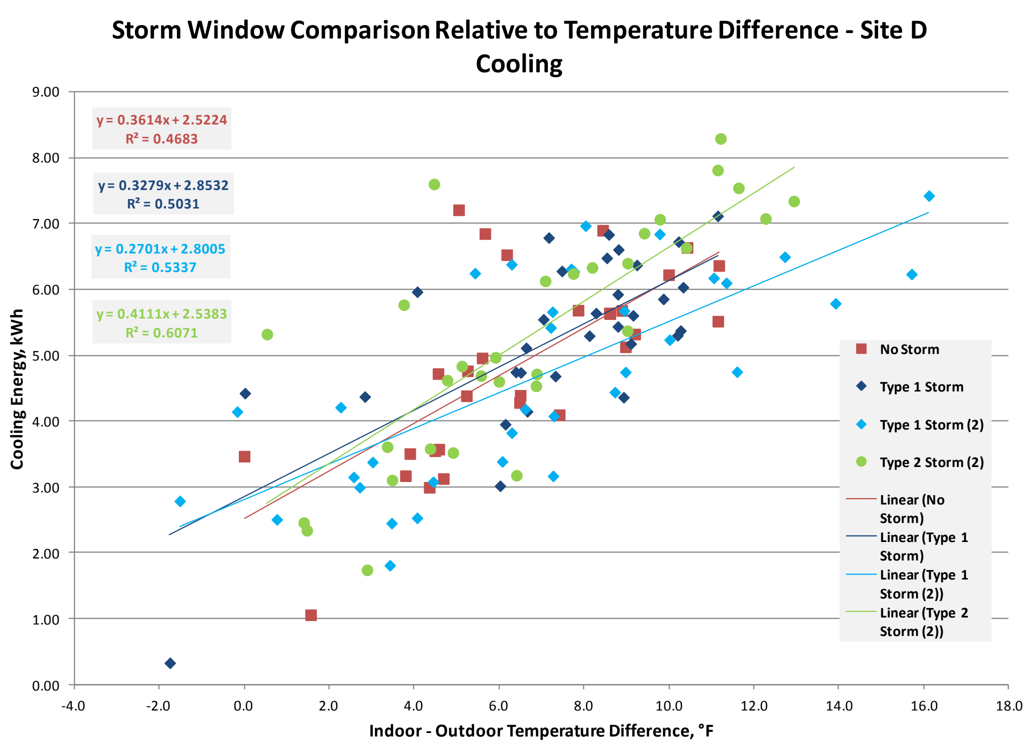
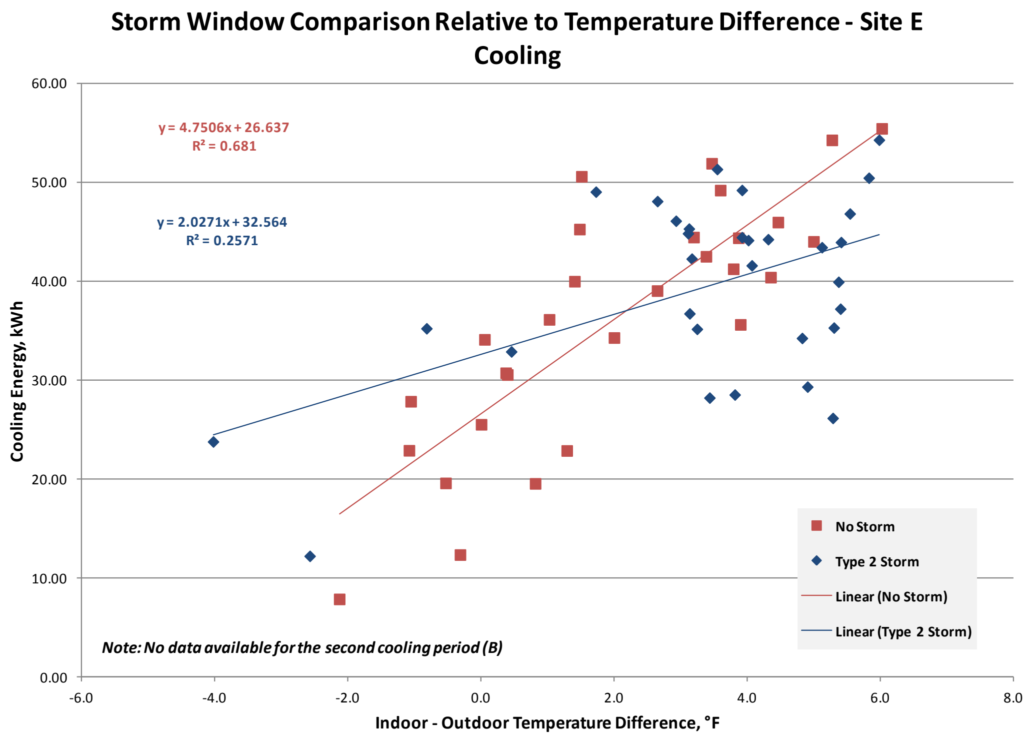
Appendix C:
Cooling Energy for Each Test Home

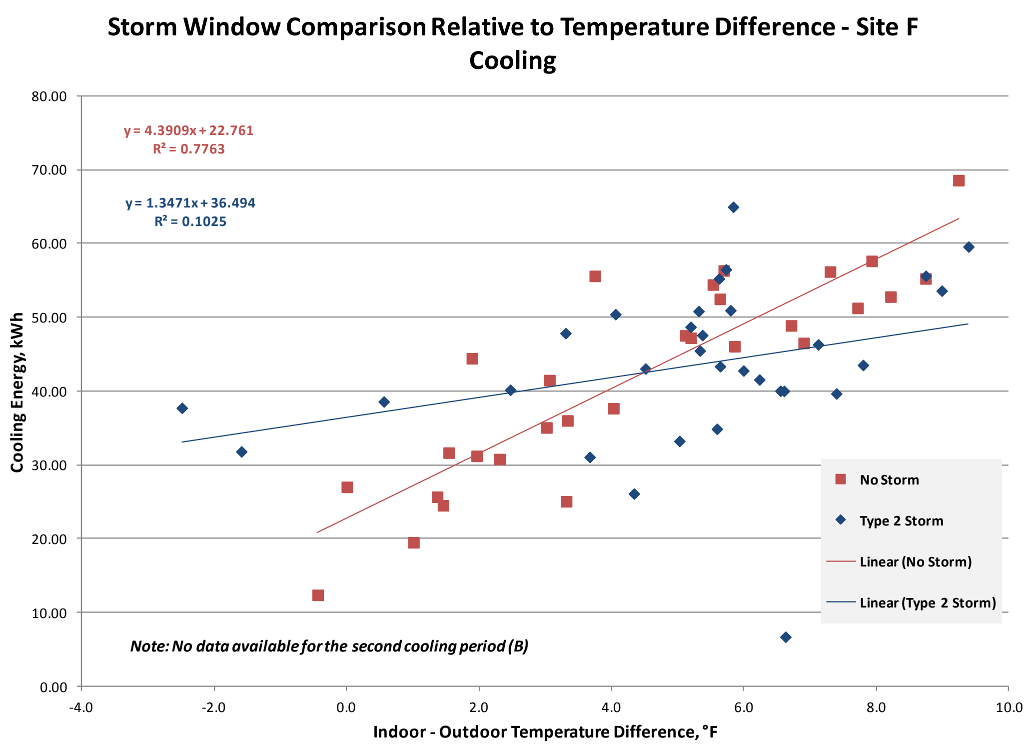


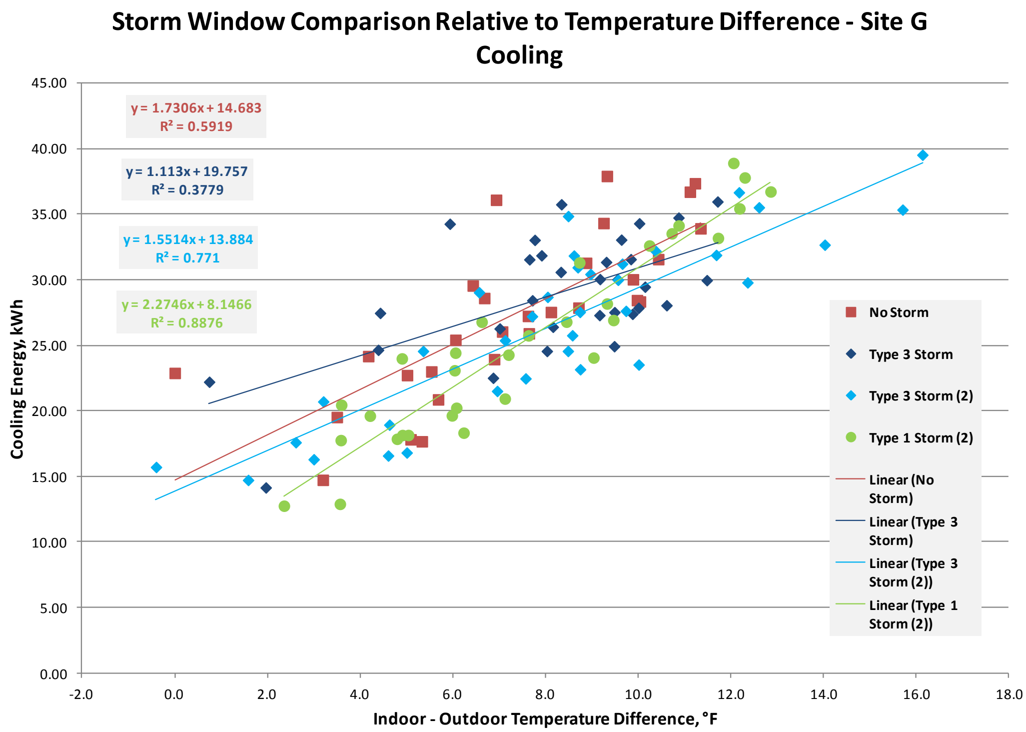


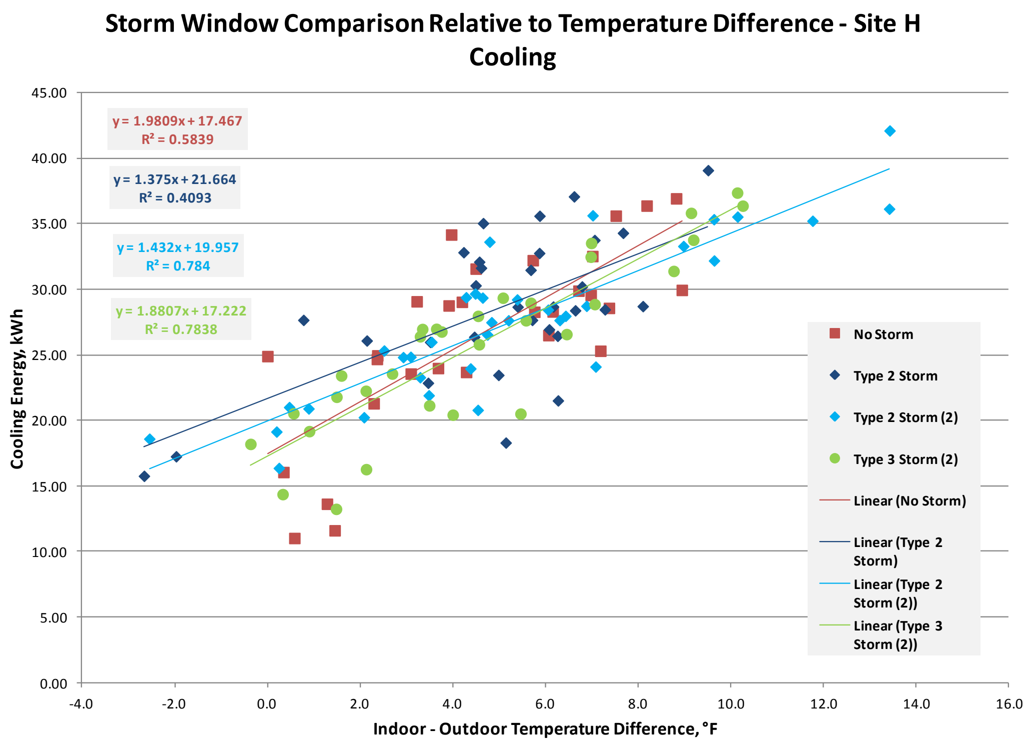

Storm Window Comparison Relative to Temperature Difference - Site C Cooling
y = 1.6191x + 7.2845
R² = 0.5948
y = 0.9699x + 10.515
R² = 0.2408
y = 1.061x + 10.816
R² = 0.5899
y = 1.5257x + 8.8356
R² = 0.6093
Cooling Energy, kWh
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 3 Storm
Type 3 Storm (2)
Type 1 Storm (2)
Linear (No Storm)
Linear (Type 3 Storm)
Linear (Type 3 Storm (2))
Linear (Type 1 Storm (2))

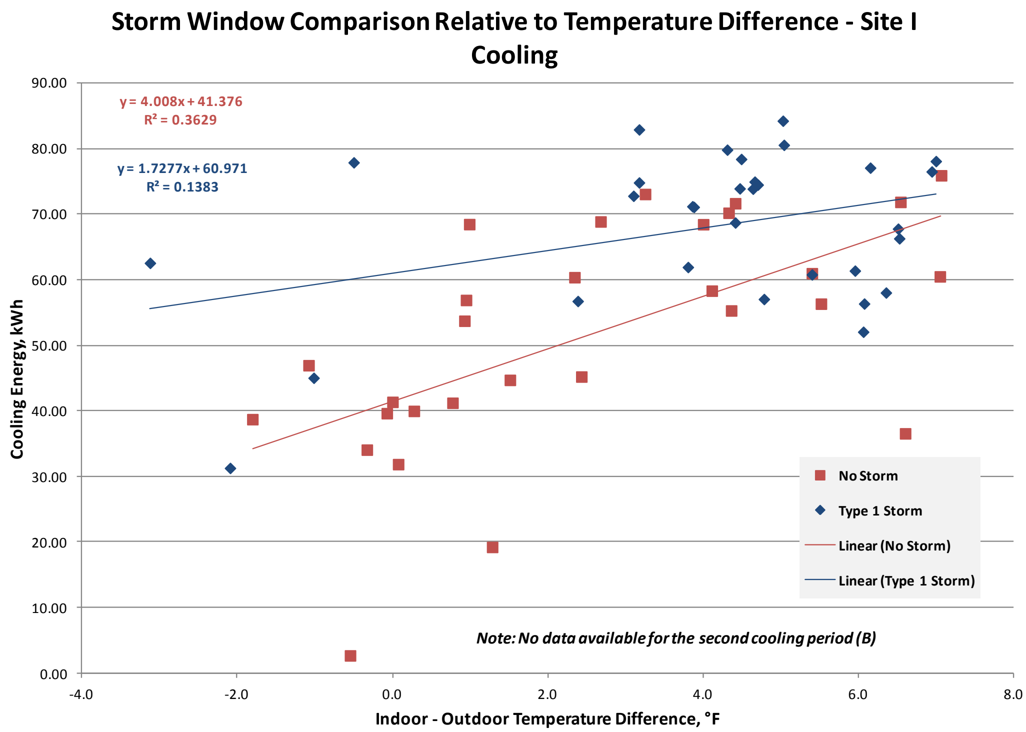

Storm Window Comparison Relative to Temperature Difference - Site D Cooling
y = 0.3614x + 2.5224
R² = 0.4683
y = 0.3279x + 2.8532
R² = 0.5031
y = 0.2701x + 2.8005
R² = 0.5337
y = 0.4111x + 2.5383
R² = 0.6071
Cooling Energy, kWh
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 1 Storm
Type 1 Storm (2)
Type 2 Storm (2)
Linear (No Storm)
Linear (Type 1 Storm)
Linear (Type 1 Storm (2))
Linear (Type 2 Storm (2))


Storm Window Comparison Relative to Temperature Difference - Site E
Cooling
y = 4.7506x + 26.637
R² = 0.681
y = 2.0271x + 32.564
R² = 0.2571
Cooling Energy, kWh
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 2 Storm
Linear (No Storm)
Linear (Type 2 Storm)
Note: No data available for the second cooling period (B)

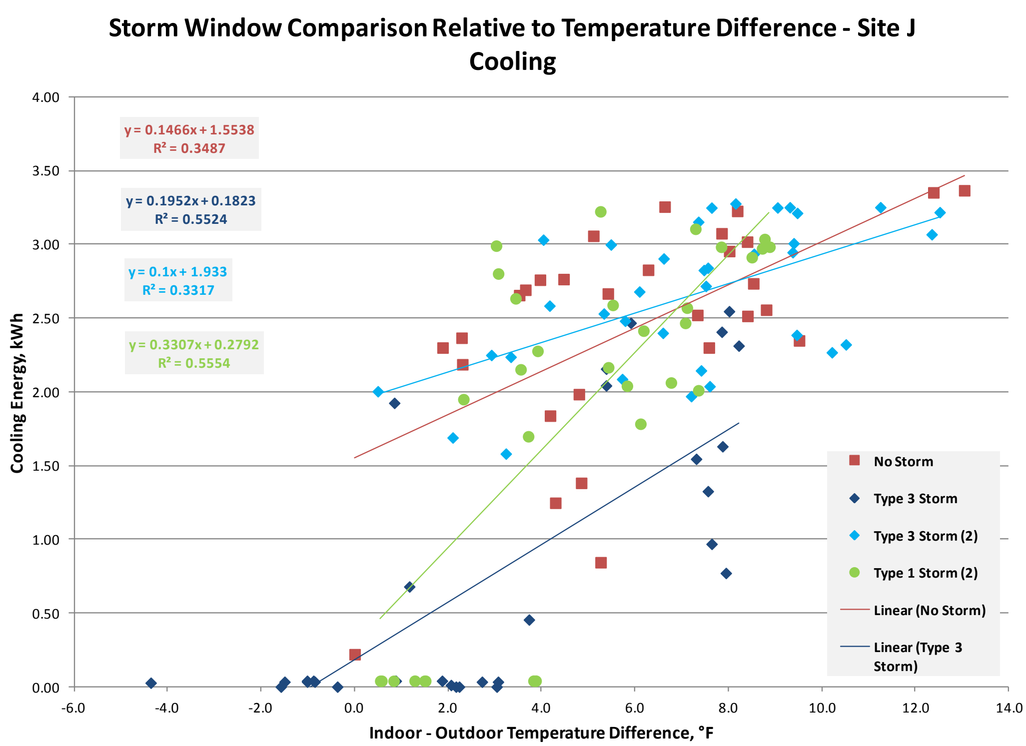

Storm Window Comparison Relative to Temperature Difference - Site F
Cooling
y = 4.3909x + 22.761
R² = 0.7763
y = 1.3471x + 36.494
R² = 0.1025
Cooling Energy, kWh
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 2 Storm
Linear (No Storm)
Linear (Type 2 Storm)
Note: No data available for the second cooling period (B)


Storm Window Comparison Relative to Temperature Difference - Site G
Cooling
y = 1.7306x + 14.683
R² = 0.5919
y = 1.113x + 19.757
R² = 0.3779
y = 1.5514x + 13.884
R² = 0.771
y = 2.2746x + 8.1466
R² = 0.8876
No Storm
Type 3 Storm
Type 3 Storm (2)
Type 1 Storm (2)
Linear (No Storm)
Linear (Type 3 Storm)
Linear (Type 3 Storm (2))
Linear (Type 1 Storm (2))
Cooling Energy, kWh
Indoor - Outdoor Temperature Difference, °F


Storm Window Comparison Relative to Temperature Difference - Site H
Cooling
y = 1.9809x + 17.467
R² = 0.5839
y = 1.375x + 21.664
R² = 0.4093
y = 1.432x + 19.957
R² = 0.784
y = 1.8807x + 17.222
R² = 0.7838
No Storm
Type 2 Storm
Type 2 Storm (2)
Type 3 Storm (2)
Linear (No Storm)
Linear (Type 2 Storm)
Linear (Type 2 Storm (2))
Linear (Type 3 Storm (2))
Cooling Energy, kWh
Indoor - Outdoor Temperature Difference, °F



Storm Window Comparison Relative to Temperature Difference - Site I
Cooling
y = 4.008x + 41.376
R² = 0.3629
y = 1.7277x + 60.971
R² = 0.1383
Cooling Energy, kWh
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 1 Storm
Linear (No Storm)
Linear (Type 1 Storm)
Note: No data available for the second cooling period (B)



Storm Window Comparison Relative to Temperature Difference - Site J
Cooling
y = 0.1466x + 1.5538
R² = 0.3487
y = 0.1952x + 0.1823
R² = 0.5524
y = 0.1x + 1.933
R² = 0.3317
y = 0.3307x + 0.2792
R² = 0.5554
Cooling Energy, kWh
Indoor - Outdoor Temperature Difference, °F
No Storm
Type 3 Storm
Type 3 Storm (2)
Type 1 Storm (2)
Linear (No Storm)
Linear (Type 3 Storm)

Home Innovation
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Appendix C

Performance Comparison of a Low-E Retrofit Window
in a Philadelphia Office Building

Performance Comparison of a Low-e Retrofit Window in a Philadelphia Office Building

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Pedricktown, NJ 08067

Funded by U.S. Department of Energy
project #DE-EE0004015

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OCTOBER 2013

Report # 3323.001_10232013

Disclaimer

Contents

Tables

Figures

Background

Controlling rising energy costs in older multistory office buildings can take various pathways such as envelope or equipment improvements. Equipment upgrades, such as the use of high efficiency motors or boilers can result in reduced energy costs. However, for older building envelopes with lower wall insulation levels and lower performance windows with high U-factors, the efficiency gains from equipment improvements may be hindered. While the equipment may be more efficient, the discomfort of the occupants in inefficient buildings often leads to increased energy use (e.g., supplemental heaters are used in office spaces near windows). Furthermore, the equipment upgrades in older buildings must be sized to service the same loads whereas in more efficient envelopes, the equipment upgrades can be sized smaller thus saving upfront costs as well as ongoing fuel costs.

Figure 1. Office Building Upgraded with Low-e Window Retrofit Panels

Envelope upgrades, however, can be very expensive for building owners. Envelope upgrade costs may include not only the installation of new materials, but also include removal and disposal of old materials, displacement of occupants during renovations, and modification of office sizes and floor space.

Addressing these concerns for envelope upgrades, an innovative retrofit window technology has been installed to decrease the window U-factor and add a low emissivity (low-e) coating. The window retrofit was performed on a 12-story office building located in downtown Philadelphia, Pennsylvania at 400 Market Street. The building was constructed in 1971 with single-pane windows. Prior to this retrofit, the only window alteration which had been performed was the addition of a window film on the interior surface. The window retrofits are performed such that occupants are not required to vacate office space and no existing materials other than the existing window film requires disposal.

The purpose for the window upgrade was to reduce operating energy costs; increase the comfort of the occupants, especially those located near windows; and provide a more uniform interior temperature that does not rely on use of supplemental heating units (in this case, baseboard heaters). The window upgrade technology selected is a unique retrofit panel product that effectively converts the original single-pane window into a triple pane low-e window system. Installed from the interior of the building, the low-e Retrofit Panel is a double pane, low-e coated glass panel installed on the interior of the existing window separated with a ½" gasket and held into place with an aluminum extruded frame.

The Low-e Retrofit Panel manufactured by JE Berkowitz, LP used for the window upgrades was the Renovate Platinum product. The retrofit panel is configured as a double pane IGU with one pane solar control low-e glass and one pane clear glass, filled with argon gas between the panes of the IGU. The center-of-glass U-factor of the final installed assembly (including the existing glass) is 0.18 and the solar heat gain coefficient is 0.44.

Test and Analysis Methodology

In order to understand the benefits of the low-e window retrofit panel upgrade and to compare the differences between the pre- and post-retrofit characteristics of the office space, two pairs of offices were instrumented with temperature sensors and controls, and an energy monitoring system connected to the specially installed heating and cooling systems for each office. All four of the offices were 10 ft. by 12 ft. with one nominal 6 ft. by 6 ft. window. One pair of offices was east facing and had an unobstructed view of the rising sun and one pair of offices had a northern exposure. For each pair of test offices, one office was kept with the original single-pane window with an interior film and the other office was retrofitted with the low-e retrofit panel. Prior to the installation of the low-e retrofit panel, the existing window film was removed to provide a clean surface on the existing window.

Figure 2. Side x Side Test Offices

Figure 3. Window Area in Test Office

The office pairs provide a side-by-side comparison of the room energy use, temperature, and light characteristics through both the heating and cooling seasons. Using dedicated heating and cooling equipment and performing infiltration testing, each office pair test was designed to isolate the influence of the window as the primary driver of heating and cooling energy use in the office space. In addition to isolating the heating and cooling energy (the building mechanical systems were deactivated in all four test offices), the test offices were outfitted with incandescent lamps to simulate internal gains from occupants and equipment. These simulated internal gains were controlled on a daily basis using programmable timers in accordance with weekday and weekend schedules consistent with the benchmark office building model from Pacific Northwest National Laboratory. Constant operating fans were employed to provide air mixing since the building ventilation system was closed off to the offices for the duration of the tests. Finally, the doors to offices were closed to isolate the offices from the adjoining common areas. The doors were outfitted with sensors to verify when and for what time length the doors were opened.

A programmable data logging system was used to control the temperature for the test offices which were kept at 69°F for heating and 71°F for cooling, through operation of the dedicated heating and cooling systems. The test offices and the common areas outside of the test offices are unoccupied during the monitoring period.

The test office energy use is used to analyze the pre- to the post low-e window retrofit panels. Though individual offices are a subset of the whole office building that includes conference rooms and open interior work space, the results do provide a controlled evaluation of the office spaces adjacent to windows. The results are representative of the savings expected for the perimeter areas of the building. Less clear in this analysis; however, is the effect that the windows will have on the core building heating and cooling energy (i.e., the office spaces without windows but separated by interior walls).

To better approximate the whole building performance, an initial analysis of the utility bills for the preceding year and the year following the window retrofit affords an opportunity to estimated actual savings. This analysis; however, is limited by changing building occupancy and weather patterns from year to year and thus serves only as a marker of energy savings. The benefit of the utility bill analysis is to generally confirm the savings based on the test office study and to generally estimate a magnitude of the savings that can be realistically expected from the window retrofits.

Lastly, the analysis provides general office light characteristics using photometric measurements to compare the pre- to post-window retrofit. A comparison of light levels and glazing temperatures are used to provide relative levels of lighting at different times of the day in various orientations and relative glazing temperatures, extremes of which can lead to discomfort for office personnel.

Instrumentation and Monitoring

Pairs of offices facing east (on the 6th floor) and offices facing north (on the 11th floor) were selected for the study. One of the test offices in the pair were upgraded with the low-e window retrofit panel and the adjacent office in the pair was left unaltered from the original single-pane glazing with interior solar control film. The building heating and cooling systems were shut-off and the ceiling diffuser for the ventilation system was sealed. The offices were tested for infiltration leakage and determined to be very similar in air leakage for each pair. Table 1 provides the leakage results at 50 Pa air pressure difference with the common area based on leakage measured from 10 Pa to 60 Pa in 10 Pa increments. The air leakage results indicate that leakage to the outdoors attributed to the glazing is negligible compared with the leakage to the adjacent common office space, and that the effects related to any air exchange to the interior should be equal within each pair.

Figure 4. Typical Instrumentation in Each Test Office

Figure 5. Cooling Unit, Mixing Fan, and Variable Light Loads

Table 1. Test Office Infiltration Test Results

50 Pa Pressure Difference	East Facing, Retrofit Panel	East Facing, Original Glazing	North Facing, Retrofit Panel	North Facing, Original Glazing
Leakage Flow, CFM	1,010	1,000	860	861

Each test office was equipped with two portable heaters – Broan model 6201-A (1500W) with blower fans for heating. A portable Sunpentown air conditioner model WA-1140DE (11,000 Btu/h) was installed to provide cooling. The condenser air flow was ducted to the common area outside of the test office. A separate floor fan was used to mix the room air to avoid stratification. The incandescent lamps, used to simulate internal gains from office personnel and equipment, were controlled by a programmable timer.

Interior temperatures were measured at three levels. The mid-level temperature was measured using a Vaisala humitter that records temperature and humidity and was used as the source temperature for space conditioning control. Other room temperatures were measured using Type T thermocouples. Type T thermocouples were also used to record temperatures on the interior glass surface. One other temperature sensor was placed on the exterior of the test offices in the common area. This temperature reading was used to modify the test office set temperature based on the setback or setup of the HVAC system during nighttime or weekend periods.

Light levels were recorded using a LiCor-210 Photometric sensor used to measure interior lighting levels primarily from the window. Differences in light levels based on the glazing coatings and films were intended to provide a qualitative, rather than quantitative, comparison between the adjacent test offices. The photometers were located in a horizontal position within three feet of the window center (see Figure 4 for representative location).

A Campbell Scientific data logger was used to both program the space conditioning control and record energy, temperature, and light data. The data was measured in five-second increments and averaged over a 15-minute period.

Monitoring was conducted from November 2011 through October 2012.

Perimeter Office Monitoring Results

The data presented in subsections below is based on each office, one pair facing east and one facing north. One office in each pair has been upgraded with the low-e window retrofit panel while the adjacent office has been unaltered from the original single-pane glazing with an interior solar control film.

Test Office Energy Use Comparison

The primairy metric to quantify the benfit of the retrofit window panels is energy consumption. The office test study is designed to isolate the effect of the window upgrades as the sole driver for energy conmsumption diffeences between offices in each pair.

Space conditioning energy was calculated for a heating period from December 1, 2011 through February 29, 2012 and a cooling period from July 27, 2012 through September 30, 2012. These periods were selected as primary heating and cooling periods where there was the least crossover between heating and cooling system operation. Table 2 provides a summary result of the energy consumption in heating and cooling for each test office.

Table 2. Estimated Energy Savings for Test Offices

Test Office/Orientation	Heating Energy[A], kWh	Cooling Energy[B], kWh
	December - February	July 27 - September[C]
East, Original Glazing, Film	372	341
East, Low-e Retrofit Panels	226	217
East Office Energy Savings	**39%**	**36%**
North, Original Glazing, Film	863	222
North, Low-e Retrofit Panels	343	202
North Office Energy Savings	**60%**	**9%**

[A] Heating Energy is adjusted to account for minor discrepancies in the Internal Gains in each office pair based on a 1:1 ratio.
[B] Cooling energy is adjusted to account for minor discrepancies in the Internal Gains in each office pair based on an EER of 9.0.
[C] Cooling data period constrained by errant operation of one AC unit.

The energy use data for space conditoning in offices with a direct connection to a window results in the following summary observations for an annual period:

- For offices with access to direct solar gains (i.e., unshaded east, west, south orientations), the low-e window retrofit panels result in about 40% heating energy savings over the existing windows. North facing offices result in about 60% heating energy savings with the low-e window retrofit panel.
- For offices with access to direct solar gains (i.e., unshaded east, west, south orientations), the low-e window retrofit panels result in about 35% cooling energy savings over the existing windows. However, for north facing offices with inherently lower solar gains, cooling energy savings is more modest, generally less than 10% with the low-e window retrofit panel.

Two general performance concepts highlighted by the window retrofit are demonstrated by these summary energy use results:

- Heating energy savings is greater for window orientations that do not have direct solar gain , because heat transfer in the space is dominated by thermal heat loss through the windows, so improvements in the U-factor of the window assembly have a larger impact. For other window orientations that do have direct solar gain, the solar heating offsets a portion of the energy needed for space heating, so the savings due to the improved window U-factor are significant but not as high as on the north side.

- Impact on cooling energy savings is more complicated since energy savings varies widely depending on the orientation of the windows. Cooling periods have a lower temperature difference driver (rendering the U-factor improvement slightly less effective) while solar and internal gains play a much more prominant role. Furthermore, in some climatic conditions such as swing seasons, heat loss through the original less efficient windows at night may decrease loads on the cooling system, as is the case in this test. (This energy savings, however, may be offset by discomfort from large temperature changes at the surface of the glazing during the daytime.) Overall, the addition of the solar control low-e retrofit panel did result in significant cooling energy savings in the east-facing office by reducing the solar heat gain, and the same would be expected for other orientations with direct solar gains.

In many commerical buildings, the electric peak demand may be a significant factor in energy costs. While the testing of this study can only point to potential demand savings, the opportunity to reduce demand charges can be demonstrated by comparing the demand for each office in both orientations. Figure 6 and Figure 7 show the electic demand curve for each set of offices in both orientations, based on measured electric data for each office. The heating for this test was from electric heaters so is not representative of the building energy supply for heating (which is natural gas).

The electric demand curves demonstrate the reduced demand for the offices with the low-e retrofit panels. General observations include:

- Heating peak demand in north facing rooms is double that of the east facing (and by extension west and south) offices.

- The demand for heating decreases and ends more rapidly with the window retrofit panel upgrades.

- Cooling demand in the east facing (and by extension, the west and south) offices is significantly lower and decreases much more rapidly with the window retrofit panel upgrades. Cooling peak demand is reduced by over 10% and remains over 10% for nearly a quarter of the cooling period.

- Cooling demand in north facing offices demonstrates modest, but measurable benefit from the retrofit panel upgrades.

Test Office Interior Temperature Comparison

A secondary metric of interest to compare the perfomance of the low-e window retrofit panels with the existing single-pane glazing with solar control film is the temperature changes in the room and on the glazing surface. The following four figures (Figure 8 through Figure 11) provide an example of the temperature profile for a cold sunny winter day and a hot sunny summer day, for each test office orientation.

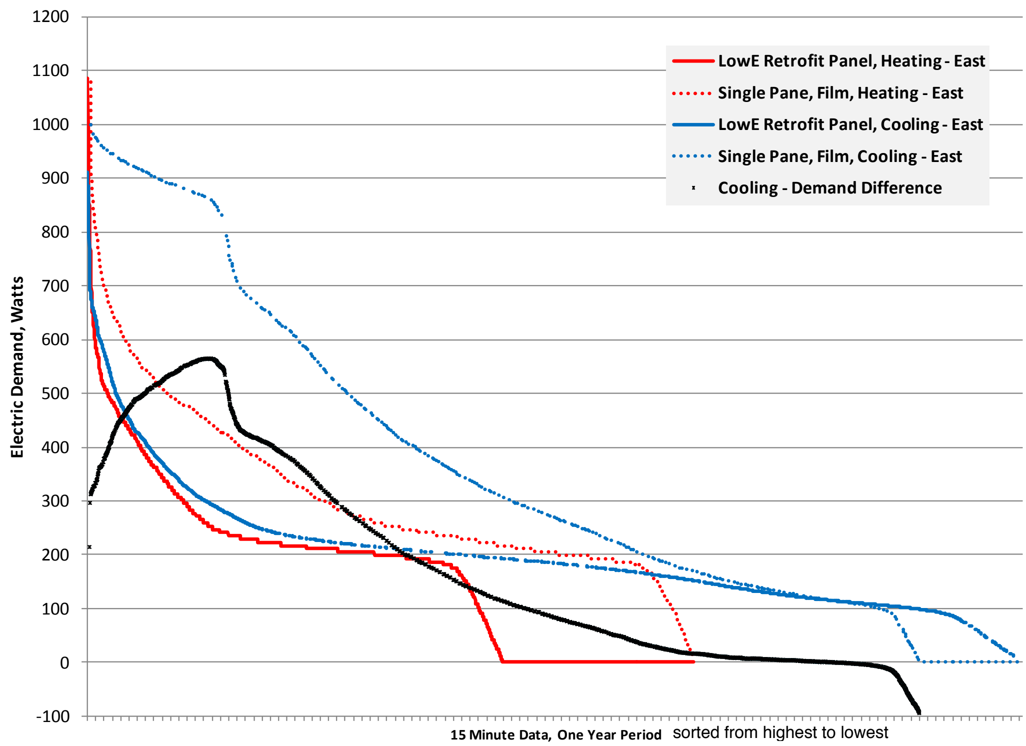

Figure 6. Electric Demand - East Facing Offices

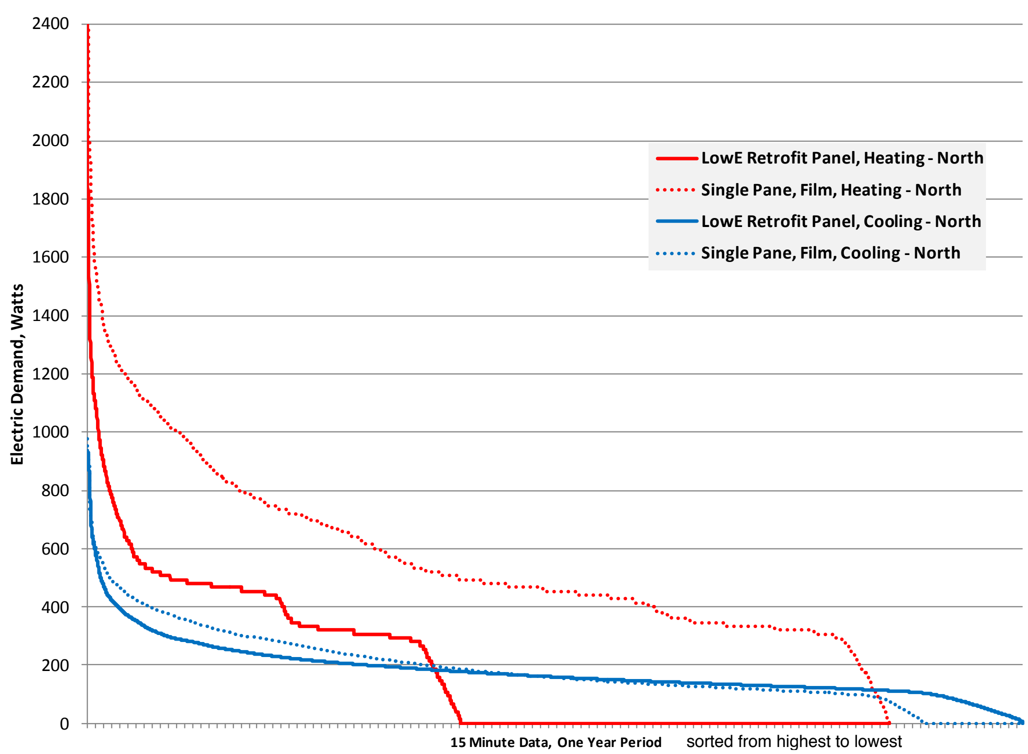

Figure 7. Electric Demand - North Facing Offices

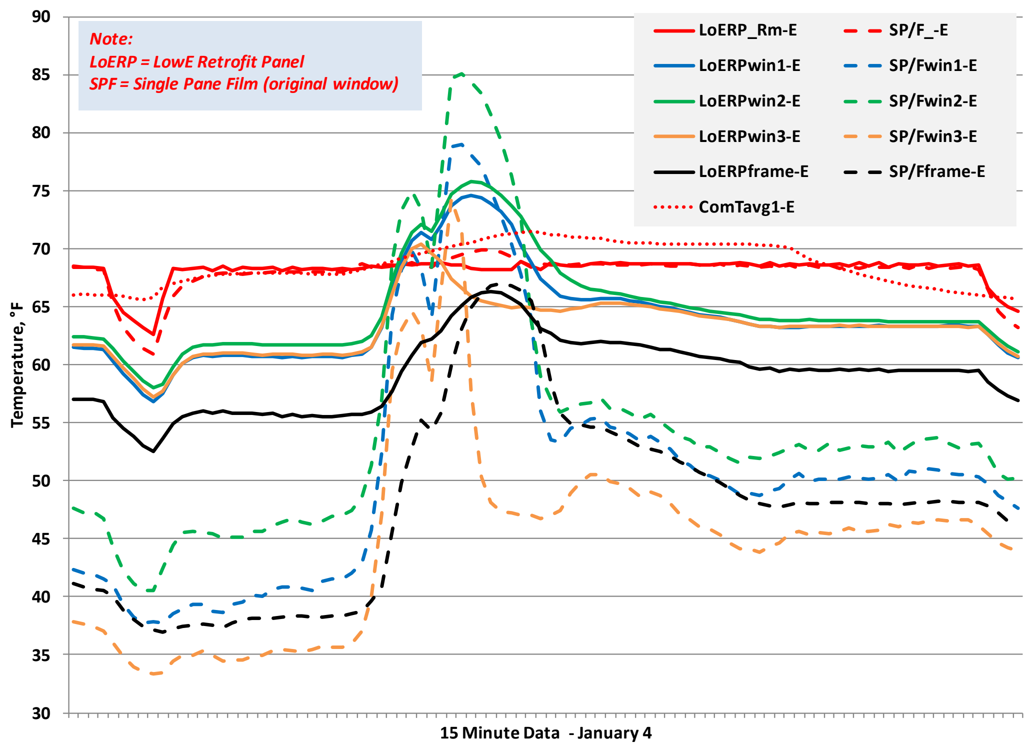

Figure 8. Glazing Surface Temperatures - East-Facing Test Offices, Winter Day

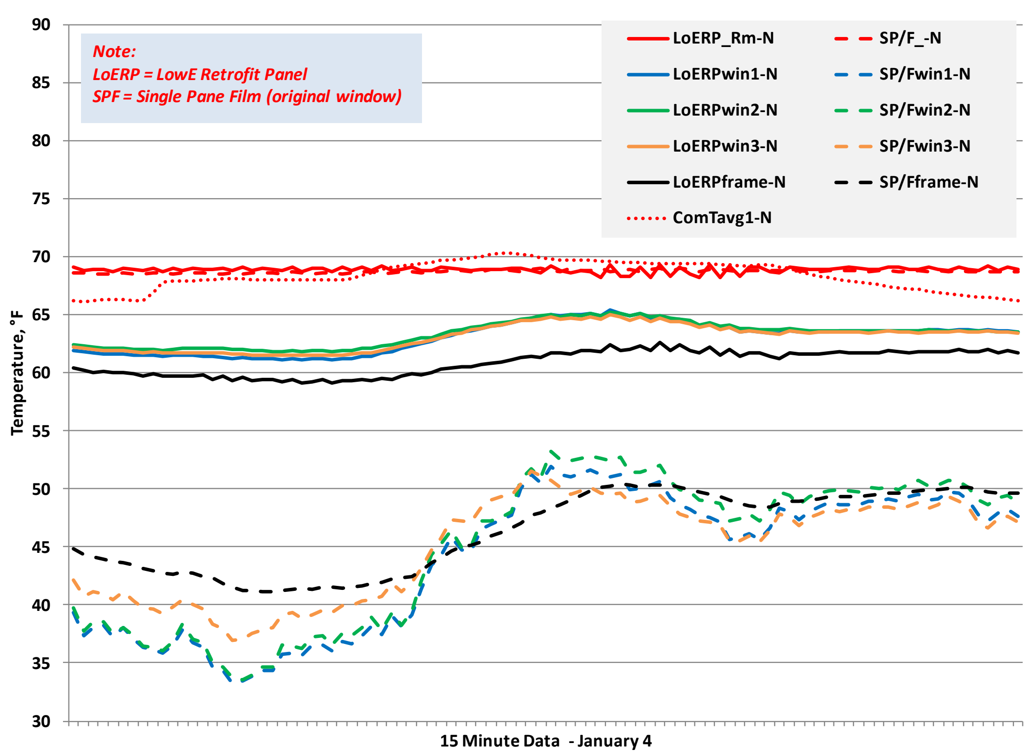

Figure 9. Glazing Surface Temperatures - North-Facing Test Offices, Winter Day

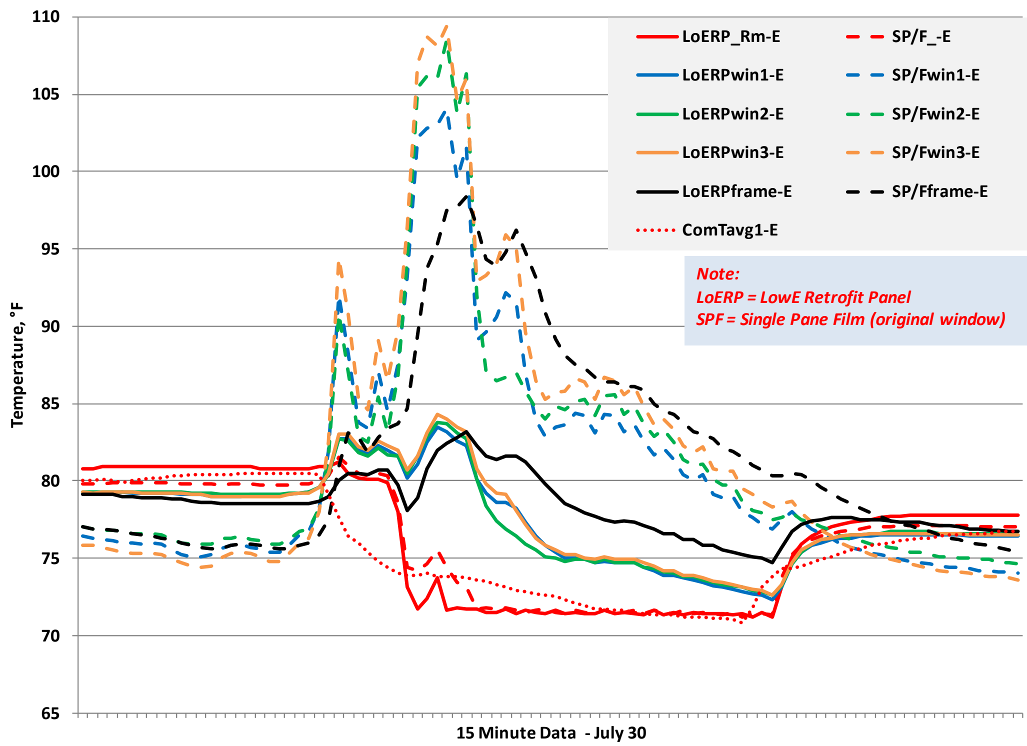

Figure 10. Glazing Surface Temperatures - East-Facing Test Offices, Summer Day

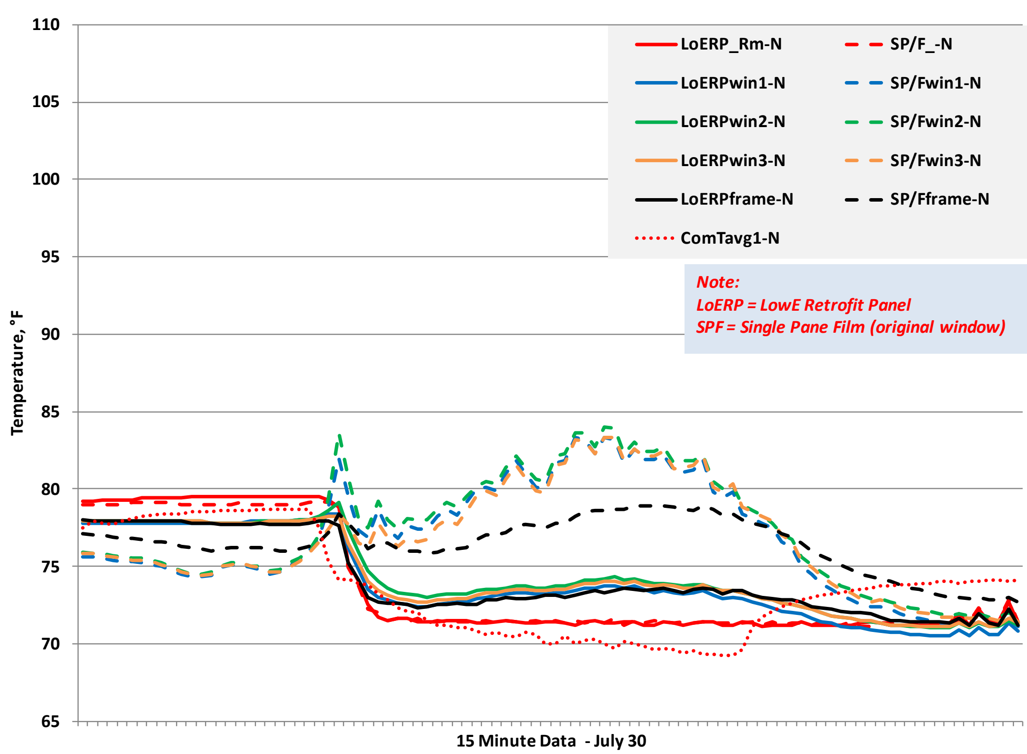

Figure 11. Glazing Surface Temperatures - North-Facing Test Offices, Summer Day

The differences between the window surface temperatures is clearly identified with the orignal single-pane glazing temperatures on the interior surface of the windows at approximately 15°F higher or lower than similar peaks on the interior window surface of the low-e retrofit panels. More pronounced; however, is the temperature swing in a single diurnal period as summarized in Table 3.

Table 3. Diurnal Glazing Surface Temperature Range for Selected Periods

Inside Glass Surface Temperature Profile	East Facing		North Facing	
	Low-e Retrofit Panel	Original Single Pane/Film	Low-e Retrofit Panel	Original Single Pane/Film
Winter day, Maximum during day	70 - 76°F	75 - 85°F	65°F	52 - 53°F
Winter day, Minimum during day	57 - 58°F	33 - 40°F	61 - 62°F	34 - 37°F
Summer day, Maximum during day	84°F	104 - 109°F	73 - 74°F	83 - 84°F
Summer day, Minimum during day	72 - 73°F	74 - 75°F	71°F	72°F

For the East facing windows, the inside surface temperature of the glass for the low-e retrofit panel may vary by almost 20°F depending the location on the glass, the outside temperature, and the level of solar radiaition. For the existing glazing with the solar control film, the range may be over 50°F in a diurnal period. For the north facing windows, the range for the low-e retrofit panel is only a few degrees (since no direct solar impinges on the surface), and ranges to 19°F for the original single pane with solar control film. The significantly reduced temperature swings for the windows with the low-e retrofit panel would be expected to improve occupant comfort and reduce the use of supplemental heating/cooling systems.

Light levels were measured in each test office using photometers located within three feet of the window. Light levels were generally driven by light through the window areas, rather than electrical lighting. Figure 12 shows the relationship of the light level for each pair of offices as a percentage of the maximum measured across all office pairs (i.e., the east-facing LowERP office which has the highest light levels across all four test offices). The light levels are sorted on the largest values. As expected, the east facing rooms (red curve, left axis) have a sharp decline in light levels once the sun moves toward the southernly sky. The north-facing offices (blue curve, right axis) have a much smaller maximum, about one-tenth that of the east facing rooms but have a more modest slope. For the north-facing offices, it is apparent that the low-e retrofit panel provides more light than the darker solar control film on the original window.

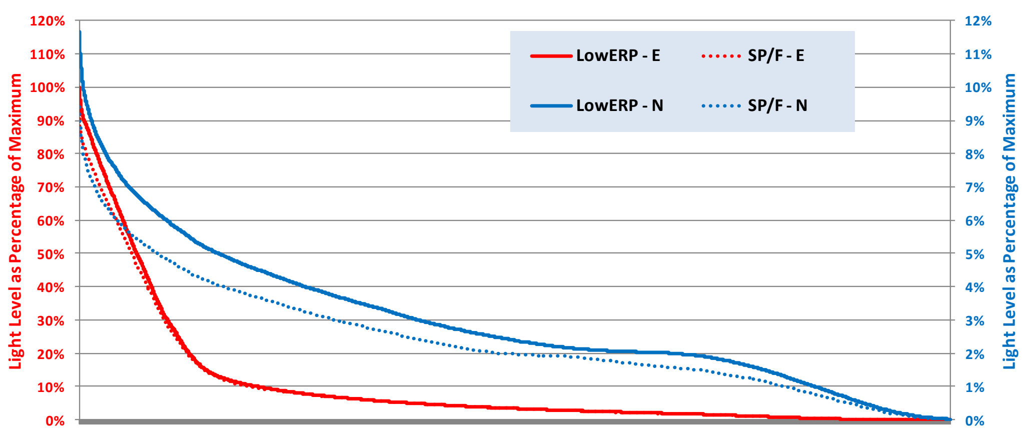

Figure 12. Relative Light Levels Measured in Each Office Space over Monitoring Period

Whole Building Energy Use Estimates

Following the retrofit of the entire building with low-e window retrofit panels, an initial analysis of utility bills was performed. The utlilities include gas use and electric use. Both heating and cooling periods prior to the window upgrades was compared with heating and cooling periods following the window upgrades. The utility bill analysis is complicated by different weather conditons, variable building occupancy, and any changes in office space by individual tenants. However, a general analysis is reasonable as an indication of expected savings given that future higher occupancy levels will likely confirm or enhance energy savings.

Natural gas and electric utility bills from portions of 2010 through 2013 were obtained and arranged into seasonal periods for before- and after-window upgrades. Using weather data, a calculation of heating and cooling degree days was made for the same periods. Degree days are used to normalize utility data across seasonal periods. Figure 13 shows the rollup of the data used for comparison of the pre- and post-window retrofit (non-normalized results). Given the much colder period in the 2010-2011 heating season, fuel use is expected to be higher.

Based on a select portion of the heating season (periods when there is little crossover cooling expected) the energy use is normalized to the heating degree days for the respective periods. Figure 14 shows the normalized use and calculated savings in post-window retrofit in the 2nd and 3rd heating seasons. The savings is 28% (season 2) and 23% (season 3) over the base first year. Given the mild winter in the 2011-2012 heating season and the changes in occupancy, the estimated savings attributed to the window upgrades is generally about 25%.

Figure 15 depicts the primary cooling season whole building electrical usage and cooling degree days over a monthly period. Whole building electric includes all electric loads; however, increases in electricity use over periods of mild outdoor temperatures would approximate the cooling energy use apart from other electricity uses.

Given that the electricity use for cooling is only a portion of the totals building electricity, a rough estimate of cooling energy is made by subtracting from the peak cooling months, the electricity use in a month that has minimal cooling (and heating), in this case the April monthly use. Figure 16 shows the estimated cooling electricity use for two cooling periods prior to the window upgrades, and one cooling period following the window upgrades. The cooling energy is not normalized to cooling degree days since the relationship is tenuous at best given the large influence of internal gains and limited data set to monthly resolution.

In addition to the total electricity use, the peak power demand is also an important factor in utility costs. Electricity demand, as reported on utility billing, for pre- and post-window retrofit periods is shown in Figure 17.

With only the limited data set, it appears that the peak electricity demand has remained somewhat consistent from pre- to post-retrofit periods, indicating that peak demand is driven by numerous factors in addition to window loads.

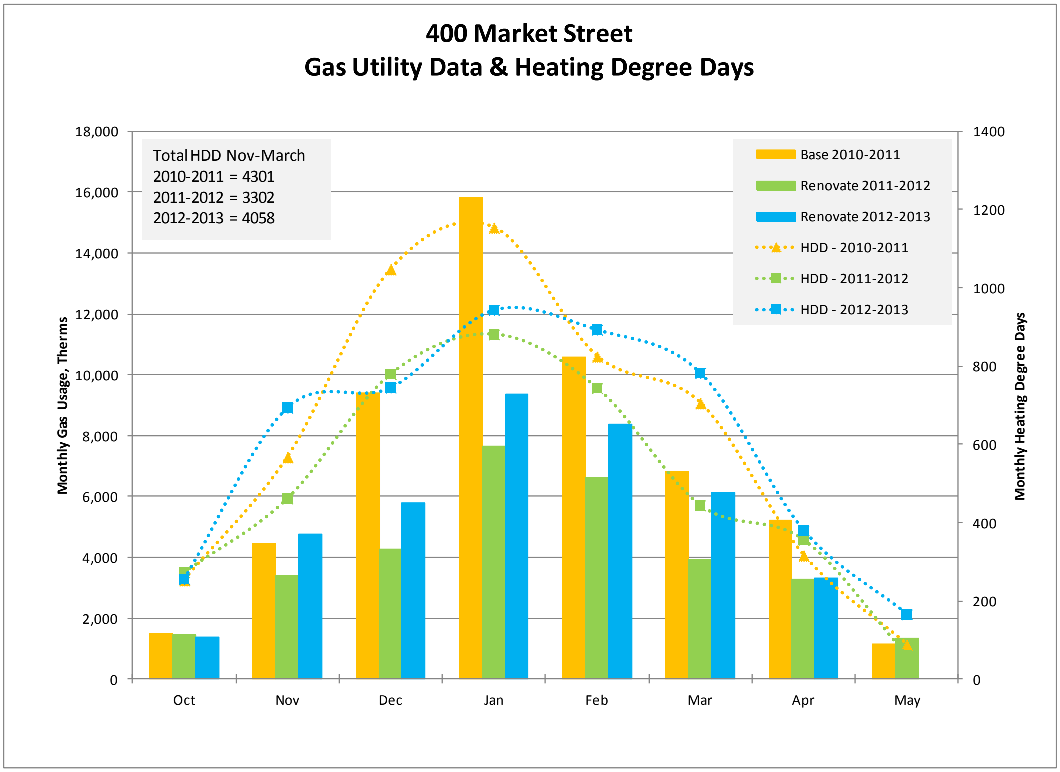

Figure 13. Monthly Fuel Use for Pre- and Post-Window Retrofit

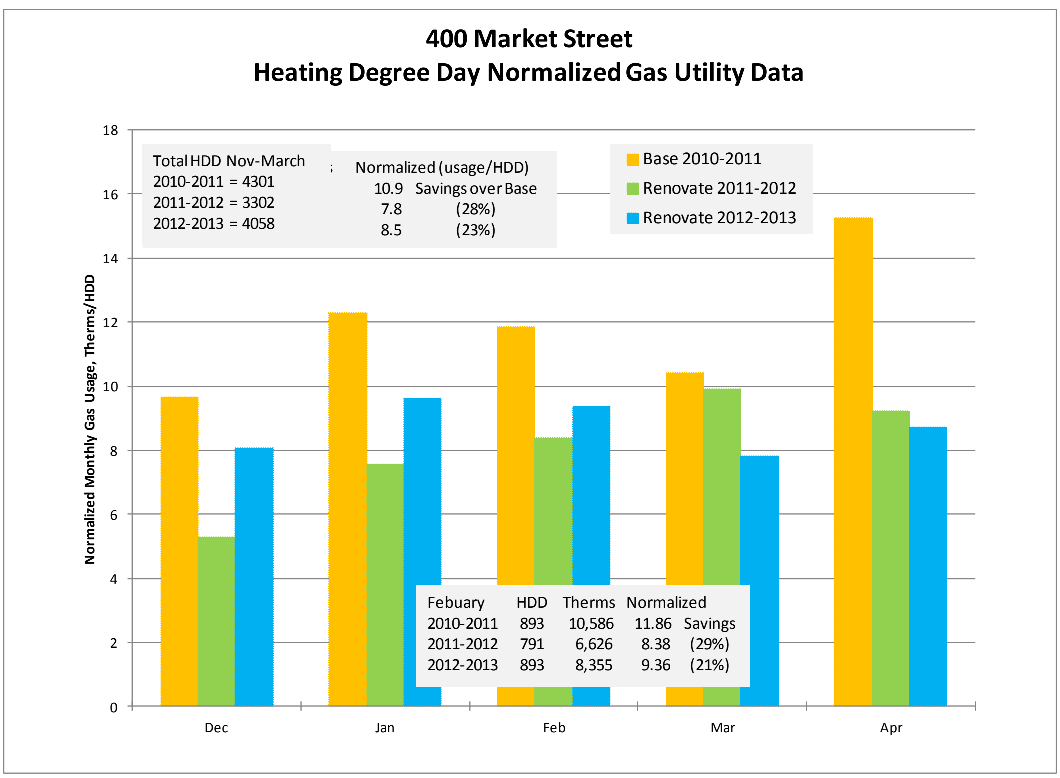

Figure 14. Normalized Heating Fuel Use

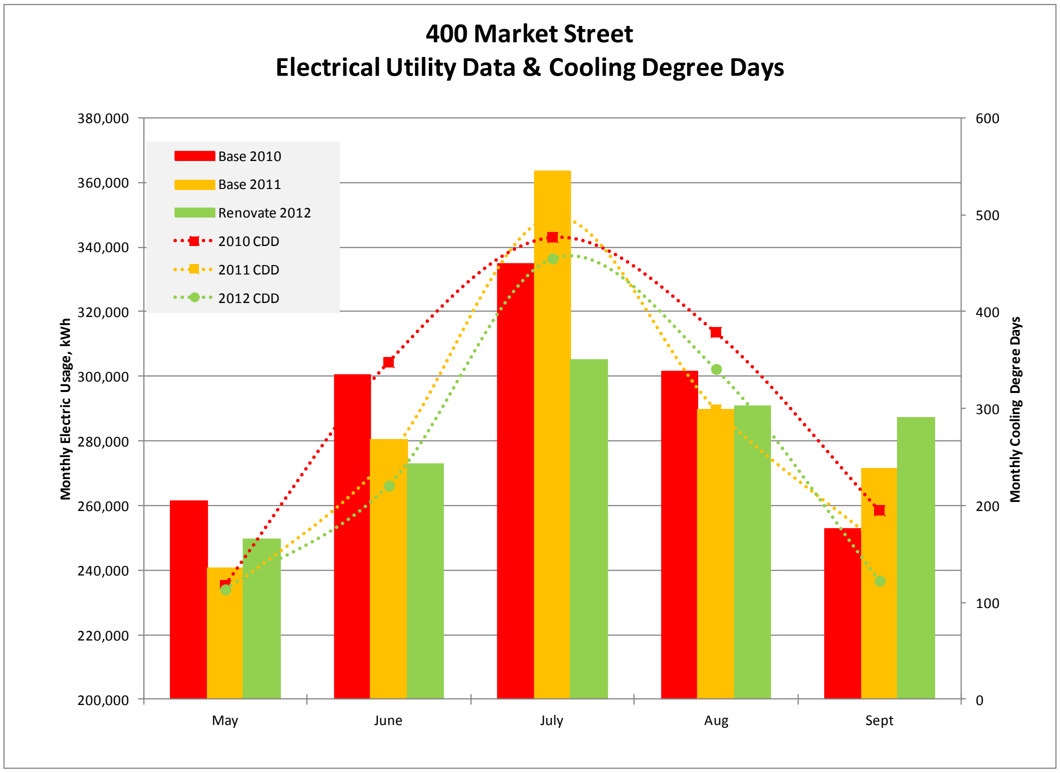

Figure 15. Monthly Electricity Use for Pre- and Post-Window Retrofit

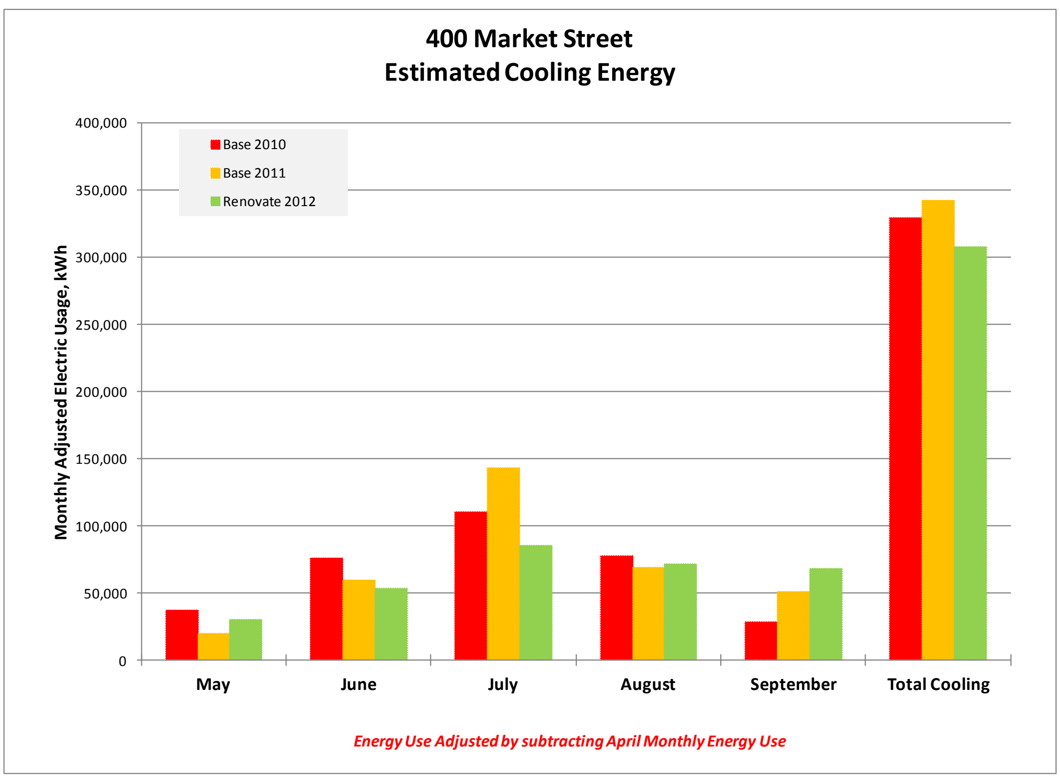

Figure 16. Estimated Cooling Electricity Use

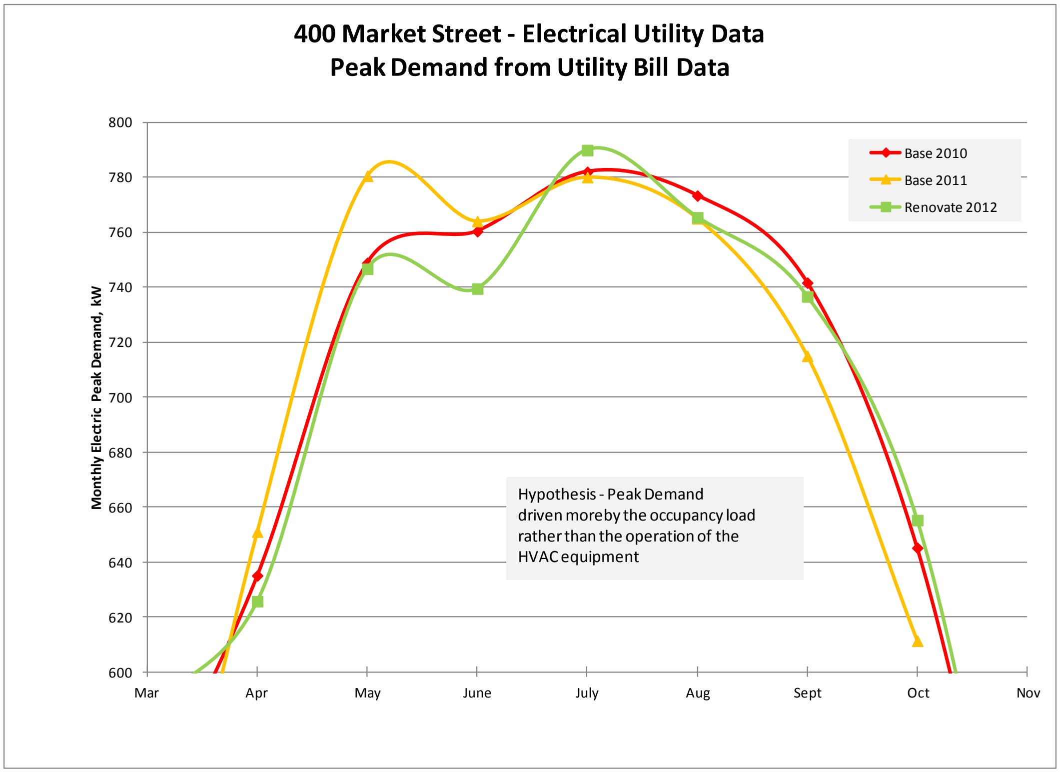

Figure 17. Monthly Peak Power Demand for Cooling Periods

Energy usage based on utility bill data does demonstrate energy savings when comparing pre- and post-retrofit periods for heating but is much less clear for cooling energy savings. Heating energy savings may be identified more clearly in the relationship with outdoor temperatures as the temperature difference between interior and exterior is much larger than in warmer seasons. Due to the lower indoor-outdoor temperature difference in cooling and the more variable latent load removal, the direct relationship between temperature conditions in cooling is not representative for this climate. Table 4 shows the overall energy use and estimated savings based solely on utility bill data.

Table 4. Energy Use Comparison Based on Monthly Utility Billing

Heating	11/2010 to 03/2011[A]	11/2011 to 03/2012[B]	11/2012 to 03/2013[B]
Heating Degree-Days, HDD	4301	3302	4058
Gas Use, therms	47080	25895	34358
Normalized Use, therms/HDD	10.9	7.8	8.5
Heating Savings Over Base		28%	23%
Estimated Electric for Heating, kWh	139,923	42,333	116,057
Normalized Use, kWh/HDD	33	13	29
Electric Savings Over Base		61%	12%
Combined Gas/Electric Heating Savings Over Base[C]		31%	22%

Cooling	05/2011 to 09/2011A	05/2012 to 09/2012A	05/2013 to 09/2013B
Net Cooling Electricity Use, kWh	328,944	341,784	307,583

[A] Pre-window retrofit.
[B] Post-window retrofit.
[C] Calculated using a site conversion to Btu and normalizing with HDD

Conclusions

The energy efficiency upgrade of low-e window retrofit panels at the 400 Market St. office tower has demonstrated significant energy savings when evaluating office spaces directly influenced by the window upgrades. Heating energy reductions of between 40% and 60% were measured in perimeter offices, with the largest benefit occurring in offices with less direct solar gains (such as the north orientation). Cooling energy savings ranged from less than 10% to over 35%, with higher energy savings in the offices more influenced by solar gains.

Window interior surface temperatures were found to be far less variable following the installation of the retrofit panels, with diurnal variations only about 4°F for the retrofit panel and nearly 20°F for the original window in the north orientation. When exposed to direct solar gain in the summer, the maximum interior glass temperature was reduced by more than 20°F for the retrofit panel office. The reduced daily temperature swing and extremes are expected to result in a higher level of comfort for personnel working near window areas. This benefit is anticipated for all window orientations.

In addition to energy savings and comfort enhancement, room light levels were found to be very similar or slightly higher for the low-e retrofit panel offices than the original single-pane clear glazing with solar control film.

Peak electricity demand, based on utility bill reporting, appears to remain the same for the whole building for pre- and post-retrofit periods, although significant reductions in cooling demand was observed in the east-facing perimeter office.

An initial utility bill analysis, which includes all building office space, indicates that gas savings resulted in about 25% gas use reduction and generally the same for the electricity used for heating. Cooling energy savings from utility bills is much less clear given the effects of occupancy and weather variables of direct solar gains, and latent loads. Analysis of ongoing utility costs and a review of the heating and cooling equipment operation with building engineers is recommended to fully understand the benefits of the window upgrades.

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Appendix D

Performance Comparison of a Low-E Retrofit Window
at the Kevon Office Building

Performance Comparison of a Low-E Retrofit Window at the Kevon Office Building

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Funded by U.S. Department of Energy
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NOVEMBER 2013

Report # 3323.001_11132013

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Figure 1. Office Building Upgraded with Low-E Window Retrofit Panels

Background

Controlling rising energy costs in older multistory office buildings can take various pathways such as envelope or equipment improvements. Equipment upgrades, such as the use of high efficiency motors or boilers can result in reduced energy costs. However, for older building envelopes with lower wall insulation levels and lower performance windows with high U-factors, the efficiency gains from equipment improvements may be hindered. While the equipment may be more efficient, the discomfort of the occupants in inefficient buildings often leads to increased energy use (e.g., supplemental heaters are used in office spaces near windows). Furthermore, the equipment upgrades in older buildings must be sized to service the same loads whereas in more efficient envelopes, the equipment upgrades can be sized smaller thus saving upfront costs as well as ongoing fuel costs.

Envelope upgrades; however, can be very expensive for building owners. Envelope upgrade costs may include not only the installation of new materials, but also include removal and disposal of old materials, displacement of occupants during renovations, and modification of office sizes and floor space.

Addressing these concerns for envelope upgrades, an innovative retrofit window technology has been installed to decrease the window U-factor and add a low emissivity (low-E) coating. The window retrofit was performed on The Kevon Center located on McClellan Ave in Pennsauken, NJ. The project structure is a four-story office building built in 1970, and comprises 100,000-square-feet of offices. It features 651 windows that cover 19,000 square feet. Prior to this retrofit, the only window alteration which had been performed was the addition of a window film on the interior surface. The window retrofits are performed such that occupants are not required to vacate office space and no existing materials other than the existing window film requires disposal.

The purpose for the window upgrade was to reduce operating energy costs; increase the comfort of the occupants, especially those located near windows; and provide a more uniform interior temperature, less affected by large temperature changes at the windows. The window upgrade technology selected is a unique retrofit panel product that effectively converts the original single-pane window into a triple-pane low-E window system. Installed from the interior of the building, the Low-E Retrofit Panel is a double-pane, dual low-E coated glass panel installed on the interior of the existing window separated with a ½" gasket and held into place with an aluminum extruded frame.

The Low-E Retrofit Panel manufactured by JE Berkowitz, LP, is also called the Renovate system. The system features two lites of low-E glass, separated by an argon-gas-filled cavity. A spacer system hermetically seals the insulated glass unit to the interior surface of the existing glass window panel, creating a permanent, no maintenance attachment. Two variations of the Renovate system were used. The RbB Platinum Plus II is featured on all but the south facing elevation, and incorporates one solar control low-E coating contained within the insulated glass unit, and a second durable pyrolytic low-E coating on the surface facing the room. The center-of-glass U-factor of the final installed assembly (including the existing glass) is 0.15 $\text{Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}$ and the solar heat gain coefficient is 0.35. For comparison, this center-of-glass U-factor is 85 percent lower than the U-factor for the original single glazing (1.0 $\text{Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}$).

The RbB Platinum Plus II XL is featured on the south facing elevation, and incorporates a lower solar heat gain low-E coating within the insulated glass unit, and the same durable pyrolytic low-E coating on the surface facing the room. The center-of-glass U-factor of this final installed assembly (all three panes) is also 0.15 $Btu/hr \cdot ft^2 \cdot °F$, but the solar heat gain coefficient is lower at 0.27. There is a slight difference in center-of-glass visible transmittance (57% and 50%, respectively), but this difference is not noticeable, especially with the different low-E coating being behind the existing glazing.

Test and Analysis Methodology

The purpose of this study is to quantify potential improvements in thermal comfort before and after retrofit, as well as assess whether there is any significant thermal stress on the glazing. The building energy savings due to the retrofit is being measured and reported separately by CDH Energy Corporation as part of a Greater Philadelphia Innovation Cluster (GPIC) and Energy Efficient Buildings Hub project.

In order to understand the characteristics of the installed low-E window retrofit panel upgrade, two offices were instrumented with temperature sensors located in various locations in the room – on the windows surfaces and in the space between the existing and retrofit window panels. One office exposure was to the west and one was to the south (Figure 2). Each office had two sets of identical windows.

Figure 2. West and South Facing Test Offices (indicated by floor cables)

Figure 3. Test Office with One Low-E Retrofit Panel Installed (left side)

For each test office, one window was kept with the original single-pane window with an interior film and the adjacent window was retrofitted with the low-E retrofit panel (Figure 3)[1]. Prior to the installation of the low-E retrofit panel, the existing window film was removed to provide a clean surface on the existing window.

The office window pairs provide a side-by-side comparison of the window surface and room temperature and light characteristics over a six-month period from the winter solstice to the summer solstice. The temperature analysis provides a general profile of the:

- temperatures between the existing glass and the retrofit panel;
- temperature on the interior surface of the glass;
- room temperature and the radiant effect on the interior office space; and
- difference in light levels through the windows.

[1] To the left in Figure 3 is the Retrofit Panel to be installed at the test conclusion.

The temperature profile is considered a marker for comfort based on the range of interior window surface temperatures and the relative change in the radiant component of the solar energy through the window.

Additionally, the potential thermal stress experienced by the glass was examined using temperature sensors on different locations of the glass. Thermal stress can develop in glass as it is subjected to changing temperatures through the day, driven by both outside conditions and solar gains. Thermal stress occurs when there is a temperature difference between the glass center and the edge when expansion of the material is restricted. This effect can be increased by the presence of shading on the glass, leading to warmer and cooler areas. This study provides a range of temperatures across the face of the glass as an indicator only of the potential for thermal stress.

The offices and the common space outside of the offices were not occupied for the entire monitoring period.

Instrumentation and Monitoring

For each of the WEST and SOUTH facing test office thermocouples (Type-T, low mass) were installed on both windows for each office:

- Low-E Retrofit Panel Window
  - Interior surface of the existing window (two locations)
  - Air gap between the existing window and the low-E retrofit panel (two locations)
  - Exterior-facing surface of the low-E retrofit panel, facing the air gap between the retrofit panel and exiting window (two locations)
  - Interior surface of the low-E retrofit panel facing the room (six locations)
- Existing single-pane glazing with Solar Control Film
  - Interior surface of the existing window (six locations)
- Radiant temperature globe in direct proximity to each window
- Solar radiation sensor (pyranometer) in direct proximity to each window
- Room temperature

Figure 4. Temperature Sensor Locations

The temperatures of six different locations on each window interior surface facing the room were measured. The layouts of the sensors are shown in Figure 5 and Figure 6.

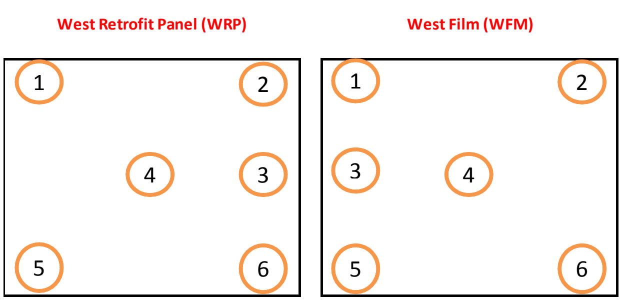

Figure 5. Interior Glass Temperature Sensors – West Facing Office

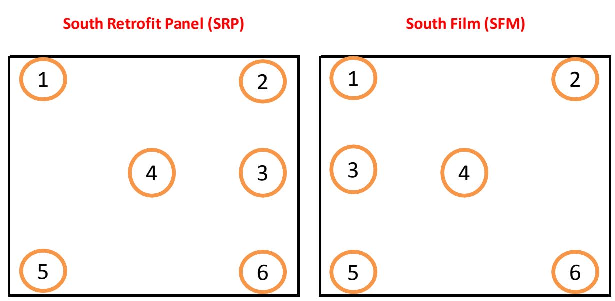

Figure 6. Interior Glass Temperature Sensors – South Facing Office

For those sensors located between the retrofit panel and the existing window, Figure 7 diagrams the sensor locations relative to the room in section and Figure 8 diagrams the sensor location in a planar view across the surfaces.

A programmable data logging system was used to record the sensors. The data logger recorded measurements every five seconds and averaged measurements over 15-minute periods.

Solar radiation levels were recorded using an Apogee silicon pyranometer sensor used to measure the solar radiation level through the window. Differences in solar radiation levels through the windows are based on the glazing coatings and films were intended to provide a qualitative, rather than quantitative, comparison between the adjacent test offices. The pyranometers were located in a horizontal position within approximately one foot from the window center to minimize the effects from the adjacent window (see Figure 3 for representative location).

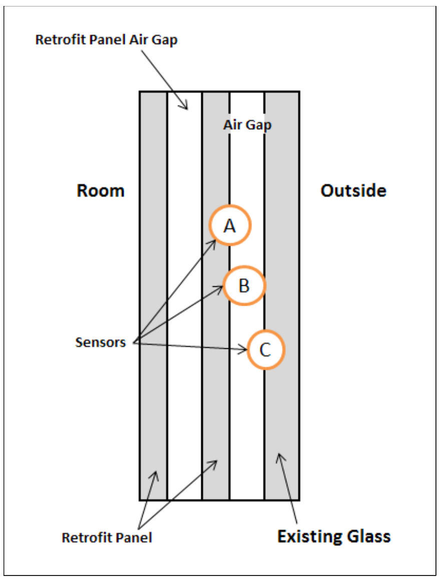

Figure 7. Planar View of Gap Sensors

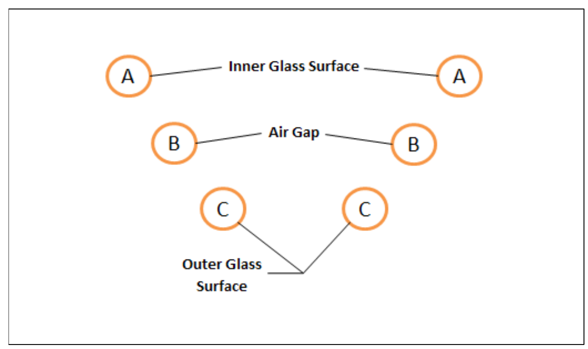

Figure 8. Section View of Gap Sensors

Monitoring Results

The temperature data presented in subsections below is based on the comparison between windows in each office. The data is analyzed to compare primarily, the temperature characteristics between windows in each office and secondarily to compare windows between office orientations. Nomenclature for the charts refer to four windows as:

- West Retrofit Panel (WRP)
- West Film (WFM), original window
- South Retrofit Panel (SRP)
- South Film (SFM), original window

Interior Glass Surface Temperatures

For the WEST office, Figure 9 and Figure 10 demonstrate the diurnal cycle and the range of temperatures on a daily basis and the change from the winter to the warmer periods. The detail data show the range of temperature changes that can be expected on the inside surface of the window facing the room. Figure 11 shows the maximum temperature at each sensor location over the monitoring period. Comparing the Retrofit Panel (WRP) with the original single pane with film (WFM), it is clear that the maximum surface temperature of the retrofit panel is over 20°F less than the maximum for the original windows. The overall average surface temperature of both windows over the monitoring period (Figure 12) is closer, with the retrofit panel averaging 5°F warmer than the original windows. For the minimum interior glass surface (Figure 13), the original single-pane windows have minimum temperatures at least 18°F colder than the low-E retrofit panel.

Finally for the WEST orientation, Figure 14 plots the daily average, maximum, and minimum temperature across the interior surface (average of all sensor locations). The daily data for the WEST facing windows highlights that the low-E retrofit panel provides a much more narrow swing in surface temperatures, and much closer average surface temperature to the room air temperature than the original windows. In essence, the low-E retrofit panel system does a superior job of moderating the environmental conditions than the original single-pane windows, by reducing heat transfer through both improved insulation (lower U-factor) and reduced solar heat gain. Results are consistent across all monitoring periods.

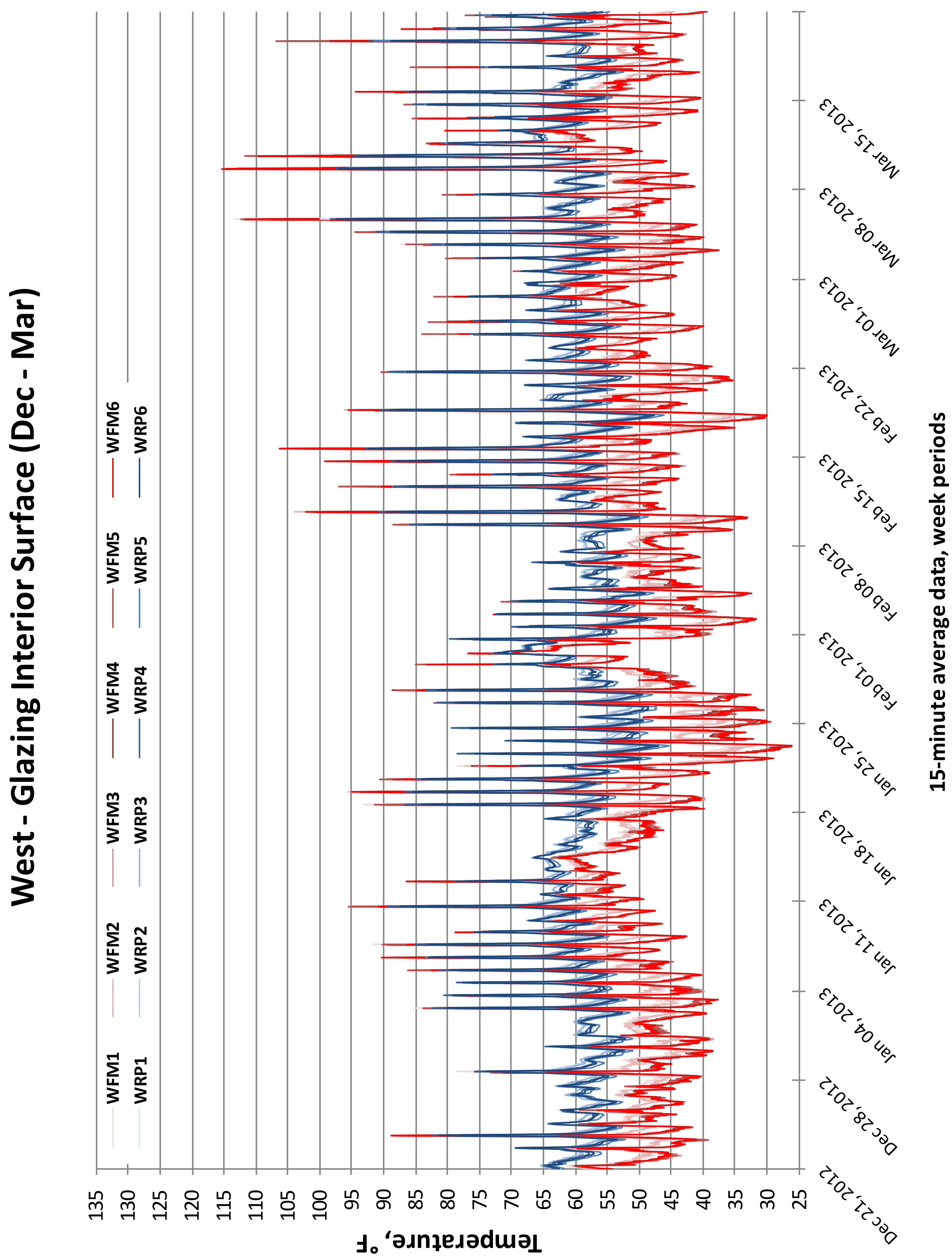

Figure 9. Window Surface Temperatures (Dec. – Mar.) – West Facing Office

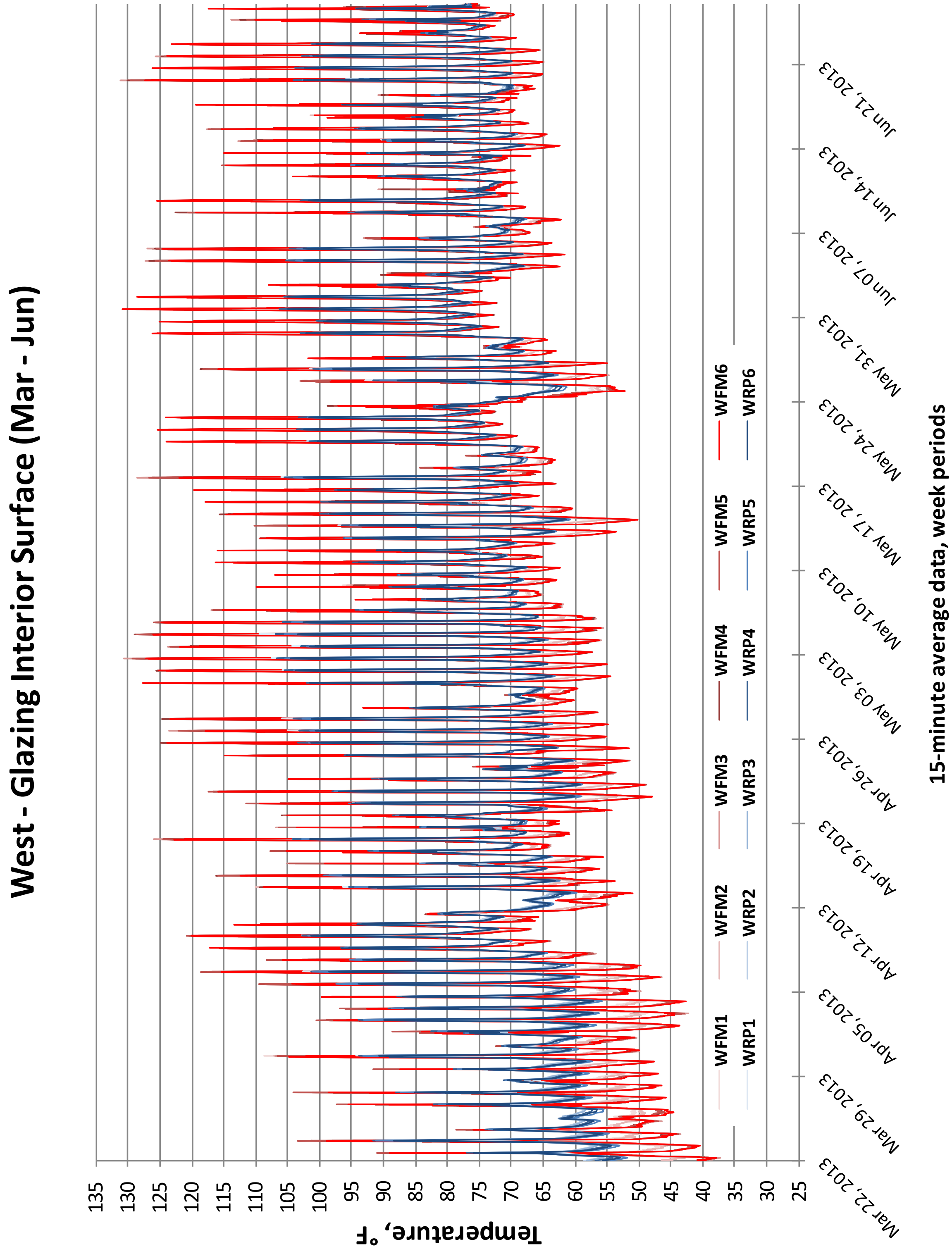

Figure 10. Window Surface Temperatures (Mar. – Jun.) – West Facing Office

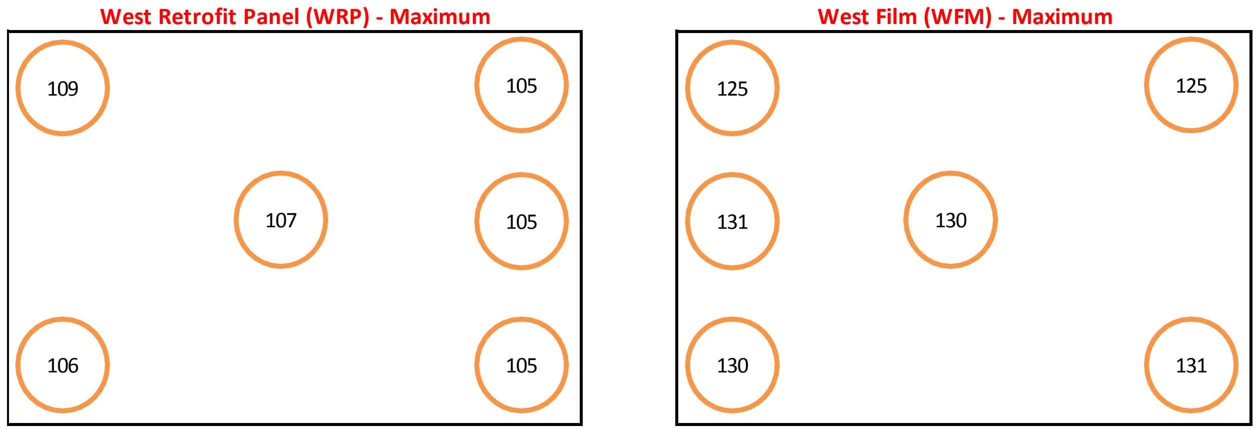

Figure 11. Maximum West Window Surface Temperature, °F

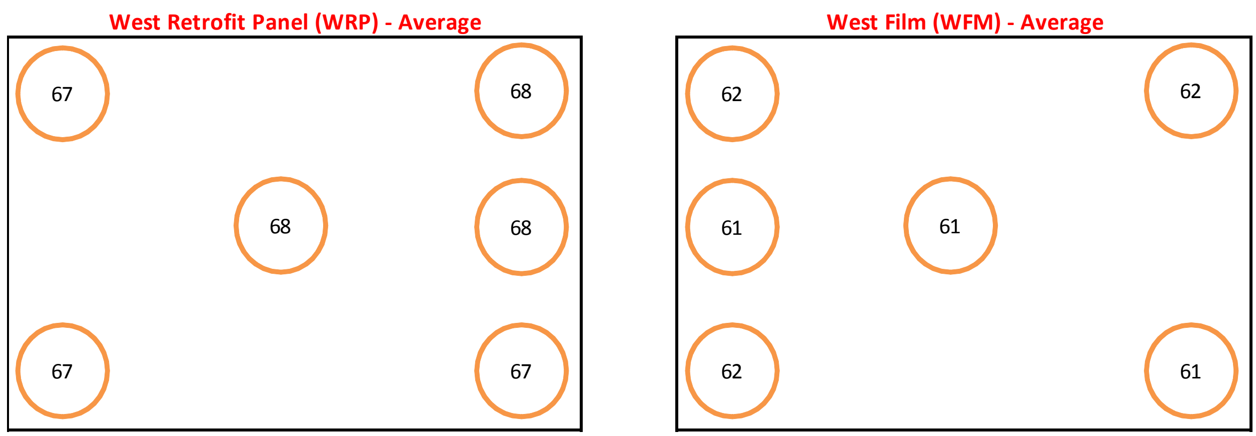

Figure 12. Average West Window Surface Temperature, °F

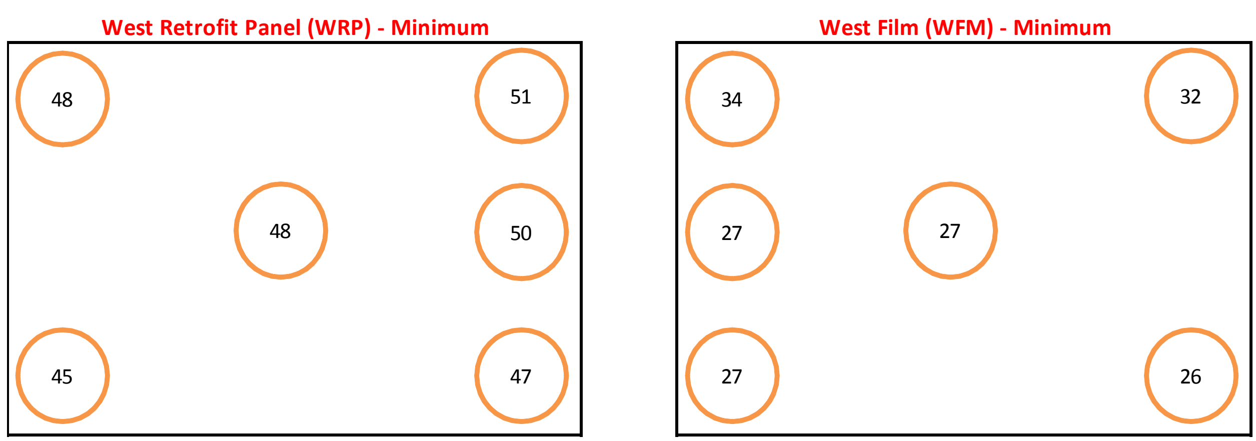

Figure 13. Minimum West Window Surface Temperature, °F

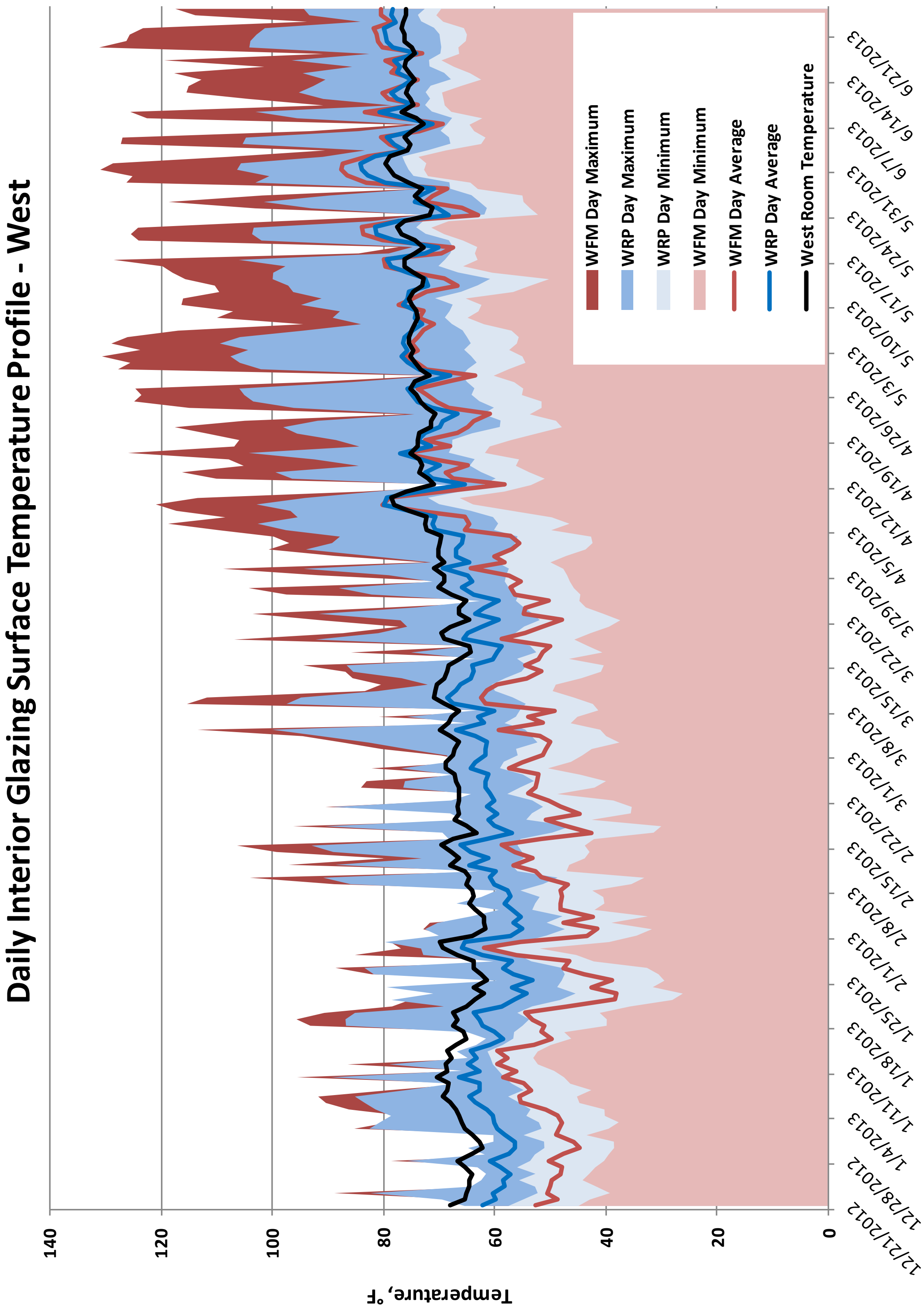

Figure 14. Daily Average Window Surface and Room Air Temperatures – West Facing Office

The SOUTH facing office demonstrates similar results as for the WEST office charts above as shown in Figure 15 through Figure 20. The sensor layout is shown in Figure 6 above. Differences between the SOUTH and WEST facing glazing consist of the evenly distributed peak temperatures across all seasons for the SOUTH window, while for the WEST glazing (and similar for the EAST), the maximum surface temperatures occur closer to the summer solstice.

Maximum temperatures for the SOUTH facing windows are lower than for the WEST facing windows but still demonstrate a similar difference between the low-E retrofit panel and the original windows. The data for the average and the minimum surface temperatures; however, are very similar between the SOUTH and WEST facing windows as would be expected since the average and minimum temperatures are less dependent on direct solar gains on the window than the maximum peak temperatures. Also note that the low-E retrofit panels on the SOUTH facing orientation have a lower solar heat gain coefficient than on the WEST orientation (center of glass SHGC 0.27 vs. 0.35).

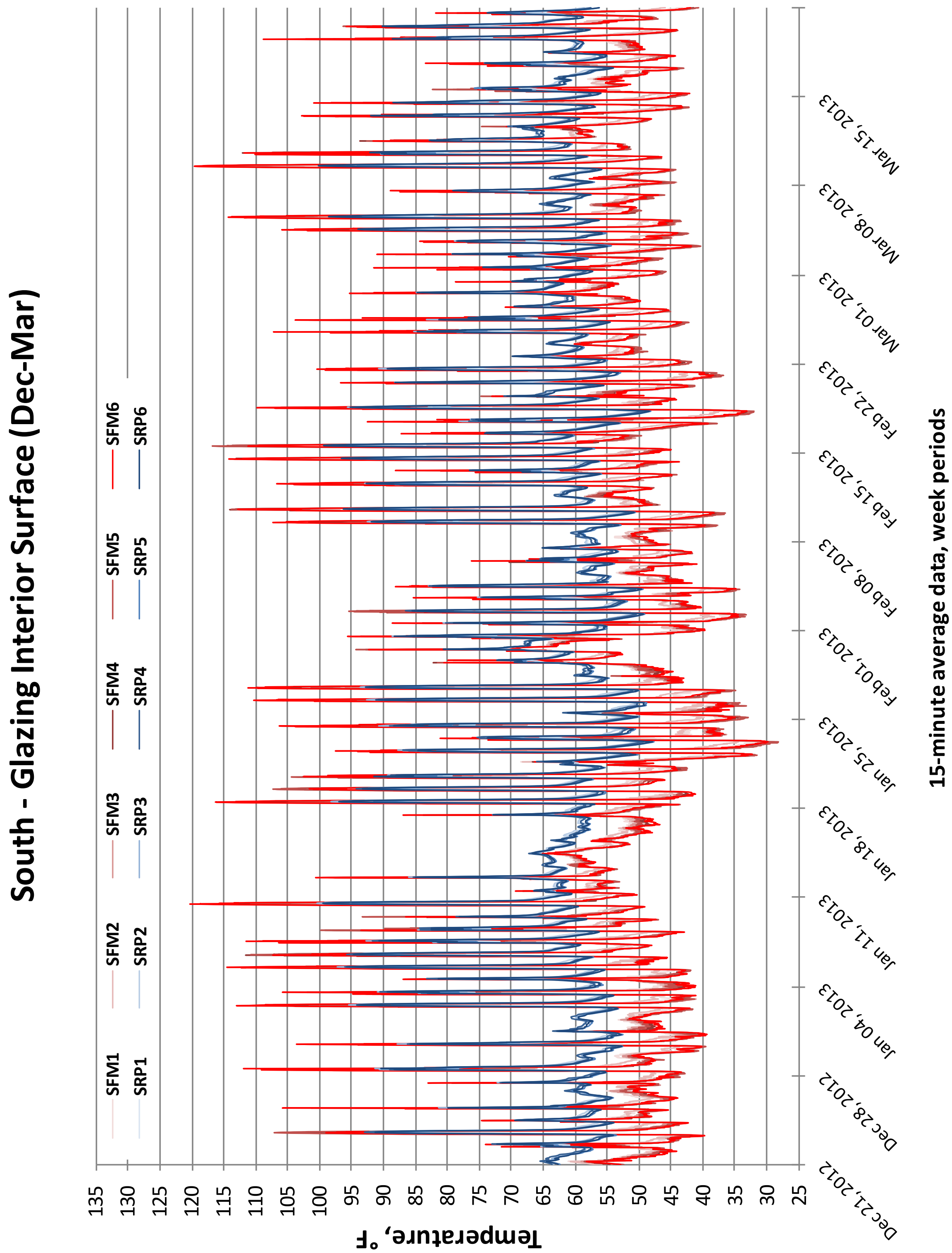

Figure 15. Window Surface Temperatures (Dec. – Mar.) – South Facing Office

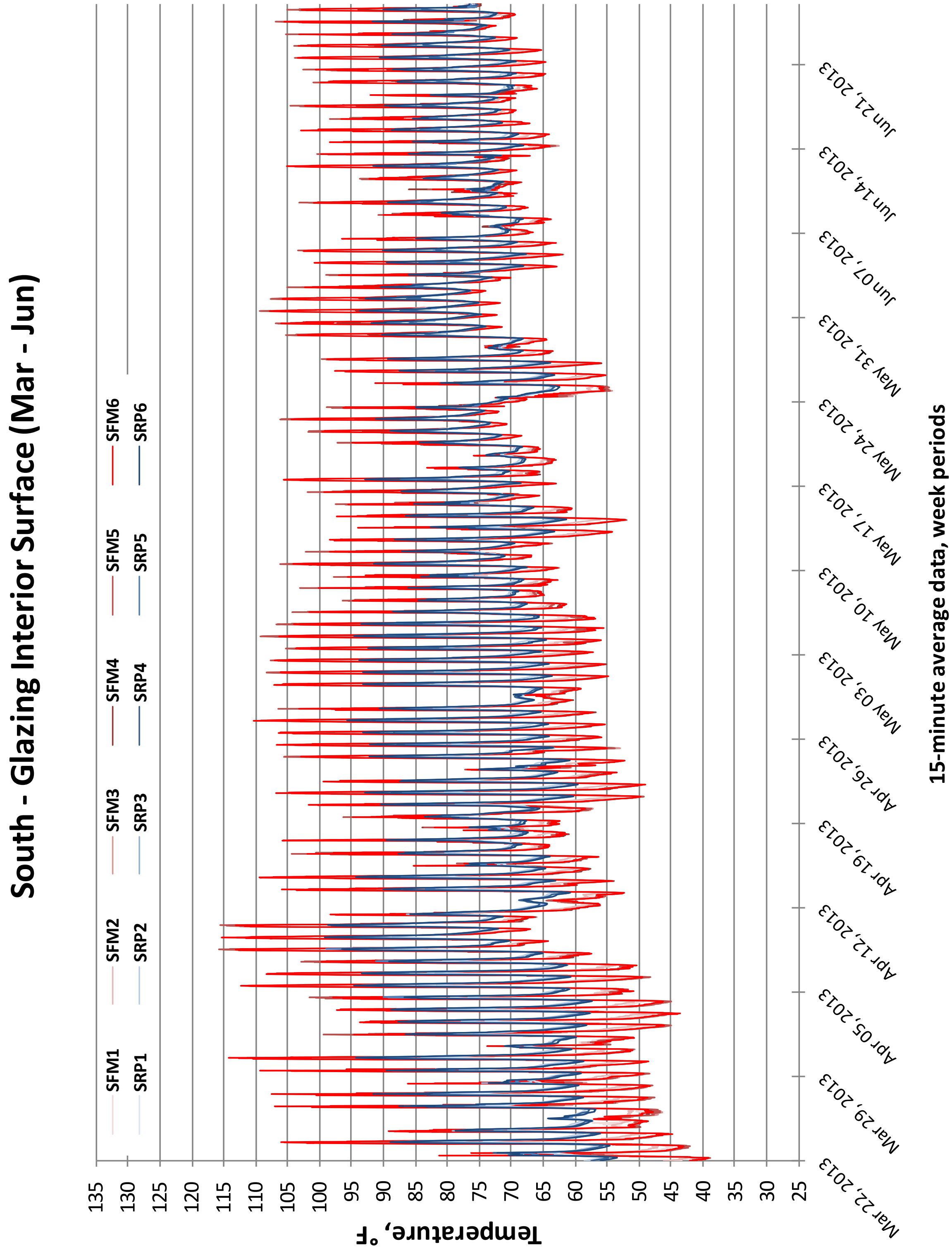

Figure 16. Window Surface Temperatures (Mar. – Jun.) – South Facing Office

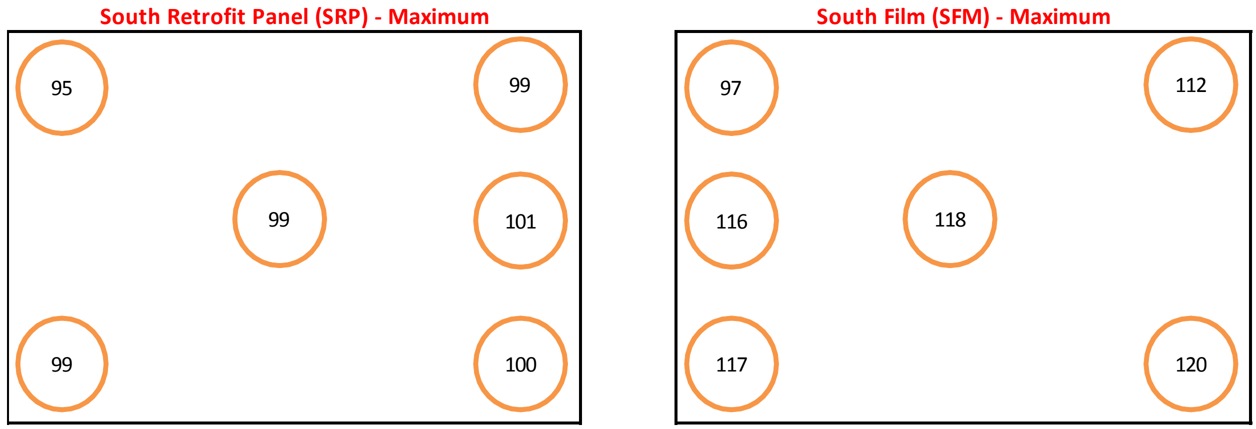

Figure 17. Maximum South Window Surface Temperature, °F

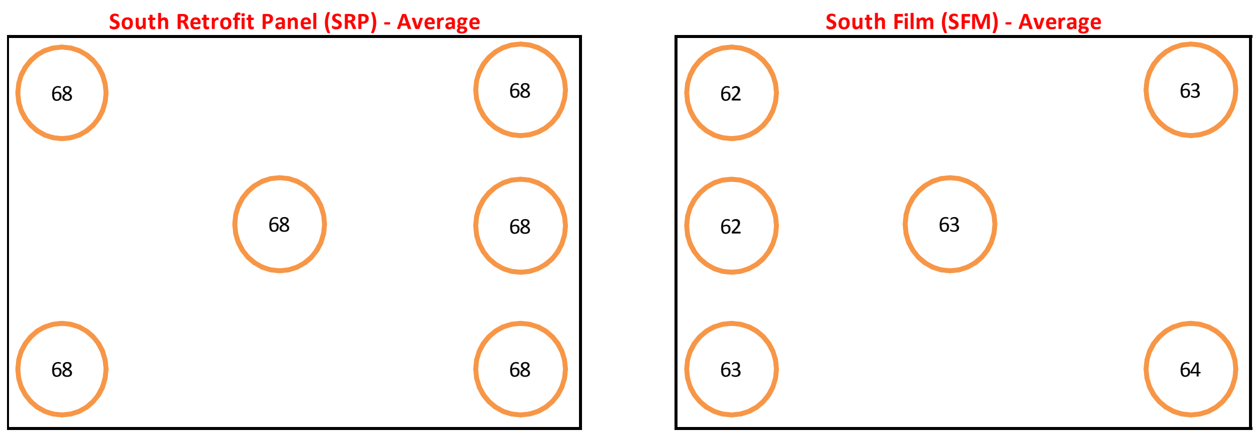

Figure 18. Average South Window Surface Temperature, °F

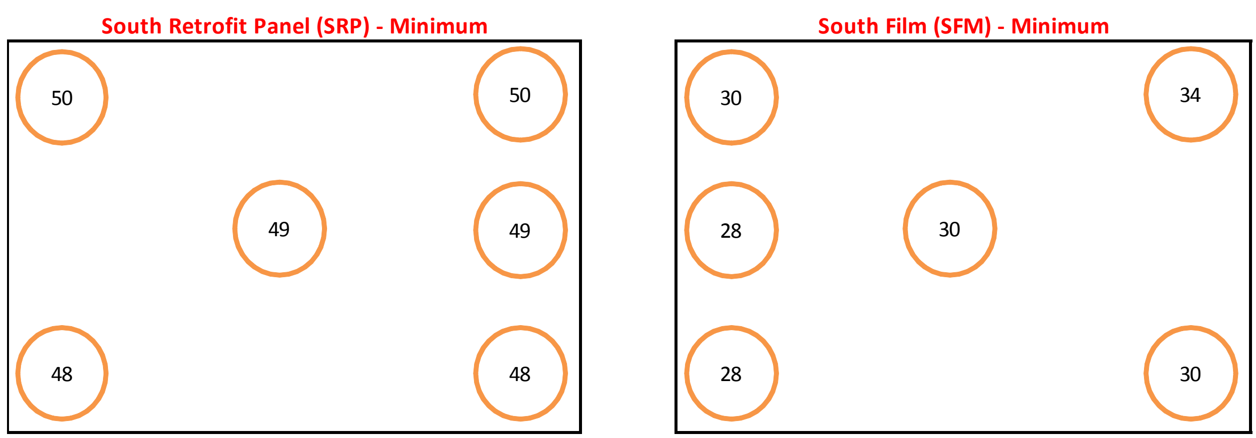

Figure 19. Minimum South Window Surface Temperature, °F

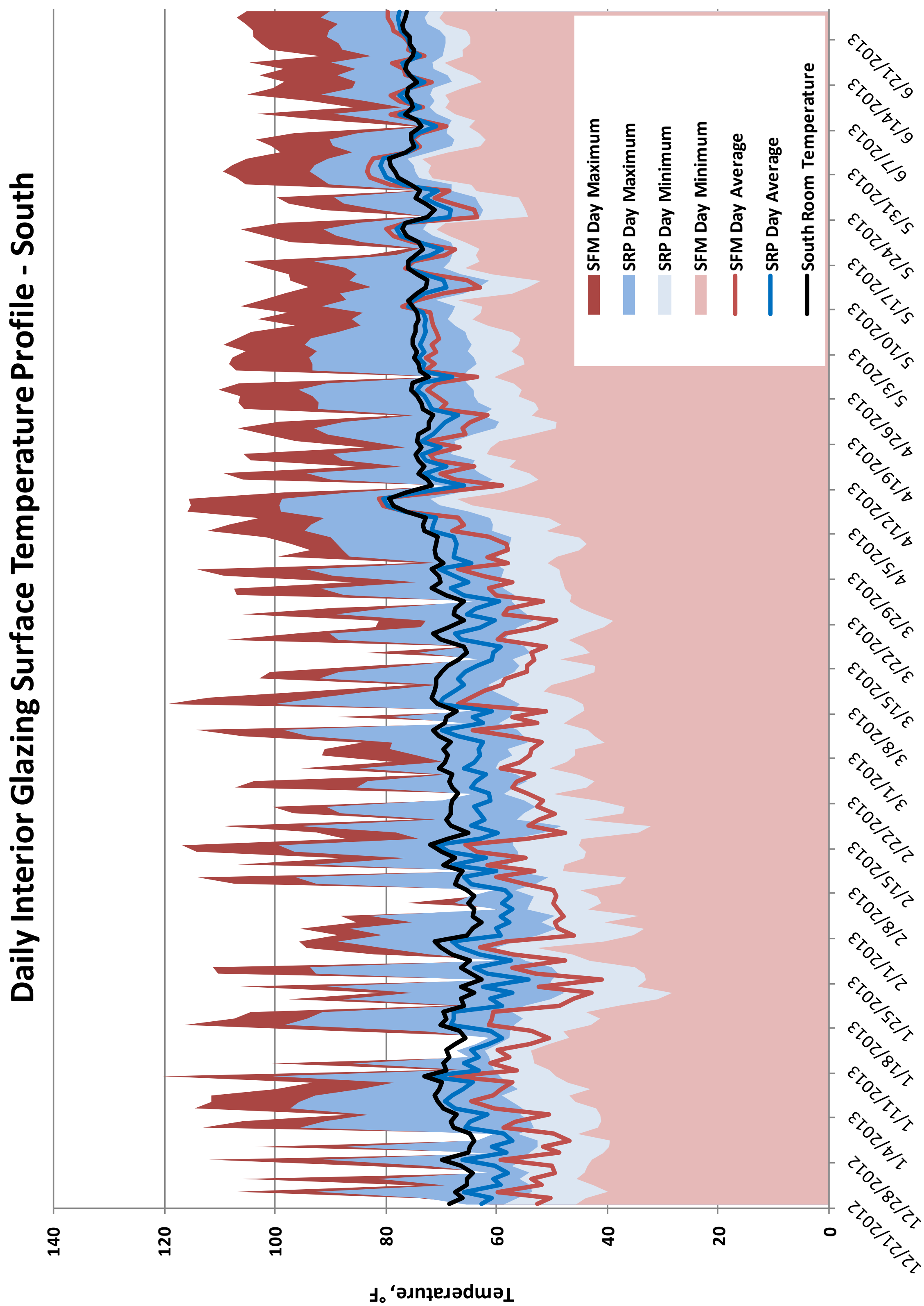

Figure 20. Daily Average and Room Air Temperatures – South Window Surface

Temperatures in Gap between Existing Window and Retrofit Panel

The temperature characteristic in the gap between the existing window and the retrofit panel is of particular interest due to the potential for heat buildup and thermal stress on the glass surfaces. This data is of course only available for the windows with the retrofit panels in the WEST and SOUTH orientations. Low mass temperature sensors (2 each) were installed on the inside surface of the existing window (C), in the air gap between the existing window and the retrofit panel (B), and on the outside surface of the retrofit panel (surface facing the gap, A – refer to Figure 7 and Figure 8 for sensor locations).

Plots of the temperatures in the gap are shown in Figure 21 for the WEST facing window and Figure 22 for the SOUTH facing window.

As expected based on the solar angles at various times of the year, the WEST facing window will have higher temperatures in the gap nearer the spring equinox to the summer solstice, and the SOUTH facing glazing will have higher temperatures nearer the winter solstice to the spring equinox.

When comparing the maximum (Figure 23), average (Figure 24), and minimum (Figure 25) temperatures in the gap between the WEST and SOUTH facing windows, it is clear that the SOUTH facing windows do not experience as high a temperature swing as with the WEST facing windows (as much as 16°F less in the SOUTH orientation). As with the inside surface temperatures, the average and minimum temperatures in each orientation are much closer due to the dilution of the solar effects across the full day cycle and when averaging over cloudy periods.

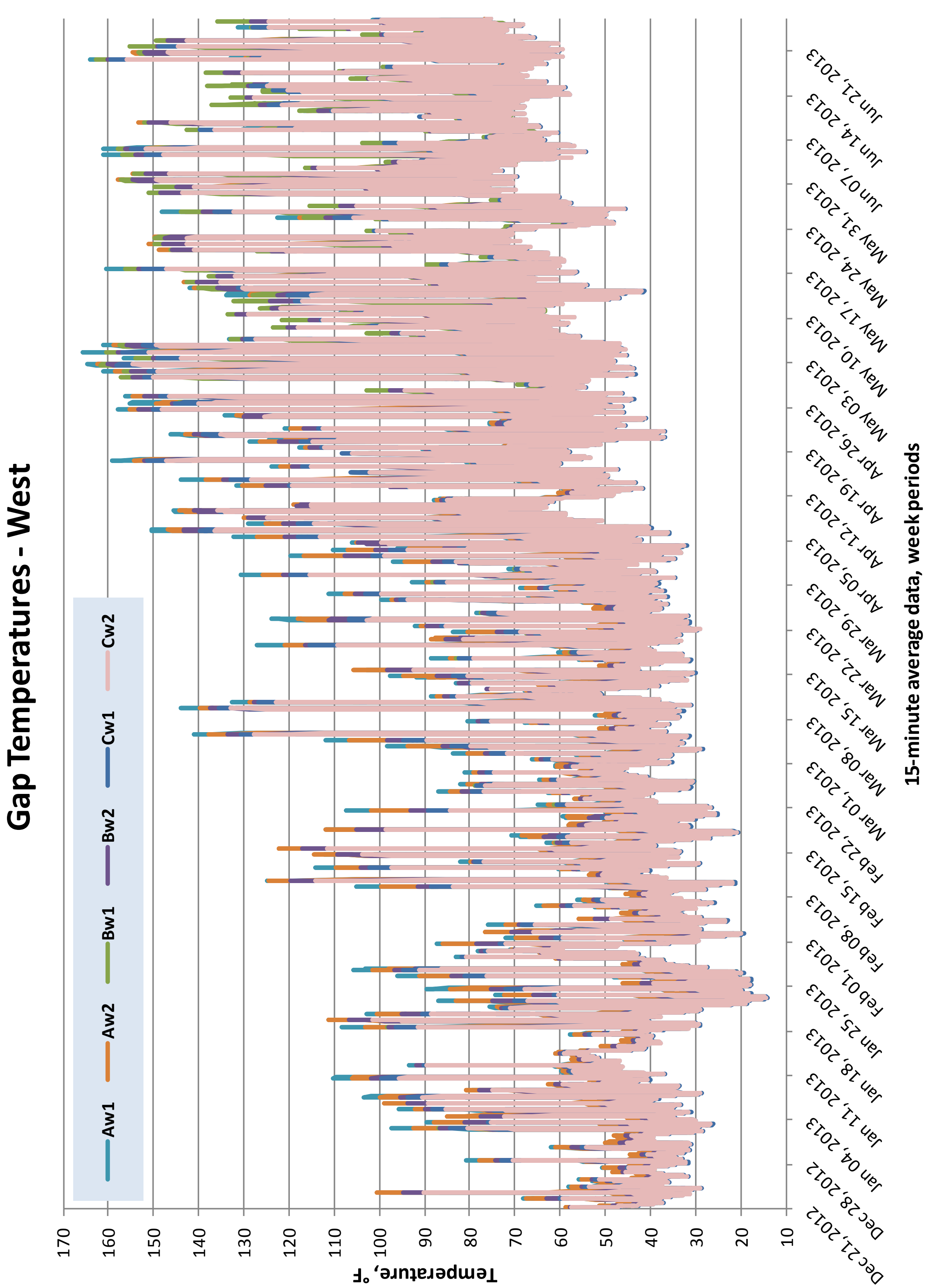

Figure 21. Gap Temperatures – West Facing Office

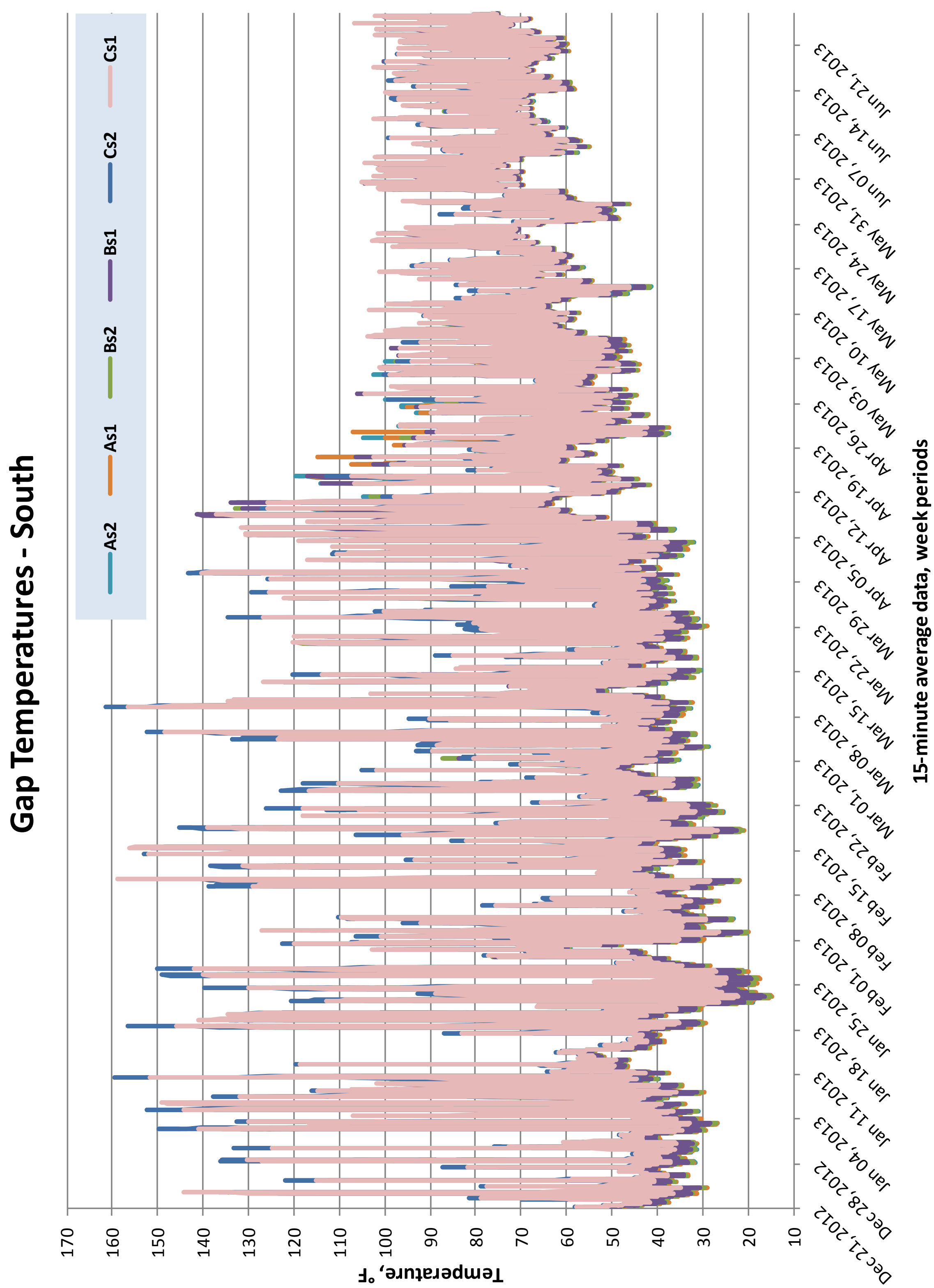

Figure 22. Gap Temperatures – South Facing Office

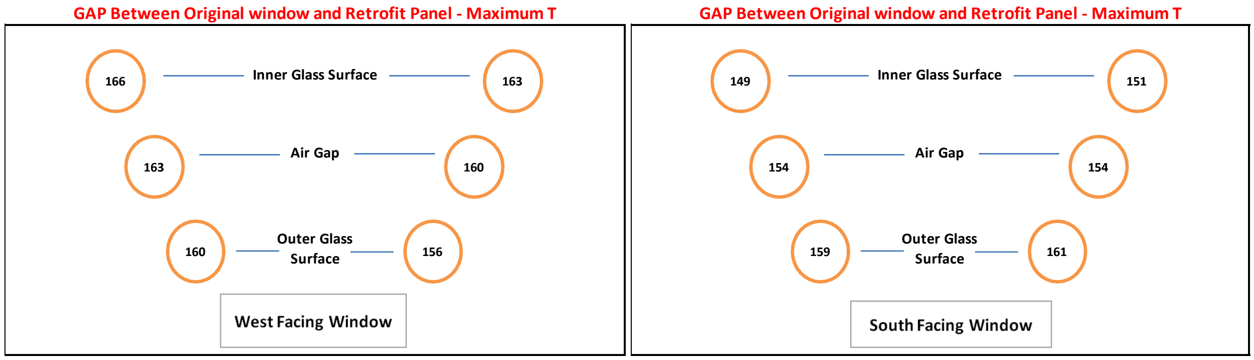

Figure 23. Maximum Gap Temperatures of Low-E Retrofit Panel Windows

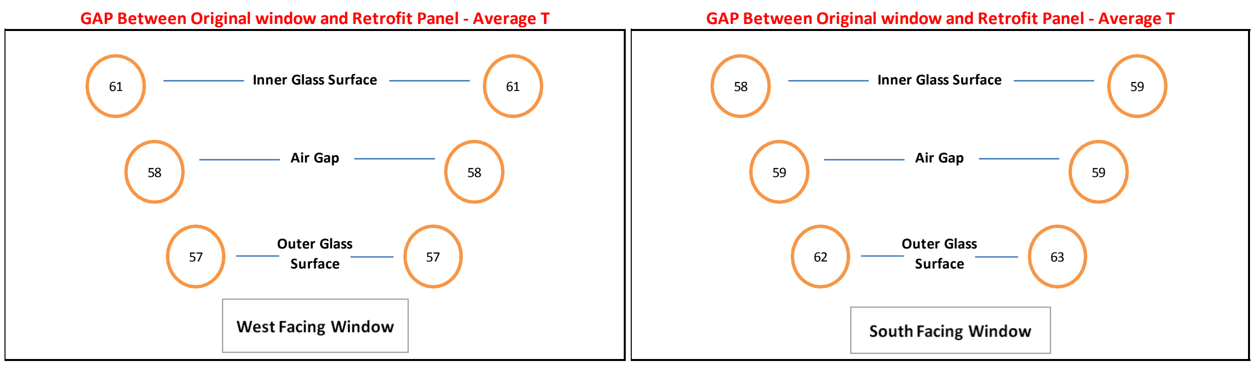

Figure 24. Average Gap Temperatures of Low-E Retrofit Panel Windows

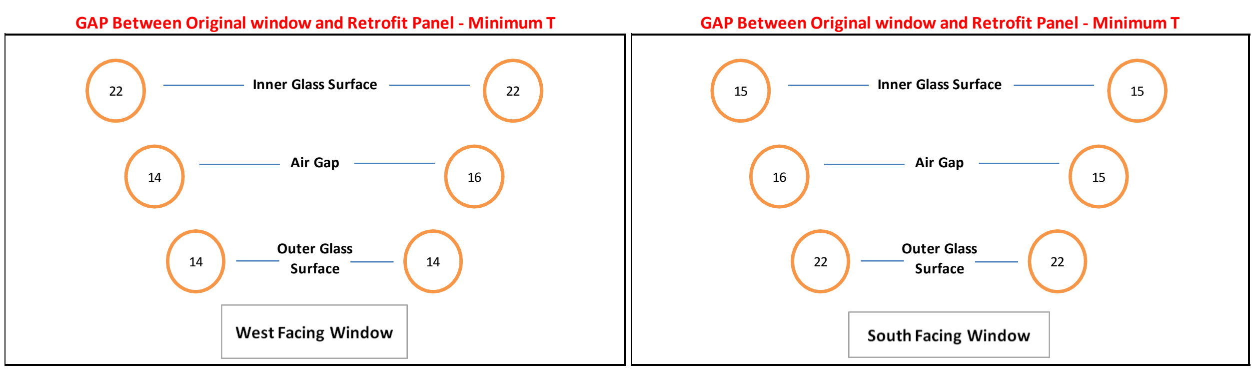

Figure 25. Minimum Gap Temperatures of Low-E Retrofit Panel Windows

In addition to the temperature change throughout the day and seasons, the temperature difference across the plane of the glass is also of interest due to the thermal stress that may be exerted on the glass when thermal expansion or contraction of the glass is restricted in the surrounding frame. The internal thermal stress may be estimated by the formula:

$$\sigma = E \cdot \varepsilon = E \cdot \alpha \cdot dt$$

where

σ = thermal stress,
E = Young's modulus,
ε = strain,
α = thermal expansion coefficient of the material, and
dt = temperature difference across two points where thermal expansion is restricted

For soda lime window glass, this ends up simply being:

σ (psi) = 50 psi/°F x dt (°F)

The mean strength of glass (average breakage point, or modulus of rupture) is typically between 7,000-18,000 psi depending on whether it is annealed, heat strengthened, or tempered. The strength also depends on the quality of the edge cut because crack propagation starts at flaws at the edge. However, average strength is not the relevant measure, as that would imply 50 percent breakage, and 8 /1000 probability of breakage is the more common metric. In practice, when the thermal stress gets above 2,000-3,000 psi, then potential breakage starts to be of concern. A common situation where maximum thermal stress typically occurs is on cold sunny days, especially if part of the glass is shaded, where the center of the glass is relatively warm, but the edges of the glass are cold from both the frame and any shading.

Figure 26 shows the temperature difference across the plane of the glass layers and the air gap for any 15-minute period. The data is sorted to show the largest difference and the duration (in hours, x-axis).

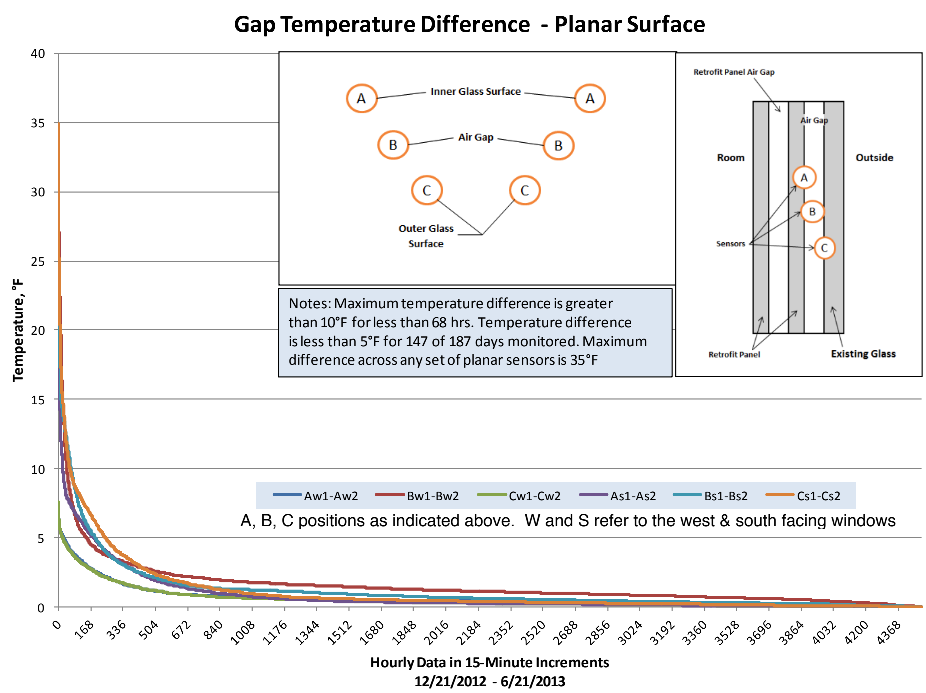

Figure 26. Planar Sensor Temperature Difference in Gap of Retrofit Panel Window

The maximum temperature difference (typically on the inside surface of the original pane, Cs1-Cs2) was only more than 10°F (500 psi) for 68 hours out of 187 days monitored, or 1.5 percent of the time. In all cases, the maximum temperature difference was no more than 35°F, or 1,750 psi. The placement of the temperature sensors may have missed some effects in the corners where the temperature difference may be more than measured here, but overall, there does not appear to be any significant concern with thermal stress when using the low-E retrofit panel. Furthermore, when comparing to similar sensor positions on the original single pane with the solar control film, there are no significant differences in the maximum surface temperature differences, and no reason to expect any difference in the potential for thermal stress breakage.

In addition to the planar temperature difference for each set of sensors, the maximum temperature difference across all positions on both sides and within the gap (censor locations A, B, and C) for all 15-minute periods, sorted by magnitude, is shown in Figure 27.

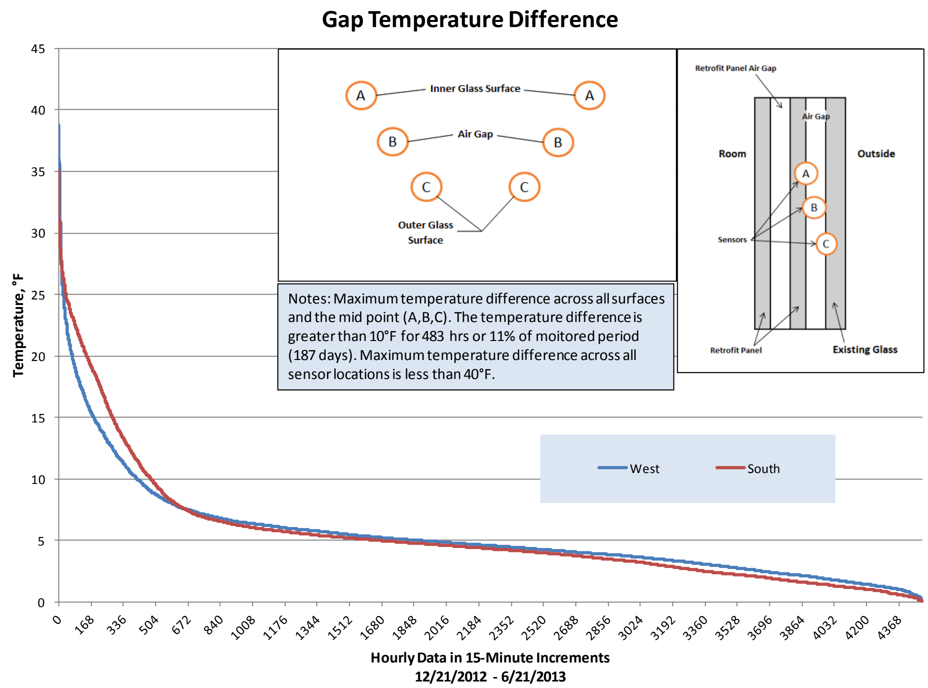

Figure 27. Maximum Temperature Difference between Gap Sensors of the Retrofit Panel Window

In all cases, there is no more than 35°F temperature difference within the gap space between the existing window and the retrofit panel during the monitoring period.

Average Temperature Profiles

Summarizing the window interior surface temperatures and the room ambient temperatures demonstrates the differences that occur when the retrofit panels are installed. The data is divided into approximately three-month periods for more clarity. Figure 28, Figure 29, Figure 30, and Figure 31 provide the average temperature detail for each orientation.

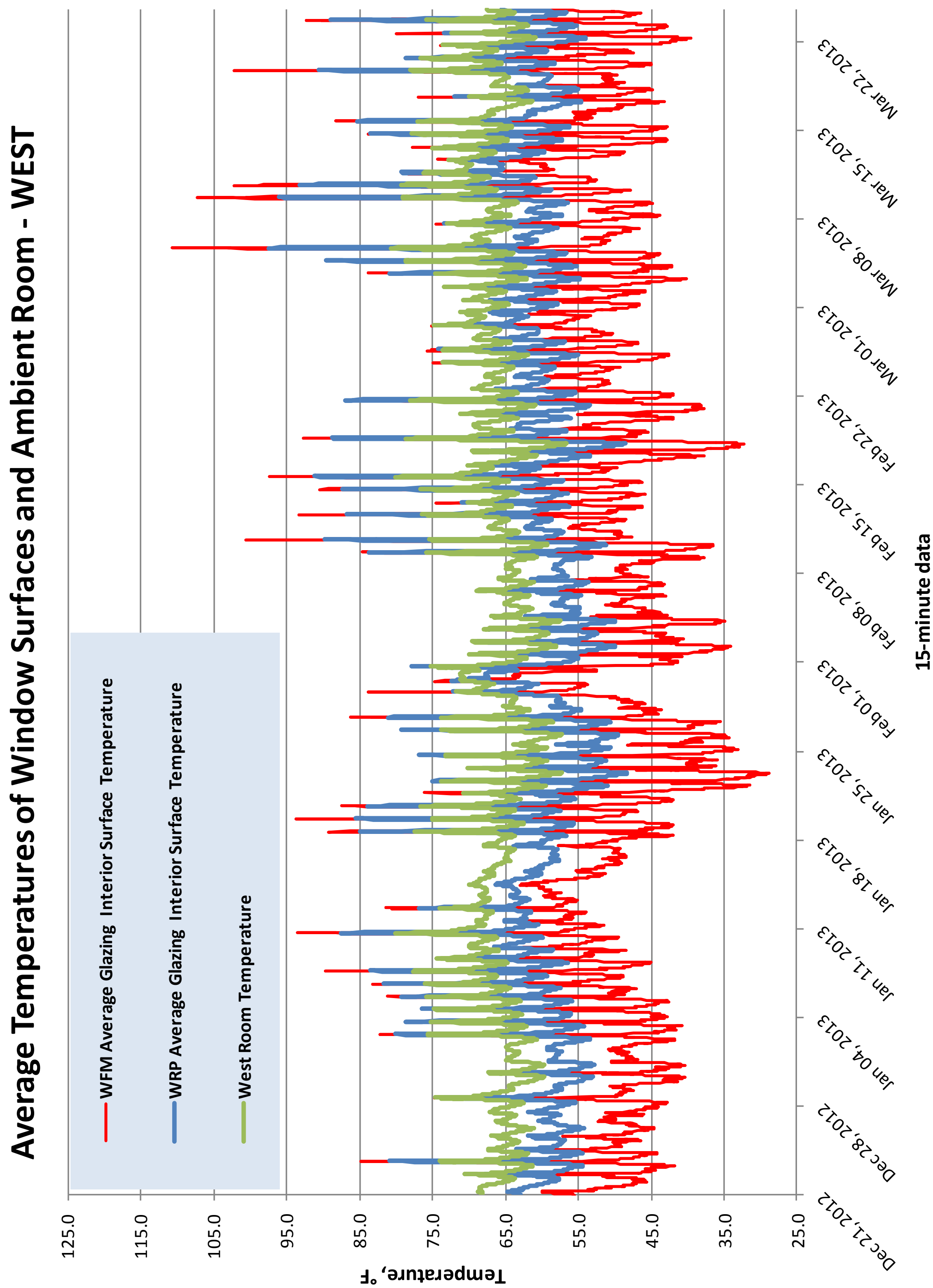

Figure 28. Average Temperatures on Interior Glass Surface (Dec. – Mar.) – West Facing Office

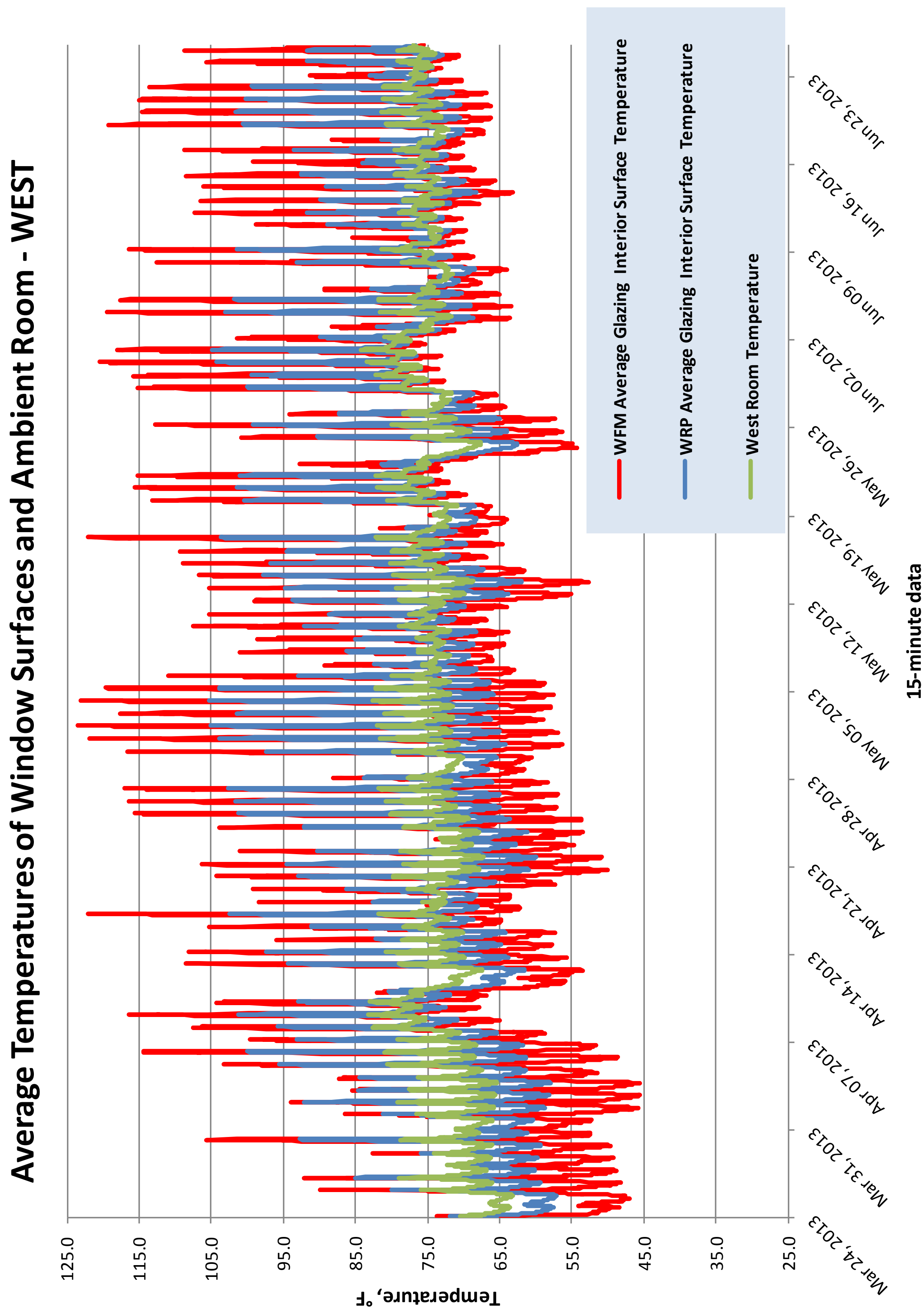

Figure 29. Average Temperatures on Interior Glass Surface (Mar. – Jun.) – West Facing Office

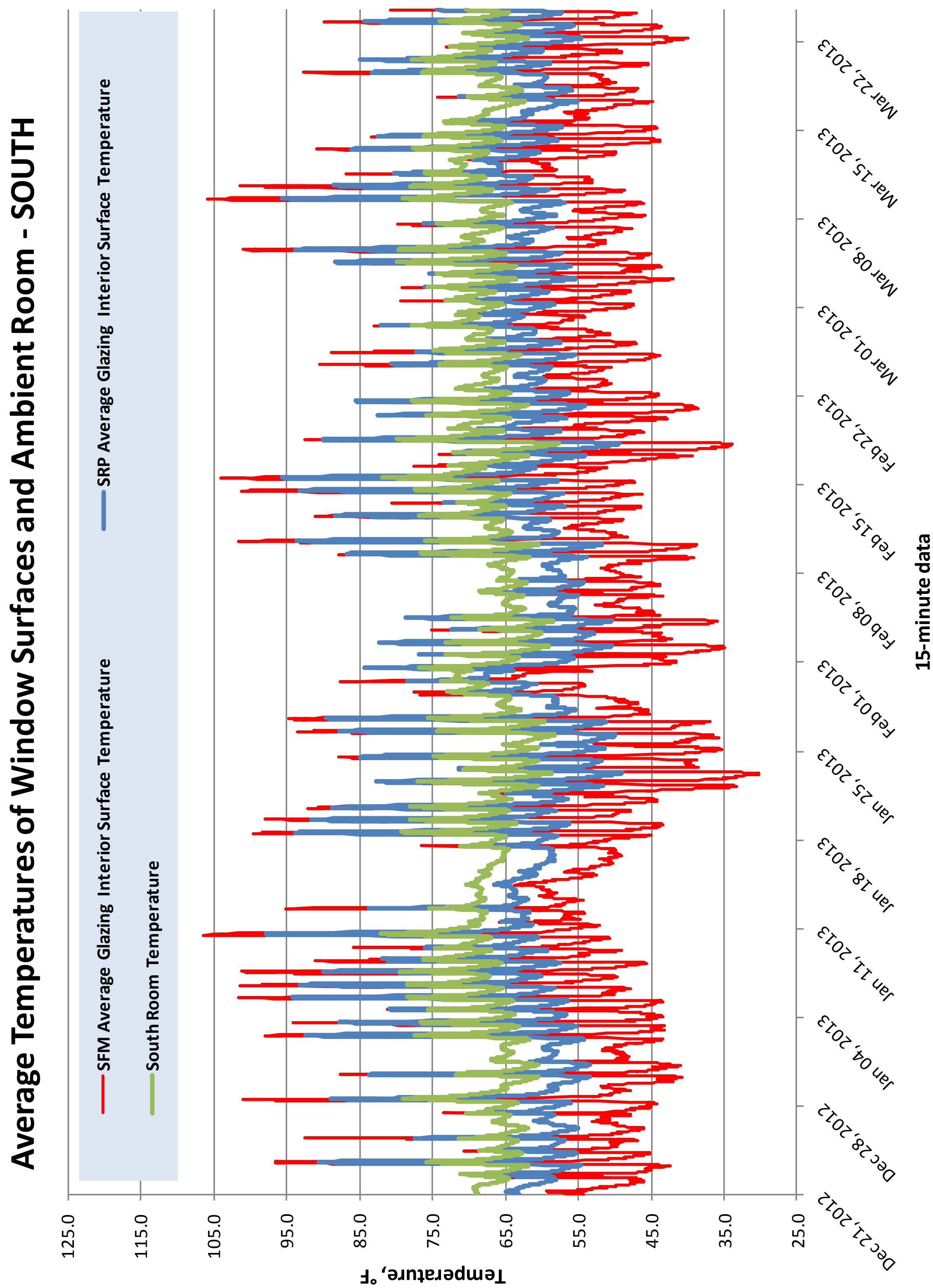

Figure 30. Average Temperatures on Interior Glass Surface (Dec. – Mar.) – South Facing Office

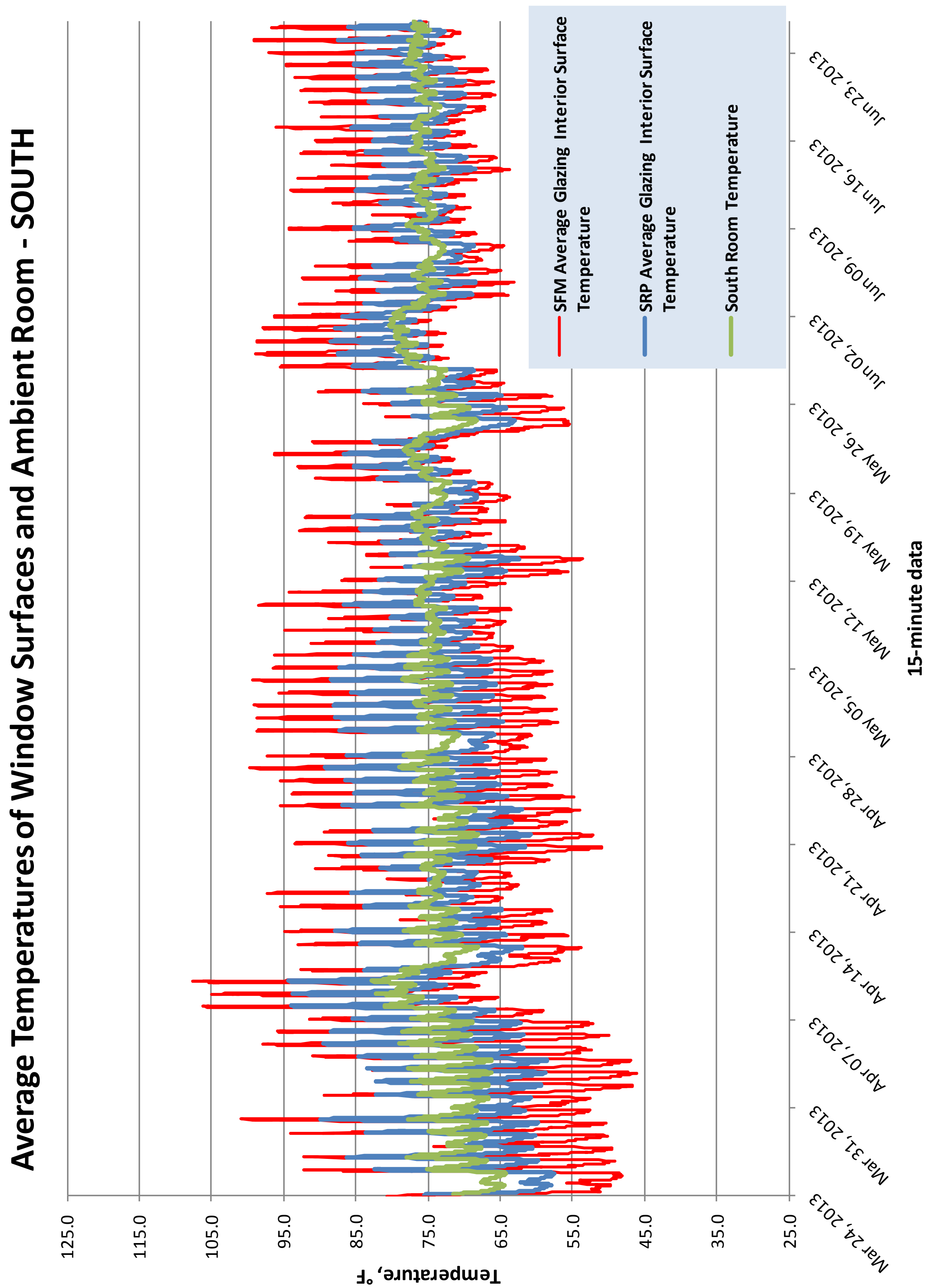

Figure 31. Average Temperatures on Interior Glass Surface (Mar. – Jun.) – South Facing Office

The summary charts showing 15-minute average temperatures demonstrate that the retrofit panel consistently results in interior glass surface temperatures that are much closer to the room temperature than the interior surface of the existing single-pane windows, warmer in the winter and cooler in the summer.

Room Temperature Profiles and Thermal Comfort

To quantify differences in thermal comfort between the low-E retrofit window and the original single-pane windows, both the mean radiant temperature and the room air temperature were measured. In this study and in a room with still air, the mean radiant temperature (a component of thermal comfort responding to radiant effects of various room surfaces) is approximated by the globe temperature. Each globe is painted black and is located in very close proximity to the window to minimize measurement effects from the adjacent window and to maximize measurement of radiant temperature asymmetry between the window and the rest of the room. In this study, the issue of occupant comfort is considered most critical when the mean radiant temperature diverges, either positive or negative, from the ambient air temperature. This is because one side of the body facing the window potentially experiences a mean radiant temperature different than the other side of the body facing the room, leading to temperature asymmetry and discomfort. Figure 32 through Figure 35 compare the room ambient temperature with the globe temperature and window average interior surface temperature for both the original window and the retrofit panel window in each orientation. The time period for each orientation is divided into three-month periods for readability.

When evaluating the temperature difference between the mean radiant temperature (assuming no air movement) and the room air temperature, it becomes clear that the colder periods demonstrate a larger divergence between the radiant and the room temperatures. A larger difference would indicate more discomfort when working within proximity of the window. Figure 36 details this phenomenon for the WEST facing office and Figure 37 for the SOUTH facing office.

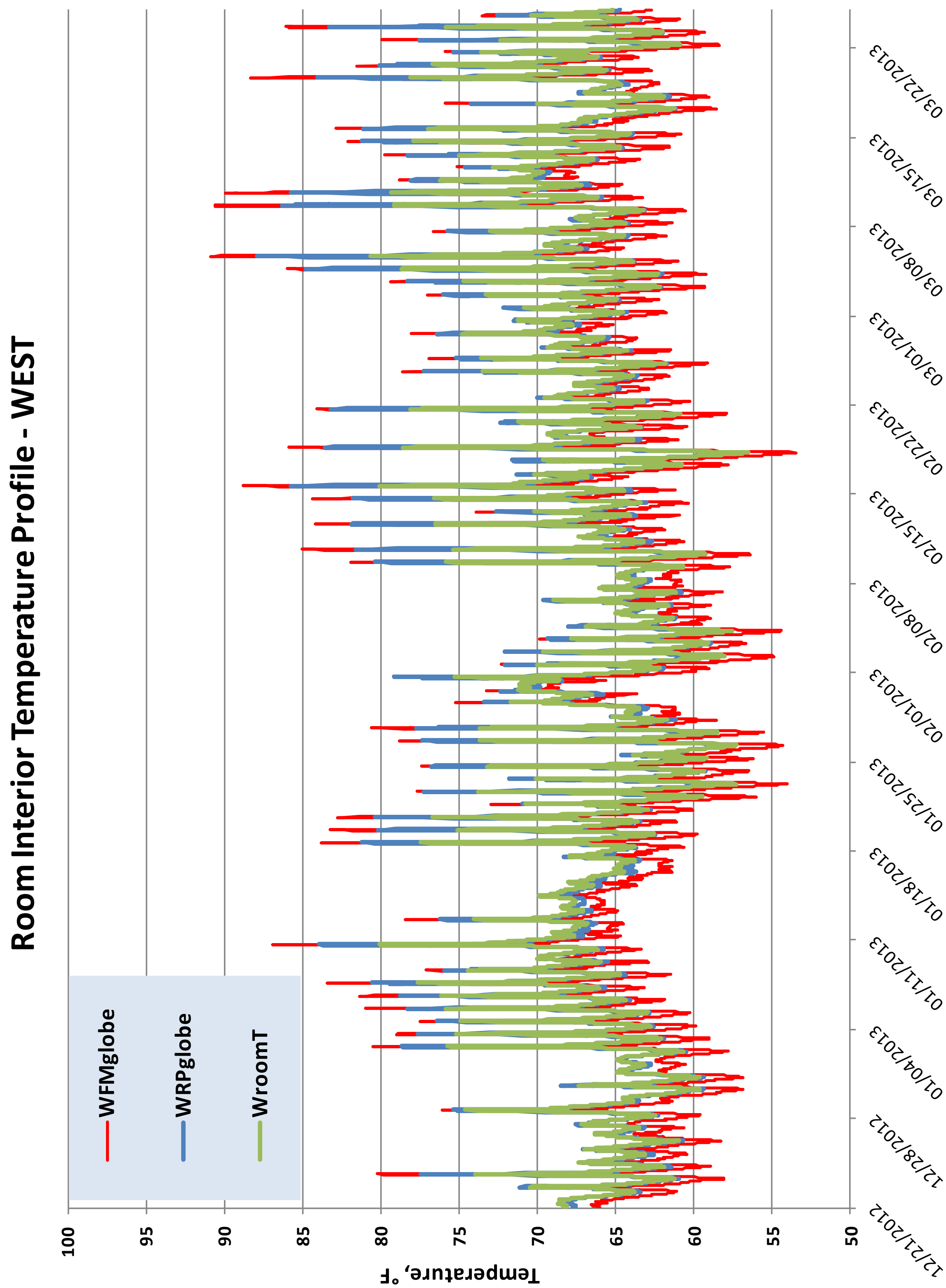

Figure 32. Interior Temperatures (Dec. – Mar.) – West Facing Office

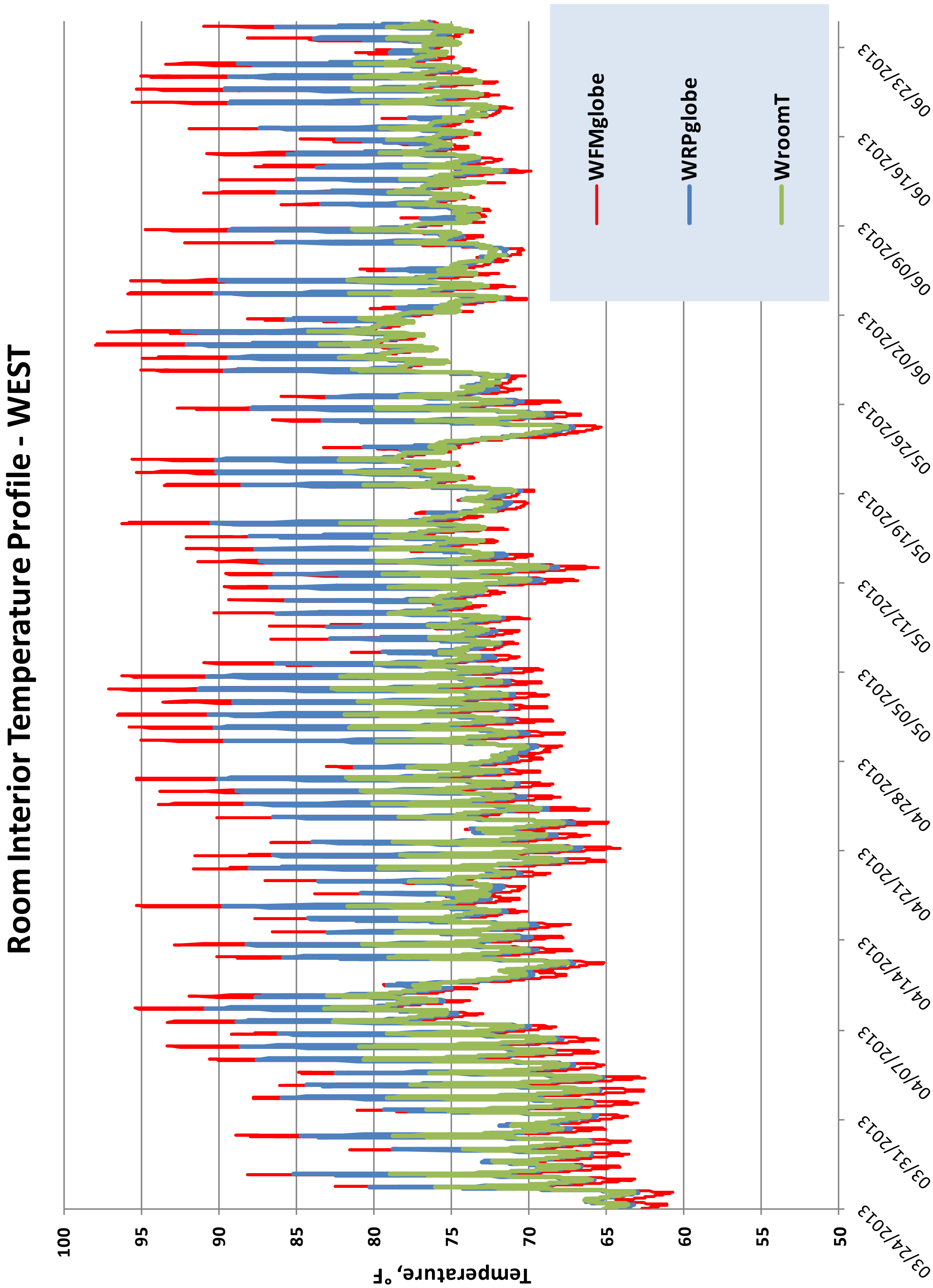

Figure 33. Interior Temperatures (Mar. – Jun.) – West Facing Office

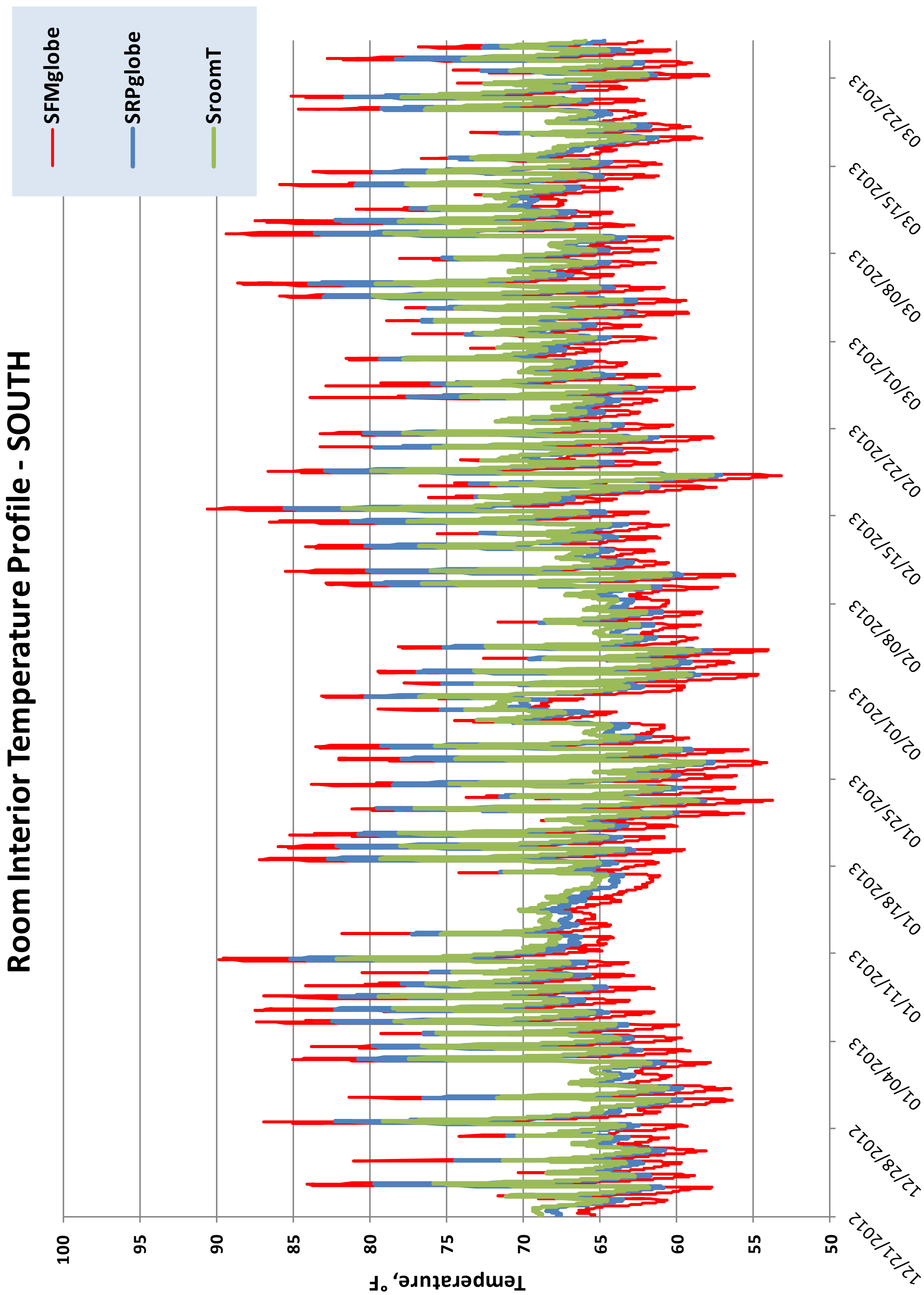

Figure 34. Interior Temperatures (Dec. – Mar.) – South Facing Office

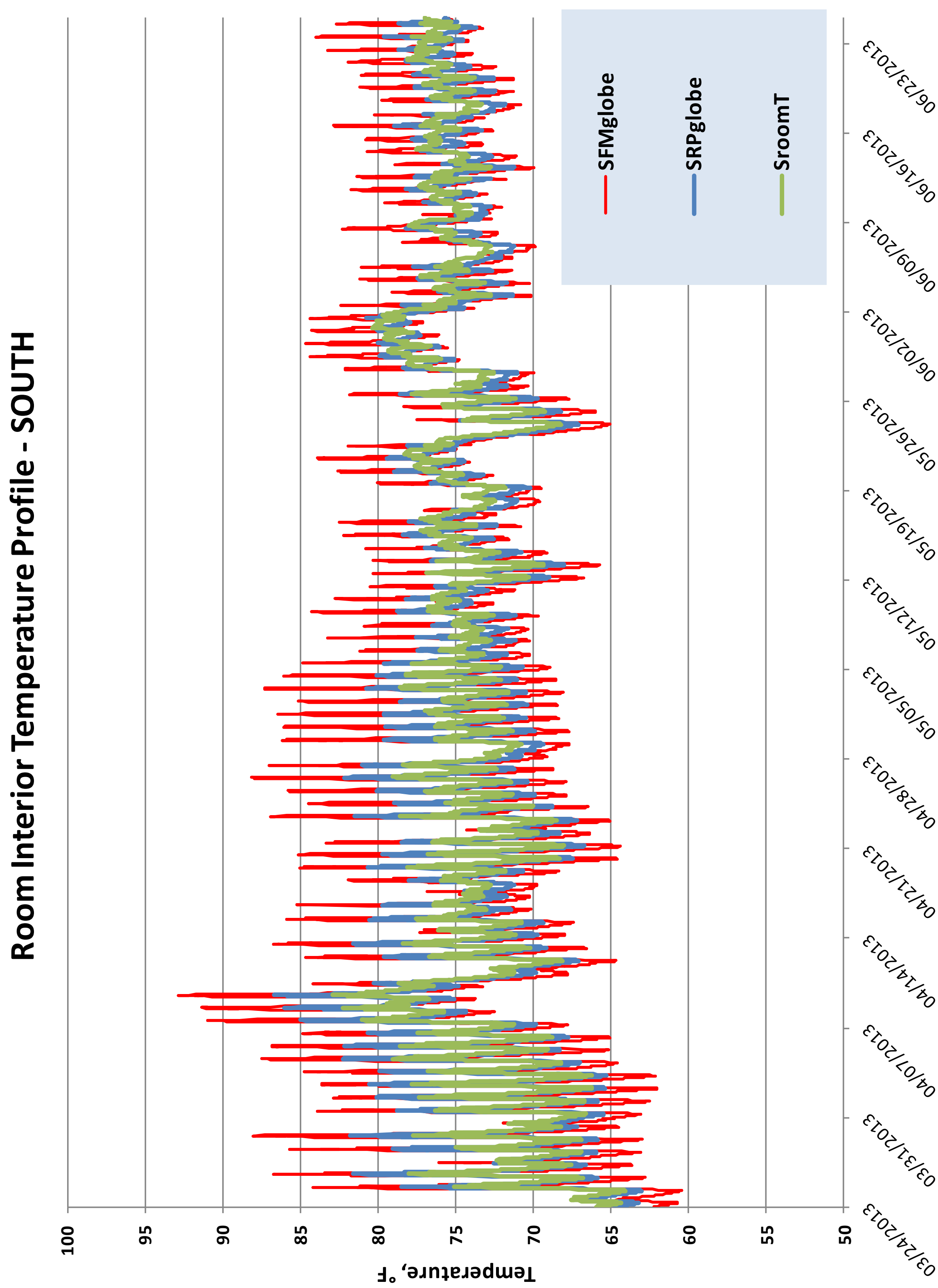

Figure 35. Interior Temperatures (Mar. – Jun.) – South Facing Office

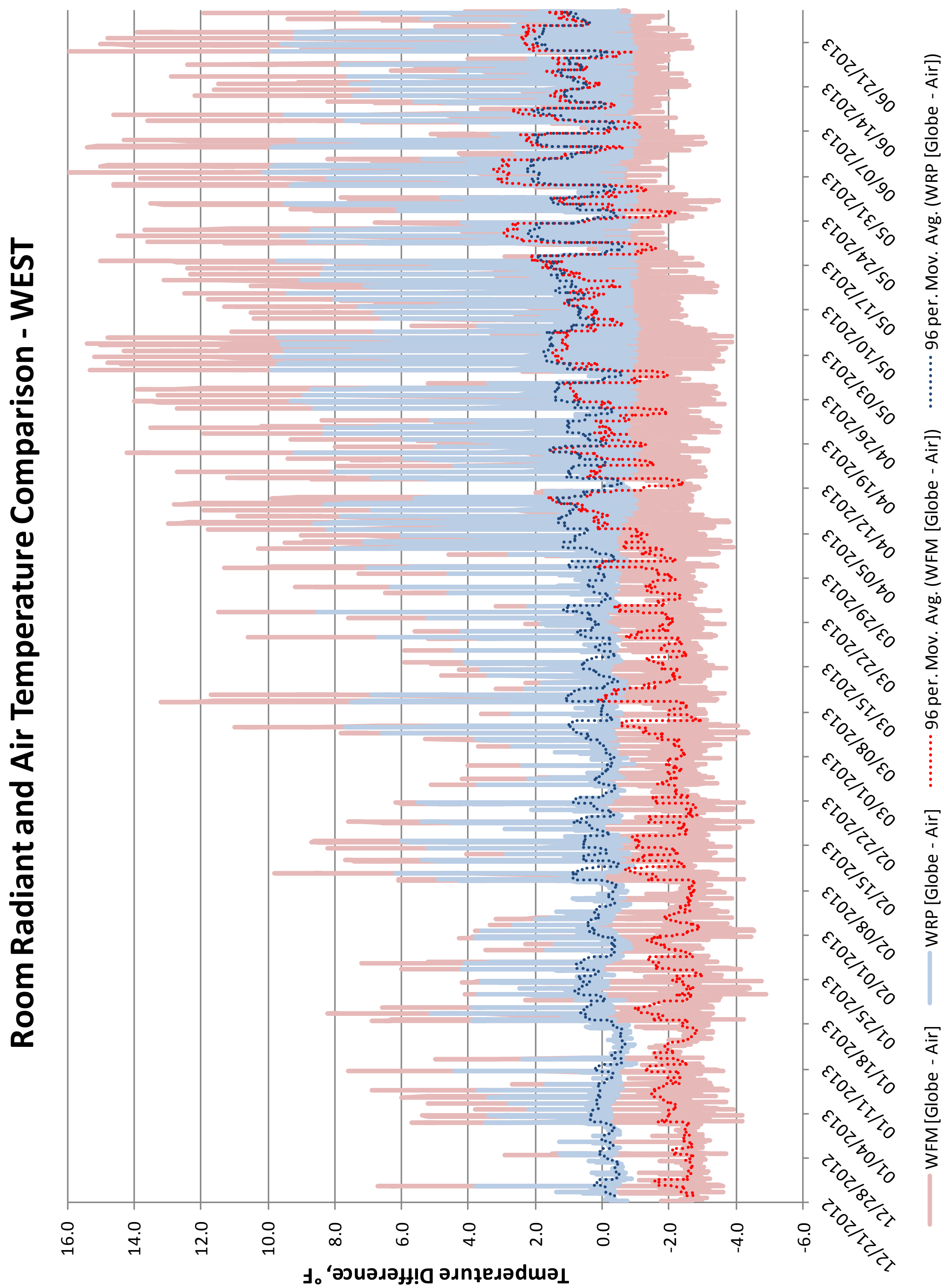

Figure 36. Radiant-Air Temperatures – West Facing Office

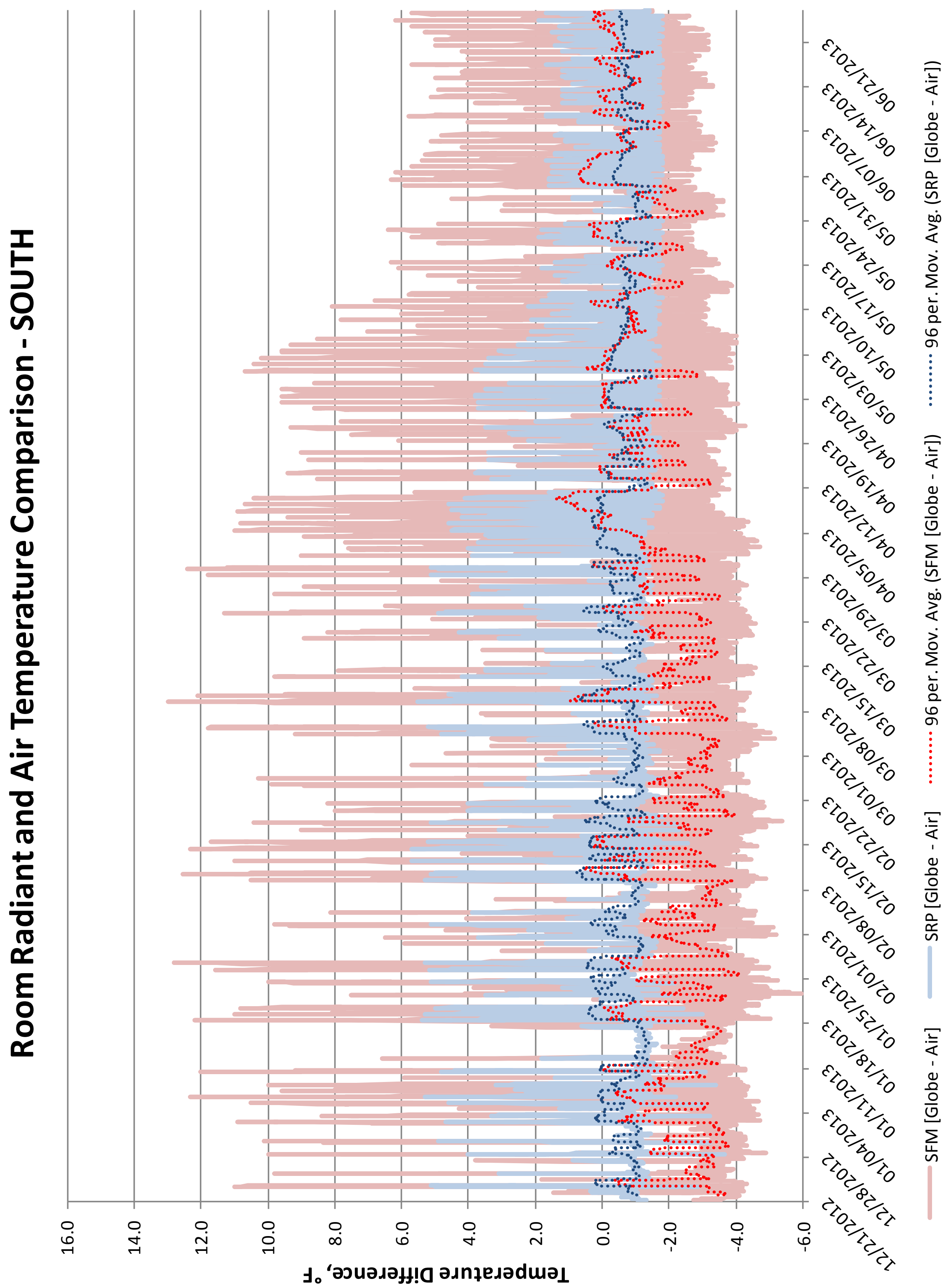

Figure 37. Radiant-Air Temperatures – South Facing Office

When comparing the measured mean radiant temperature (MRT) to the air temperature the ideal condition would see a convergence between these characteristics. When influenced by solar gains through glazing, the mean radiant temperature can cause discomfort, either hot or cold, depending on the outdoor conditions. While thermal comfort standards such as ASHRAE 55, Thermal Environmental Conditions for Human Occupancy, also include air movement and relative humidity, these effects are minor in this test. However, the effects of the MRT compared with the air temperature are a reasonable approximation for evaluating comfort in the rooms with and without the low-E retrofit panels.

Figure 38 through Figure 41 compare the MRT at the low-E retrofit panel to the MRT at the existing window with the interior air temperature (the interior air temperature is the same for the south and west comparisons). The charts clearly indicate that the retrofit panels are much closer to the indoor air temperature during both heating and cooling periods and for both the south and west facing rooms. This will lead to improved occupant comfort, both in terms of more comfortable overall temperature, and also reduced discomfort due to temperature asymmetry.

Based on the MRT comparison with the indoor air temperature, the total number of hours over the six-month monitoring period when the MRT excursions from the air temperature exceed either 3°F or 5°F are determined and outlined in Table 1. The data shows a clear reduction in the number of hours of potential discomfort when using the low-E retrofit system. The reduction of hours of potential discomfort is greater on the SOUTH than on the WEST, due to differences in direct solar gains on the WEST side. Both orientations show similar improvement in keeping the space and comfort level warm during cold / dark periods. Also note that the low-E retrofit panels on the SOUTH facing orientation have a lower solar heat gain coefficient than on the WEST orientation (center of glass SHGC 0.27 vs. 0.35).

Table 1. MRT to Indoor Air Temperature Difference

	Hours When Temperature Difference is Greater Than	
	5°F	3°F
South, Existing Film	402.25	2805.00
South, Low-E Retrofit Panel	8.25	200.25
Low-E Panel Reduction	98%	93%
West, Existing Film	337.25	1097.50
West, Low-E Retrofit Panel	222.00	369.25
Low-E Panel Reduction	34%	66%

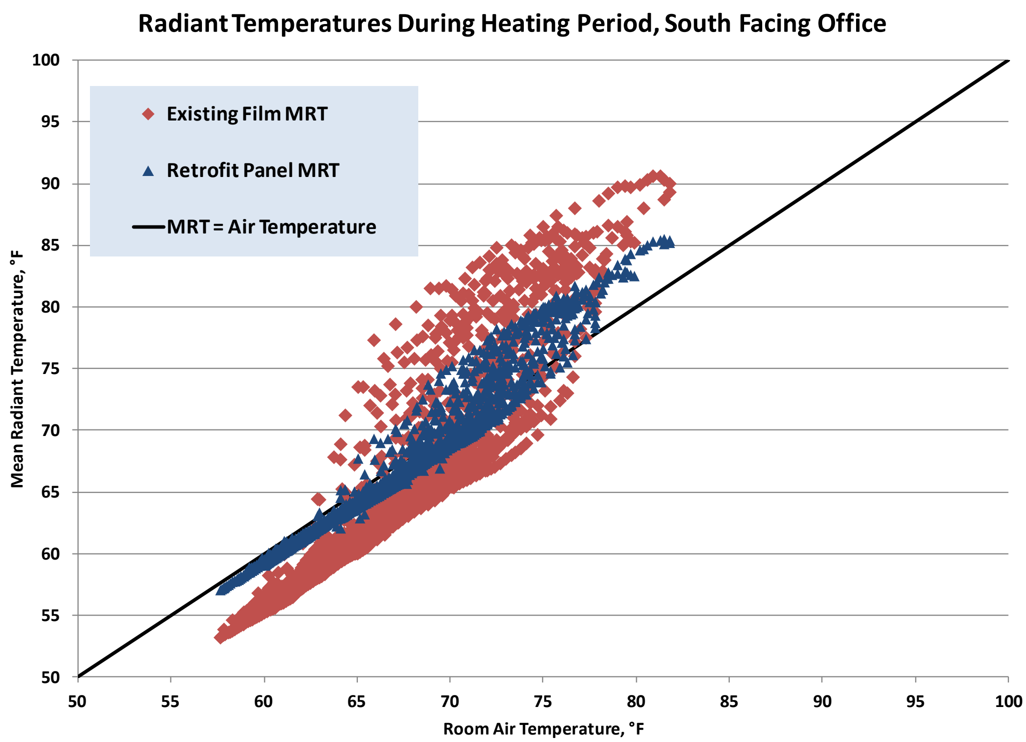

Figure 38. Heating Period MRT Compared to Indoor Air Temperature – South Facing Office

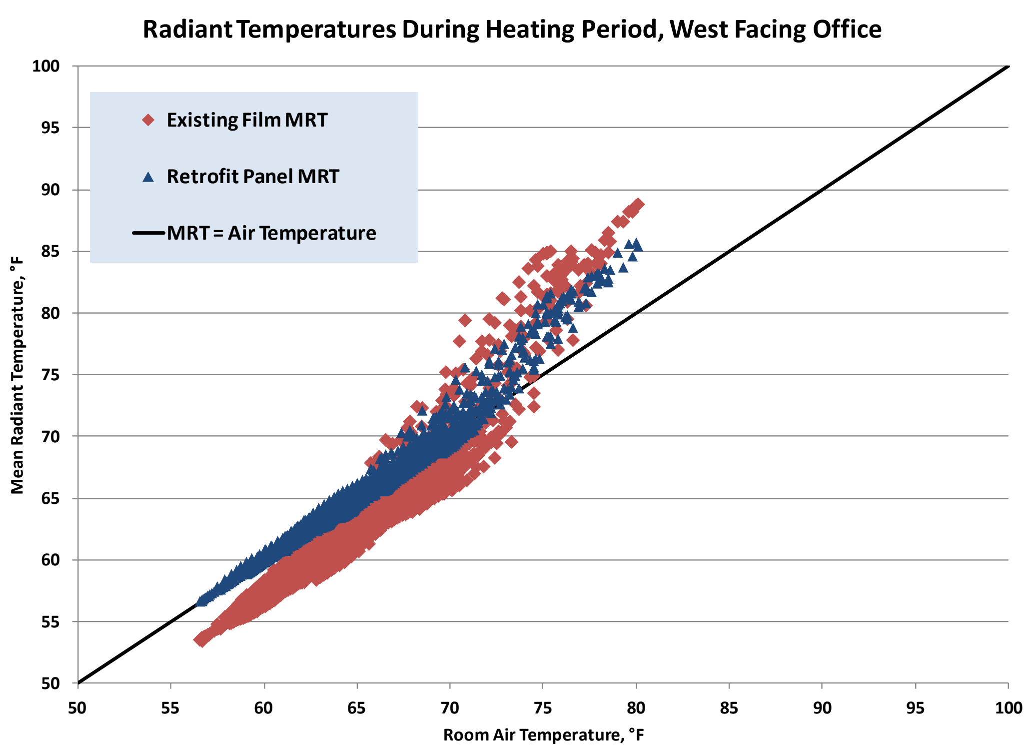

Figure 39. Heating Period MRT Compared to Indoor Air Temperature – West Facing Office

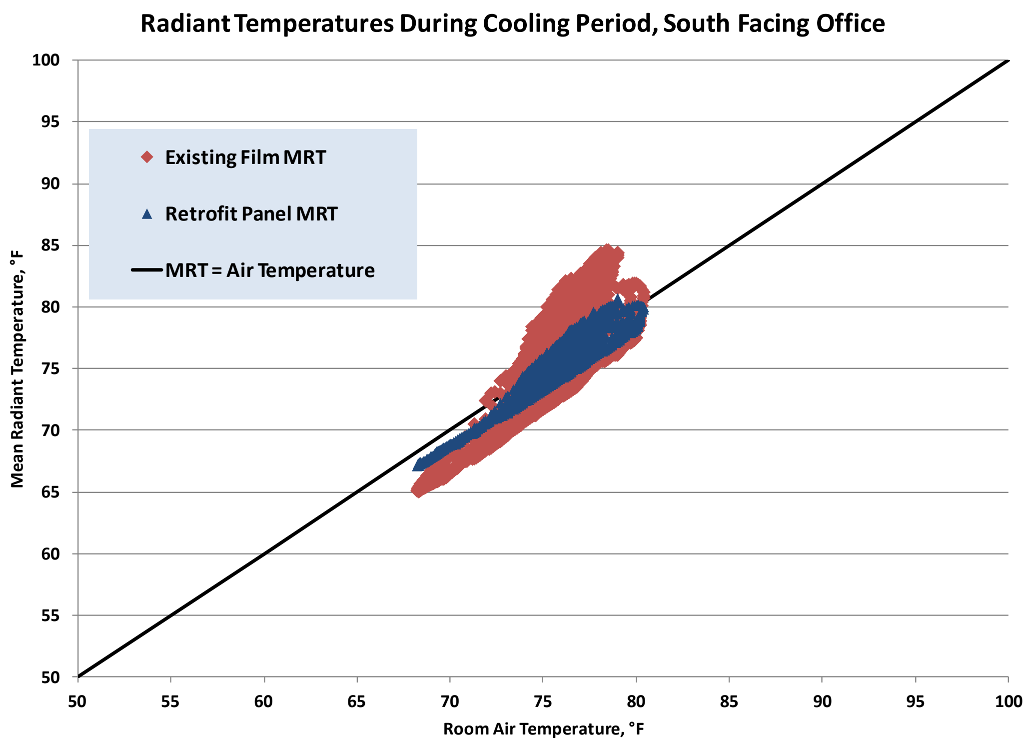

Figure 40. Cooling Period MRT Compared to Indoor Air Temperature – South Facing Office

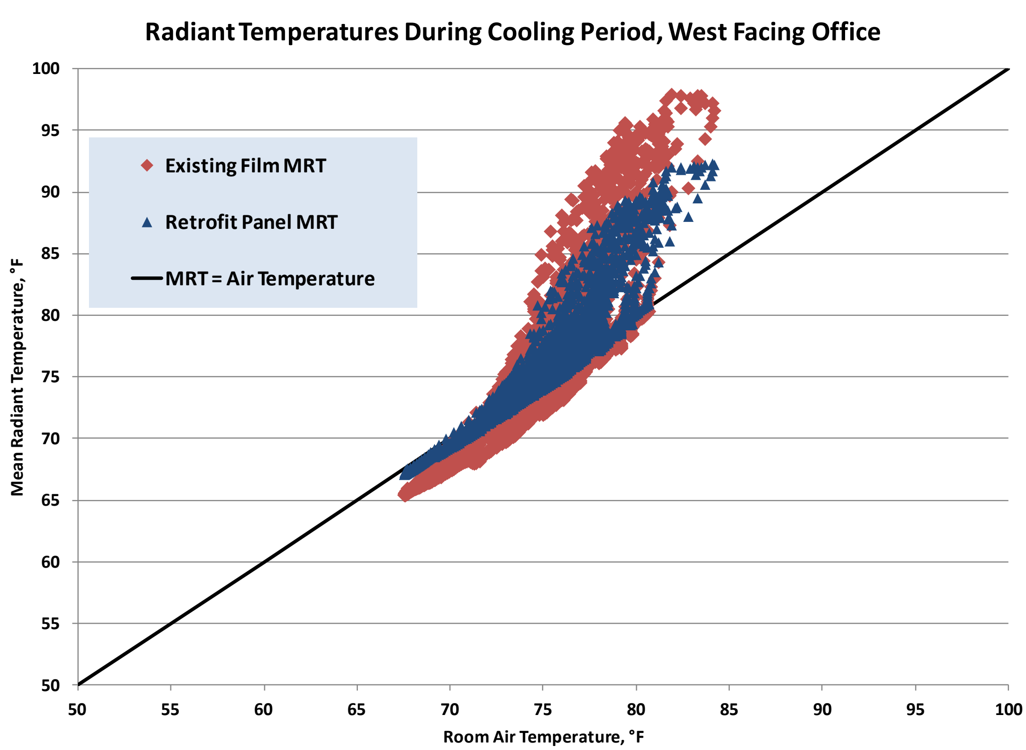

Figure 41. Cooling Period MRT Compared to Indoor Air Temperature – West Facing Office

Room Window Solar and Light Levels

An initial investigation was made into the difference in solar intensity levels in the rooms measured in this study through the solar radiation impinging on pyranometers on a horizontal surface inside the office near the windows. This is a relative measurement only and does not provide detail on other light levels in the room not from the window.

Figure 42 shows the horizontal solar radiation level for the WEST facing office and Figure 43 for the SOUTH facing office.

In the WEST facing office, the installation of the retrofit panel results in very little change in the solar intensity through the window. There is less than 0.5 percent difference over the course of the six-month monitoring period and the daily running average shows little change as the sun angle changes. This shows that the low-E retrofit panel is providing roughly equivalent solar control as the solar control film on the original window, while admitting more visible light (for example, see Figure 3). This is not surprising, as low-E glass coatings are generally more solar selective than window films with a higher ratio of visible light transmission to solar transmission.

The SOUTH facing office does demonstrate an additional reduction in solar gains (as measured by the pyranometer on a horizontal surface) for the low-E retrofit panel than the original window with the solar control film. The effect is larger with lower sun angles and appears to diminish when the sun does not directly impinge on the vertical SOUTH facing windows. The overall difference for the measurement period is about 23 percent. This is explained by the fact that the SOUTH facing low-E retrofit panels have a lower solar heat gain coefficient than the WEST facing windows (and the East and North as well). If the window film has a solar heat gain coefficient roughly equivalent to the WEST facing low-E retrofit panel, then the center-of-glass SHGC is approximately 0.35 (ignoring inward-flowing-fraction effects due to the different U-factor). Then the SOUTH facing low-E retrofit panel will have a solar heat gain coefficient approximately 23 percent lower than the window film (0.27 vs. 0.35), matching the measured data.

Overall, the WEST facing low-E retrofit panel (Platinum Plus II) provides similar solar control as the original window with film, and the SOUTH facing low-E retrofit panel (Platinum Plus II XL) yeilds even better solar control, both while admitting more visible light and providing much better insulating performance (U-factor of 0.15 Btu/hr·ft2·°F vs. 1.0 Btu/hr·ft2·°F).

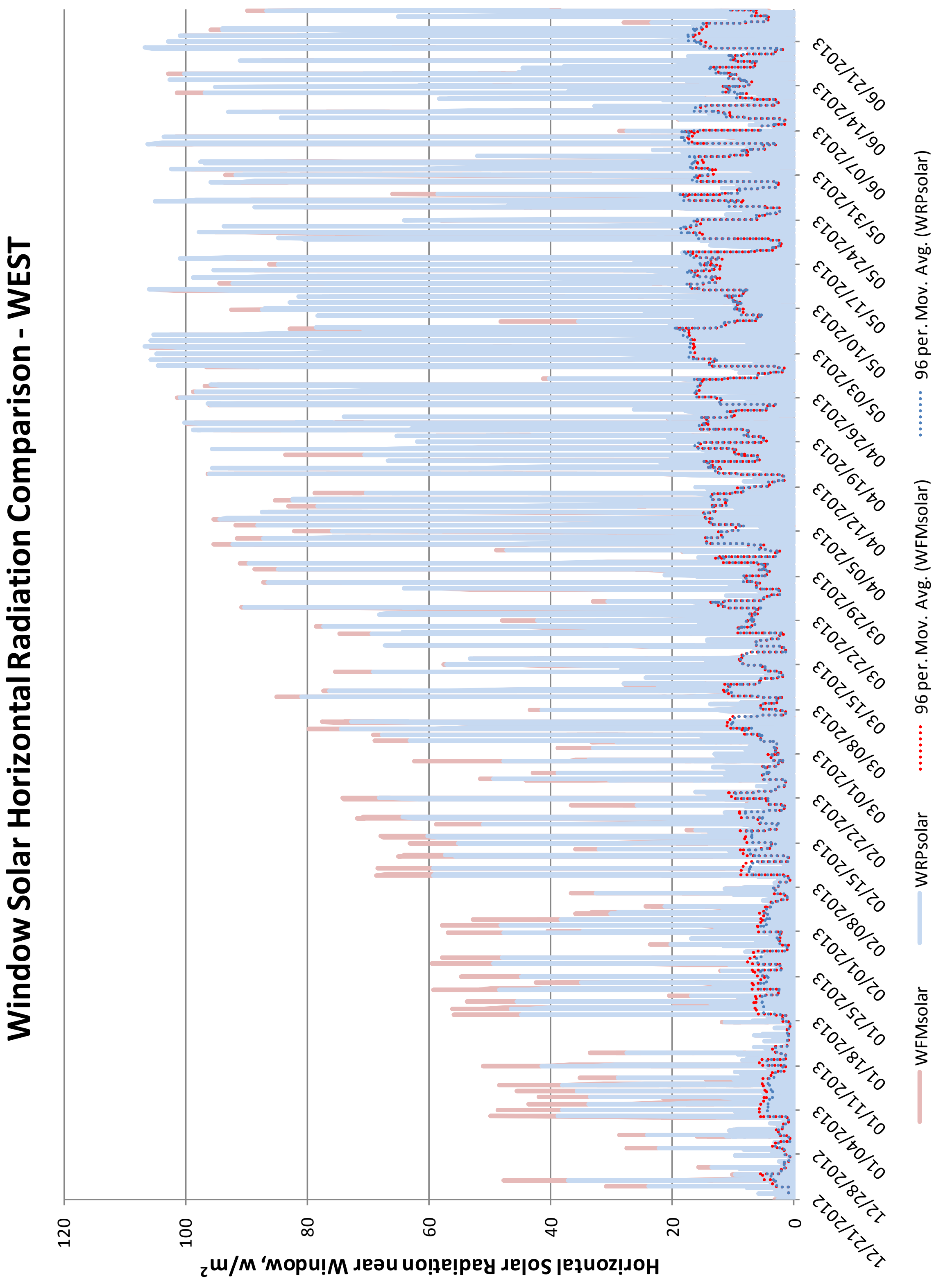

Figure 42. Solar Radiation through Window – West Facing Office

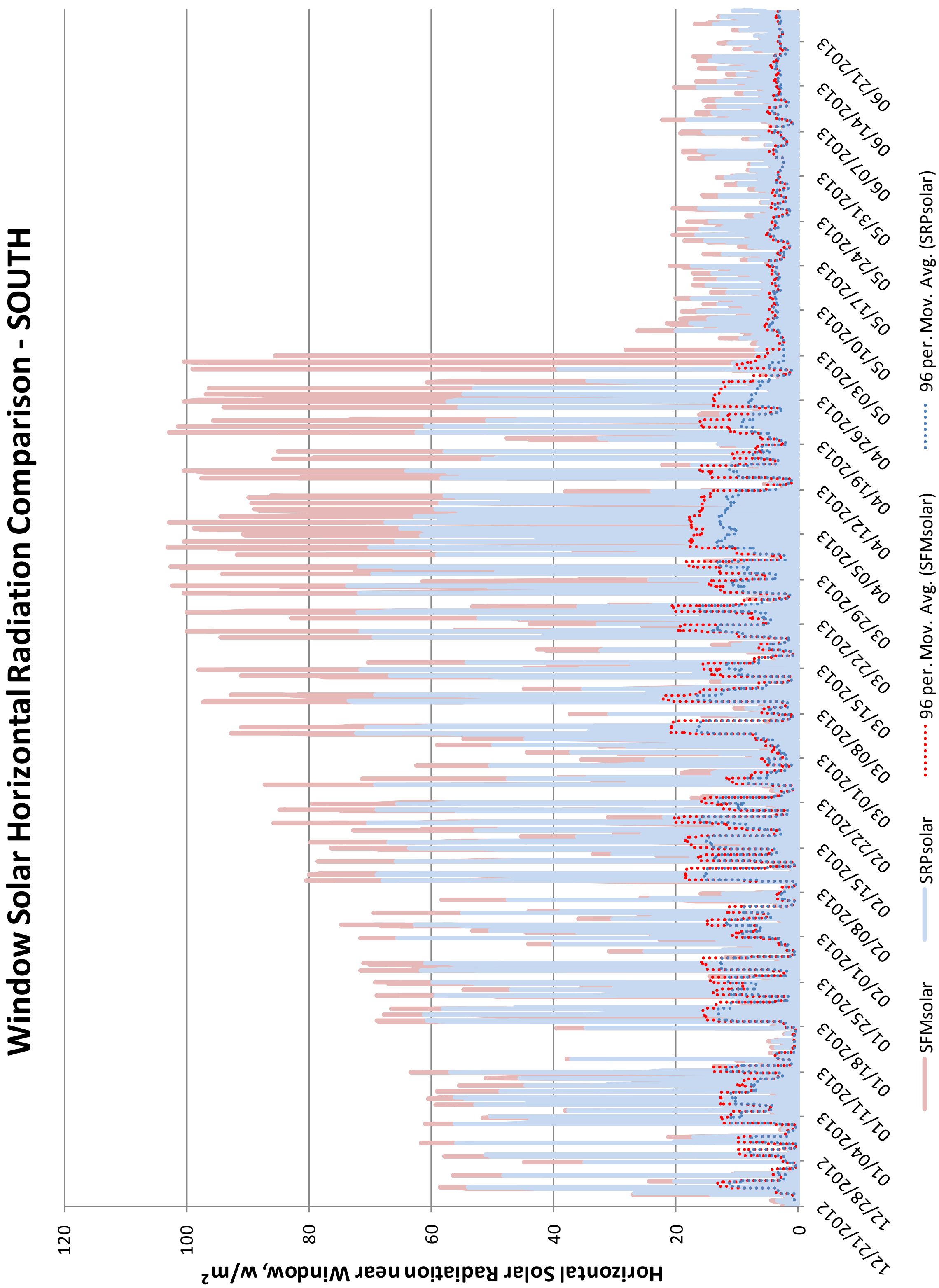

Figure 43. Solar Radiation through Window – South Facing Office

Daily Temperature Profile

One cold and one warm sunny day were selected for a more detailed review of the temperature profile for all sensors located on each window and in the offices. The daily profile is a snapshot of the diurnal change in temperature for each sensor in response to exterior temperatures and sunlight impinging on the window. The daily temperature profile demonstrates a more narrow time frame, whereas the results described above examine more of a seasonal basis. Figure 44 through Figure 47 graph temperature and sunlight data for one day in January and one day in May for both the WEST and SOUTH facing offices.

Consistent with the previous data, the daily temperature profiles show reduced temperature swing throughout the day with the low-E retrofit as compared to the original single-pane windows, as well as interior surface and mean radiant temperatures more closely matching room temperatures, increasing overall comfort for building occupants. Additionally, the low-E retrofit generally has less variation in temperature across the panel (see as spread across the green WRP1-6 lines and splits in the Cw1-2 blue lines) than in the original window with the solar control film (see as spread across the red WFM1-6 lines), suggesting that there is less potential for thermal stress in the glass.

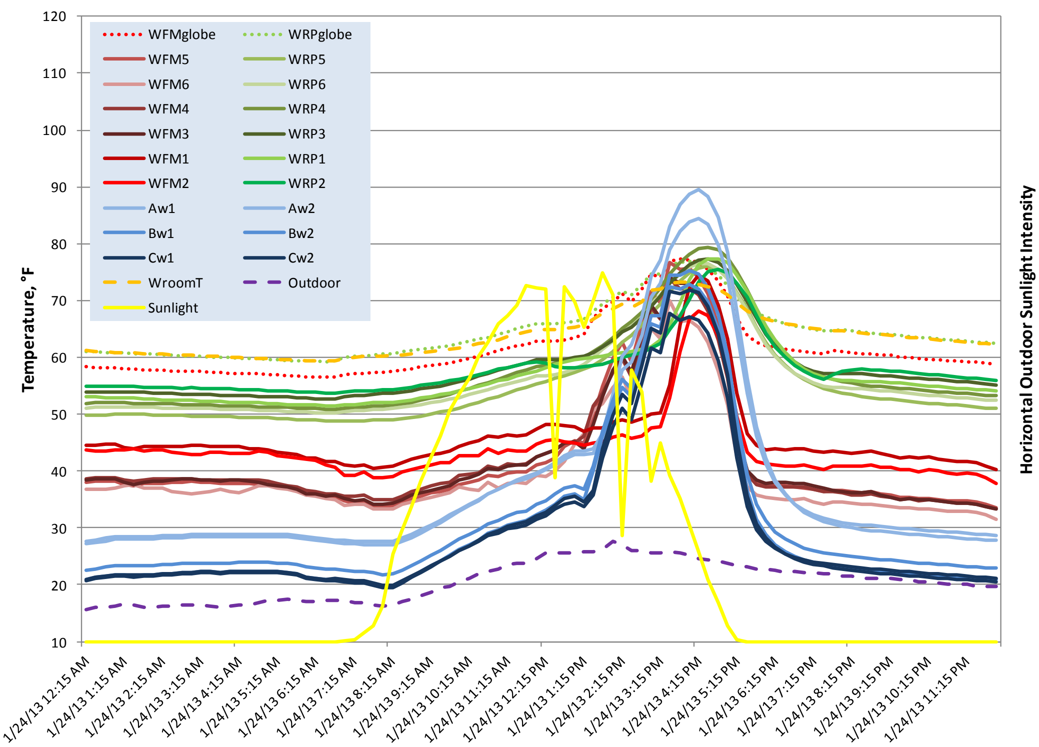

Figure 44. Temperature Profile for a Cold Sunny Winter Day – West Facing Office

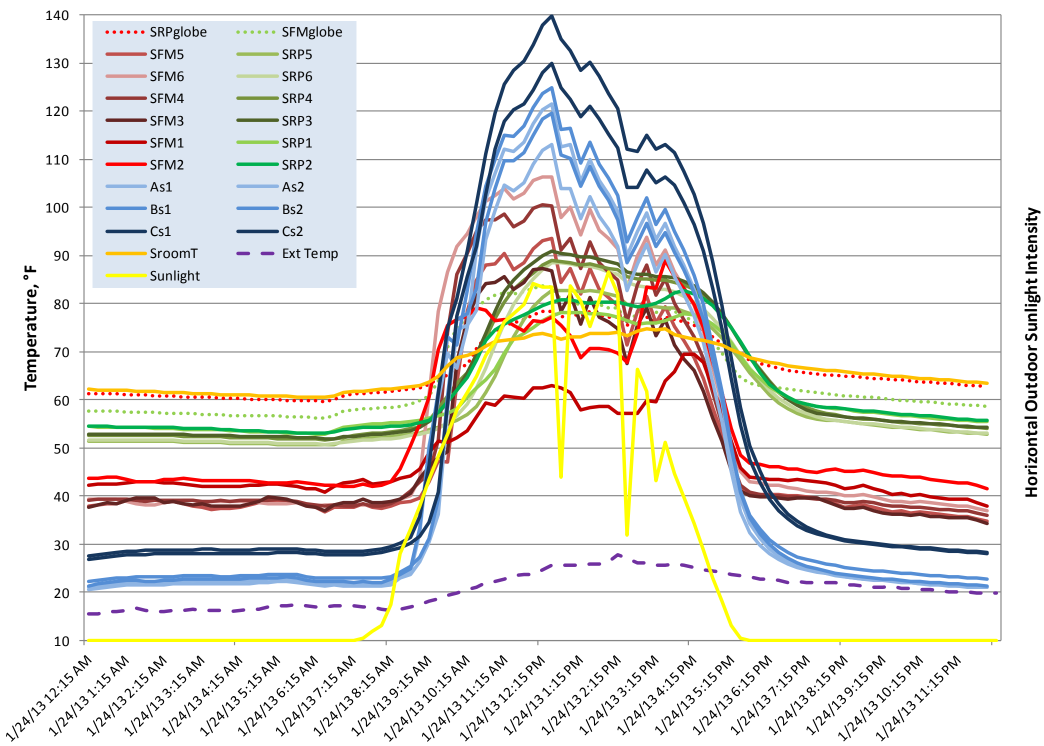

Figure 45. Temperature Profile for a Cold Sunny Winter Day – South Facing Office

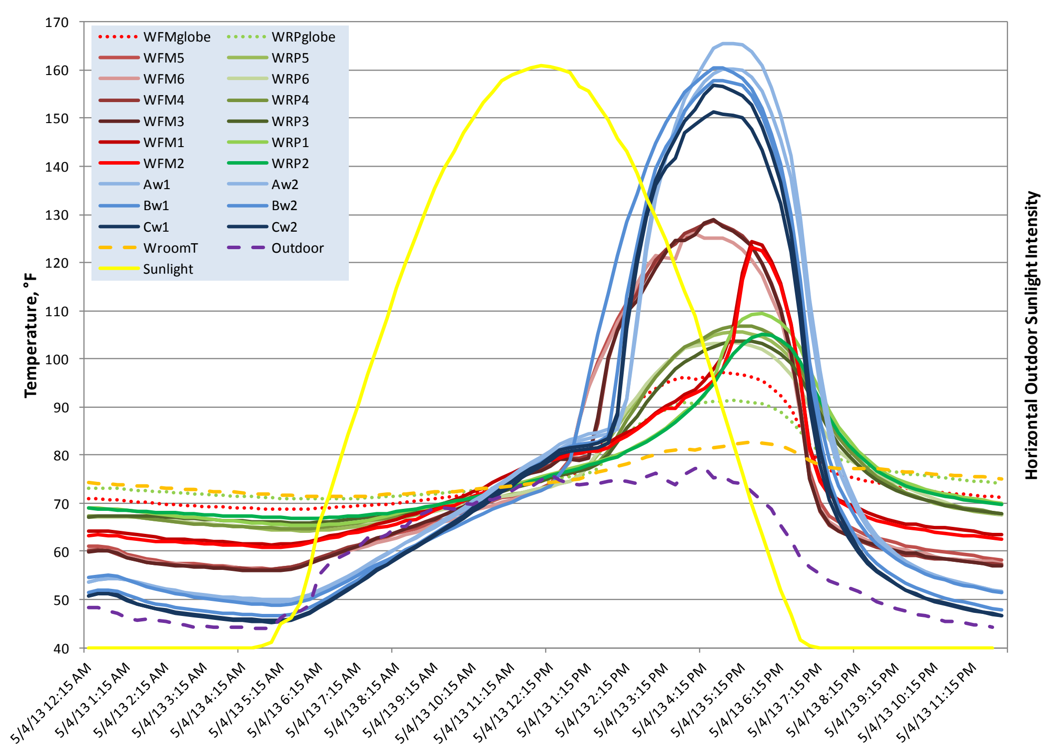

Figure 46. Temperature Profile for a Warm Sunny Spring Day – West Facing Office

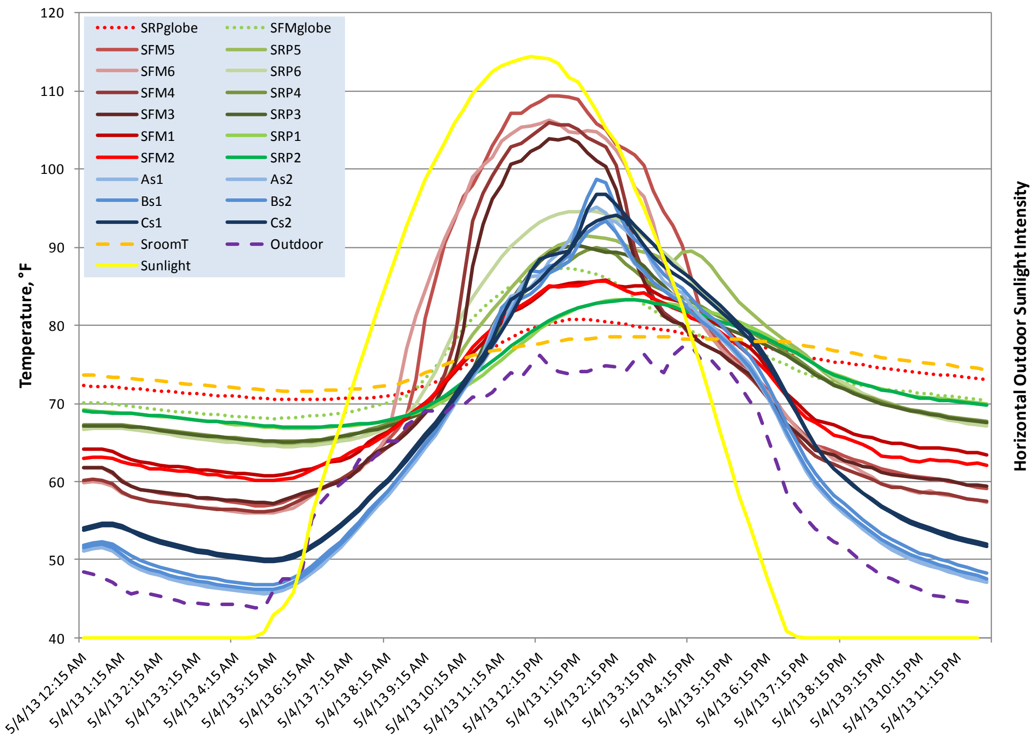

Figure 47. Temperature Profile for a Warm Sunny Spring Day – South Facing Office

Conclusions

The window upgrade using low-E window retrofit panels at the Kevon Office Building has demonstrated significantly improved thermal comfort as compared to the original single-pane windows, as measured by the effects of the windows on the mean radiant temperature difference from the indoor air temperature. Larger temperature excursions, exceeding 5°F, between the MRT and the indoor air are reduced by 98 percent in the south facing office and over one-third in the west facing office. Excursions of over 3°F are reduced by 93 percent in the south facing office and over two-thirds in the west facing office.

Additionally, the low-E retrofit panels greatly reduce daily variations in the interior window surface temperatures, lowering the maximum temperature and raising the minimum temperature by over 20°F compared to the original windows. The average window surface temperature over the monitoring period is more than 8°F colder than the air temperature for the original window, and no more than 3°F for the low-E retrofit panel window. This result is consistent for both orientations.

Furthermore, no significant thermal stress was observed when using the low-E retrofit system, as measured by temperature differences across the outer pane of glass over a variety of weather conditions. The surface temperature difference only exceeded 10°F (500 psi thermal stress) for less than 1.5 percent of the monitored time, and in all cases, the maximum surface temperature difference never exceeded 35°F, or 1,750 psi. While the sensor locations in this study may have missed some corner effects, and each building situation (geometry, exposure, shading, etc.) should be assessed individually, there does not appear to be any significant concern with thermal stress when using the low-E retrofit panel.

The mean radiant temperature, the solar radiation, and the fluctuations in the window surface temperatures are all markedly improved as intended through the upgrades.

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