THE EFFECTS OF ENERGY EFFICIENCY TREATMENTS ON HISTORIC WINDOWS

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CENTER FOR ReSource CONSERVATION

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THE EFFECTS OF ENERGY EFFICIENCY TREATMENTS ON HISTORIC WINDOWS

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By

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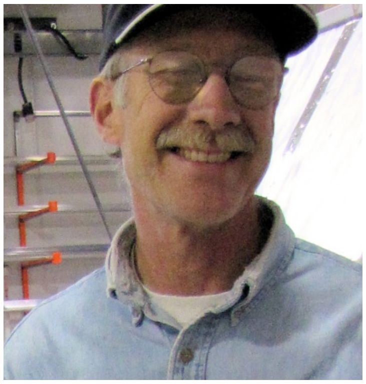
Acknowledgements

This study of the effects of energy efficient treatments on historic windows was developed with extensive help and support from many collaborators who contributed materials or worked tirelessly for little or no compensation to achieve research results. Our thanks go to Doug Ward our volunteer craftsman and Gary Cler, part of the project's technical team who helped construct the project's testing laboratory and spent many hours testing windows; Wyncia Clute, of Synertech Systems Corporation, who worked in the field, at the chamber, and on her computer in support of all aspects of the project; Brad Begin of Alpen Energy Group, who supplied abundant practical wisdom and other support throughout the project including space to house the laboratory; Lynn Bingham and the team of craftsmen, including Glenn Bingham and Jeff Griffin of Phoenix Window Restoration; Gary Nelson, President, and his colleagues of the Energy Conservatory who custom-calibrated the duct blaster and two digital pressure gauges *gratis* for this project; Leonard May of the City of Boulder's Historic Preservation Society and Landmarks Board; ReSource building material salvage yard, for supplying several free historic windows for testing in the lab; and the Colorado Historical Society. Finally, we wish to thank Gretchen Lang and Michael Wilkins, who opened their lovely historic home to the technical team and equipment used in this study. It is our fervent hope that their home is more comfortable, attractive and energy efficient as a result.



Dedication

Dedications are not routinely a part of technical reports, but the present case is exceptional. Our dear friend and colleague Gerald Lee Cler died an untimely death on October 8, 2010. Gary put in many long hours on the present project and contributed to it in a myriad of useful ways. It is singularly appropriate that this report is dedicated to his memory.

Unlike most mechanical engineers in modern times, Gary gained a world of practical wisdom even before completing his formal education. After graduating from high school in Illinois, he worked in his uncle's machine shop for seven years, where he became an excellent machinist. This experience provided clarity about what he wanted to study in college. Gary did undergraduate work in mechanical engineering at the University of Illinois and then earned an MS at Colorado State University. By the time I met him early in 2000, he had made numerous contributions to the advancement of energy efficiency and renewable energy.

We were colleagues at E-Source in Boulder and immediately formed a strong friendship. We shared the view that many broadly held opinions about energy efficiency merit careful re-examination, and that many potentially useful inventions were waiting for someone to bring them to life. So we set about inventing tools for saving energy, mostly in the areas of natural daylighting and fenestration.

Gary rarely designed things he couldn't fabricate himself (usually in his brother Larry's machine shop.) Further, he always made things as simple as they could practically be—but no simpler. We frequently found ourselves sharing ideas and building on one another's thoughts with drawings that filled the backs of bar napkins. Some of these sketches (slightly modified, to be sure) are now part of the patent literature.

Most important, as our friendship grew during the last decade, my wife Wyncia and I found ourselves in the presence of not only an excellent, creative engineer, but also a large, ancient soul. Gary was a deeply moral man who both loved life and befriended a host of people whose lives he enhanced in many ways.

It was an honor and a privilege to have known him. Gary is sorely missed.

Larry Kinney
November 2010

EXECUTIVE SUMMARY

This study focused on empirical testing of the energy efficiency and economy of a range of options for upgrading the energy performance of historic windows. The study involved retrofitting windows in a test home in a historic district in Boulder, Colorado. It included testing in a window laboratory facility developed for the study.

The 108 year old 2700 square foot brick test home includes numerous original double-hung, wood-framed, single-glazed windows. The study focused on three on the south façade and three on the north. Each was equipped with aluminum storm windows and associated screens that were added several decades ago.

During the study, five of the six windows were carefully rebuilt in ways that retained their historical character. The sixth, a small window in poor condition in a bathroom, was replaced by a custom-built wood frame window that matched the aesthetics of the original but was carefully air sealed and designed to provide ventilation through a screen when desired. Blower door testing revealed that counter weight pockets in the other five windows were leaky – these had weights removed, then were insulated and air sealed. Windows were then equipped with spring systems, which provide the functionality of the counter weight approach but cannot be seen[1]. Other improvements included filling holes, removing old paint and glazing compound, restoring the functionality of the original sliding mechanisms, installing weather stripping, sealing wood surfaces, installing new glazing compound, and adjusting (or replacing if appropriate) lock mechanisms. Post-retrofit blower door testing at the home revealed an average of about 6 therms of natural gas savings per window per heating season from diminished convective losses alone.

The work of carefully rebuilding old windows is practiced primarily by professional craftsmen who work with specialized tools and equipment. Some, like Phoenix Windows, employ a portable shop which they bring on site to enable rebuilding multiple windows in several days time. This process can breathe new life into old windows and dramatically improve comfort and energy efficiency. However, because the work is painstakingly conducted by a skilled craftsman, the cost is very different from window systems manufactured off site and left to a homeowner or local technician to install.

In addition to the above-mentioned retrofits, insulated glass units were installed in a 16 square foot window on the south facade (one whose original lites had been replaced years ago). Finally, at the request of the homeowners, three wooden storm windows designed to cohere with the character of the home were built for the project. One storm window incorporated single glazing and the other two were equipped with insulating glass units. One of these latter storm windows had fixed insulation integrated into the interior of the frame.

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[1] Replacement of counterweight systems with spring systems should not be undertaken in properties listed in the National Register of Historic Places as this technique does not comply with the Secretary of the Interior's Standards for the Treatment of Historic Properties. An alternative approach to sealing and insulating counterweight pockets, which does comply with the Standard, is provided in Appendix D of this report.

Energy losses or gains through windows vary directly with their size, the temperature difference between inside and out, and the heat transfer coefficient (U-factor), a parameter reflective of the combined thermal characteristics of both frame and glazing. (U-factors are the inverse of R-values, where R is the resistance to heat flow.) In practice, it is exceedingly difficult to measure U-factors in the field, so members of the project team built and instrumented a testing facility to measure U-factors and study air leakage. The testing facility features a super-insulated 390 cubic foot inner chamber designed to measure fenestration samples of up to 20 cubic feet. It is surrounded by another well-insulated chamber. The inner chamber is heated by electric resistance radiant panels and the outer is cooled by chilled air. The result is a difference in temperature that averages 70 degrees F. Heating energy required to maintain this temperature difference is measured precisely, as is temperature from a number of probes inside the hot chamber and between the hot and cold chambers. Data loggers record energy use and temperatures each minute for subsequent analysis.

In addition, a calibrated variable speed fan and associated two-channel digital manometer is used with the inner chamber to determine that samples are tightly mounted in the test facility and to quantify the extent of air leakage associated with cracks between fixed and moveable portions of frames.

The solar heat gain coefficient (SHGC) is the fraction of solar radiation admitted through a window that is directly transmitted and absorbed, and subsequently released inward. In this project, the team used a factory-calibrated pyranometer to take readings in both the test home and the laboratory.

Table ES-1 shows key results of laboratory testing on ten combinations of fenestration systems.

Table ES-1. Measurements of U-factors and R-values

Description	*Number of test runs*	*Total test hours counted in calcs*	*Standard Deviation of hourly U-value*	*Weighted Average (U)*	*Weighted Average (R-value)*	*Wind adjusted R*	*Wind adjusted U*
Old double hung from window 5	4	102	0.000872	0.78	1.29	0.79	1.27
Single glazed original alum storm	2	39	0.000872	0.97	1.03	0.53	1.88
New Storm w/o insulated frame	2	32	0.00132	0.27	3.65	3.15	0.32
New Storm w insulated frame	1	16	0.00077	0.24	4.11	3.61	0.28
New Storm single glazed	2	40	0.001045	0.76	1.31	0.81	1.23
Old DH from 5 + new storm w/o Ins	2	39	0.000908	0.21	4.87	4.37	0.23
Old DH from 5 + new Storm w/ Ins	1	42	0.001054	0.19	5.18	4.68	0.21
Retrofitted double hung from wind 5	1	24	0.000862	0.48	2.07	1.57	0.64
Ret DH from 5 + new storm w/o ins	2	39	0.000958	0.19	5.32	4.82	0.21
Ret DH from 5 + new storm w/ ins	3	91	0.000958	0.17	5.83	5.33	0.19
Ret DH from 5 + sg wood storm w/o ins	3	116	0.000926	0.33	3.00	2.50	0.40
New Vinyl Window	3	110	0.000926	0.36	2.75	2.25	0.45

The low standard deviations indicate consistency in measuring techniques and lend credence to the relative results of U-value testing. The wind-adjusted U-factors and R-values reflect canonical parameters of the difference in the insulating value of a still air film and an air film associated with a 15 mph wind on the exterior of a structure.

Each of the storm windows was tested on its own and with several combinations of storm windows with existing and retrofitted double hung windows. Note that the single-glazed storm outperformed the existing aluminum storm by a factor of 1.5; the new storm without insulation in the frame outperformed the aluminum storm by a factor of 5.9, and the storm with insulated frame outperformed the aluminum storm by 6.8 fold. Retrofitting the old double hung improved performance by a factor of two over the existing old double hung, whereas replacing it with a new vinyl window yielded an improvement of 2.9 fold. The overall best performance was achieved by retrofitting the old double hung then installing a new storm window whose frame was partially insulated. This yielded a 6.8 fold improvement in energy performance over the old double hung in its original condition.

Knowledge of fenestration areas, solar heat gain coefficients, and U-values can be combined with typical meteorological year (TMY) solar radiation and temperature data to calculate hourly energy gains and losses for virtually any fenestration system for which TMY data are available.

RESFEN software developed by Lawrence Berkeley National Laboratory was used to estimate the summer and winter energy performance of each of the fenestration systems shown in Table ES-1 in seven American cities: Anchorage, Atlanta, Boston, Denver, Minneapolis, Phoenix, and Sacramento. A set of tables in Section 4 of this report, and in the table below, show energy and economic performance figures based on 100 square feet of the fenestration systems installed on each of four facades. The calculations assume a retrofit cost for low-U storm window of $25per square foot, a rough average of the cost of this type of retrofit as practiced in this project and other areas of the country.[2] The data also reflects local costs of gas and electricity, which can differ substantially. For example, residential consumers in Anchorage pay $0.441 per therm for natural gas while those in Phoenix pay $1.43, three and a quarter times as much. Homeowners in Boston pay $0.17 per kWh for electricity while those in Atlanta pay $0.071, a factor of 2.4 difference.

Table ES-2 examines the old double hung window compared to the same window with a new Low U-value storm window in each of the seven cities. Absolute savings are expressed in millions of British thermal units (MBtu) where ten therms of gas = 1 MBtu and 293 kilowatt hours of electricity = 1MBtu. A million Btu is roughly the energy equivalent of a person year of labor.

Table ES-2. Savings from retrofitting double-hung window with a Low U-value storm

City	*Old DH (MBtu/yr)*	*Old DH + New Lo U Storm (MBtu/yr)*	*Absolute Savings (MBtu/yr)*	*Relative Savings (%)*	*Savings ($/yr)*	*Retrofit window cost ($)**	*Simple payback (years)*
Anchorage	95.2	17.9	77.3	81.2%	$342	$9,600	28.0
Atlanta	26.4	1.2	25.2	95.4%	$297	$9,600	32.3
Boston	56.1	5.7	50.3	89.8%	$806	$9,600	11.9
Denver	44.5	5.2	39.3	88.3%	$424	$9,600	22.6
Minneapolis	76.7	11.3	65.4	85.3%	$686	$9,600	14.0
Phoenix	33.1	4.5	28.6	86.4%	$491	$9,600	19.5

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[2] Typical “thorough” jobs are described and illustrated in Section 3.1 of the report.

Sacramento	25.1	0.6	24.5	97.7%	$311	$9,600	30.9
Averages	51.0	6.6	44.4	87.0%	$480	$9,600	20.0

* Retrofit cost is based on $25 per square foot for 100 square feet of window area on each of four facades for a total of 400 square feet (400 x $24 = $9600).

In this case, savings average 44.2 MBtu and 87%. Dollar savings are over $800 per year in Boston and average $480 overall. The savings in Anchorage are the energy equivalent of 77 person years of labor, yet paybacks are 28 years.

Assumptions and caveats associated with the above analyses are:

- The assumed cost of a highly-energy-efficient storm window reflects no economies of scale and assumes a wood frame, which is labor intensive to manufacture and has an R-value that is three times less than that of fiberglass or vinyl.
- No local, state, federal, or utility incentives are taken into account.
- The analysis does not account for such benefits as increased comfort, yet many consumers count this as a primary consideration in their decisions about windows.
- The analysis does not account for the likely increase in the lifetime of the primary window resulting from either retrofit or adding an energy-efficient exterior storm window.
- There are many circumstances in the real world in which useful lifetimes of various window treatments may be less than payback periods. These factors are notoriously difficult to quantify and therefore have not been considered in payback calculations.
- Cost-benefit calculations assume the rate of inflation in energy costs is identical to the overall rate of inflation. Accordingly, the analysis is likely to be conservative.

Before drawing inferences from the above findings, it is useful to take note of the key role played by frames in determining window energy performance. Historic window frames are typically made of wood; glazing is routinely single. An inch of dry white pine has an R-value of one (1/Btu/ft2/F). Single glazing also has an R-value of approximately one. Accordingly, **when both the frame and glazing have roughly the same R-value** (as in the case of older single-glazed windows with wood frames), **conductive losses do not change much with the ratio of the cross sectional area of glazing to frame**. However, when glazing is more efficient—modern large insulating glass units (IGUs) have R-values that approach ten—frame R-values significantly alter the overall efficiency of the window.

Frames made of either vinyl or fiberglass have R-values in the area of 3 per inch, more if insulation such as urethane is used on their interiors.

Accordingly:

- Improving the R-value of frames is highly important. (In particular, improving the R-value of a substantial portion of the fixed part of the frame of an older double hung window--like the counter weight box--can be very effective in lowering energy waste.)
- Raising the glazing-to-frame ratio of any window system whose frames have an R-value of one or less makes good sense.

- Investing in high R-value IGUs is increasingly cost effective when frame portions of the window become smaller and frame R-values higher.
- Retrofit storm windows with high R-value glazing are increasingly cost effective when frames are relatively small and have good R-values.

Modeling the case of an efficient IGU with fiberglass frames used with the existing double hung windows showed improvements in energy performance over the double-hung alone of 96%.

Final conclusions

Adding an efficient IGU to windows, in combination with air sealing and insulating the existing window and its weight pockets yields good energy savings. However, if a wooden frame dominates a window, the only practical option to achieve excellent savings while retaining the historic window is to install an energy-efficient storm window.

Adding storm windows has aesthetic advantages as well as significant thermal ones. Even with a wooden frame (whose proportions were modest while being consistent with traditional historic aesthetics), performance was well more than four times that of the original window. Switching to an energy-efficient fiberglass frame would improve the performance a great deal, probably raising the overall efficiency of the window system by a factor of six or more over a single-glazed wooden window. It is possible to fabricate fiberglass frames that appear to be virtually identical to wooden frames. Such a storm window could be manufactured at a lower cost than a wooden storm window. It would also achieve better comfort, longer life, and greater energy savings.

As far as we know, this type of frame for storm windows is not currently commercially available; however, a mass-produced, semi-custom fiberglass frame solution may find strong commercial demand among both historic homeowners and others. Analysis suggests that ten square feet or larger storm windows with fiberglass frames could be sold in bulk quantities (20 or more) for a price ranging from $14 to $18 per square foot. In the seven cities analyzed, such a system would have about the same payback period as installing a lower-end vinyl replacement window.

In general, improvements in U-factors result in lower SHGCs. Sometimes this is desirable, particularly in cooling-dominated climates and on west and east elevations. When designing appropriate storm windows for historic buildings, matching U-values and SHGC to facades is quite important. In Boulder and other climates with good sunlight for much of the year but also substantial heating loads, ensuring high SHGCs for south-facing window systems that are not substantially shaded by trees or neighbors is much more important to a home's overall wintertime energy performance than is achieving the lowest possible U-factors.

The most important conclusion flowing from this research is that it is possible to improve the overall energy performance of existing window systems by well over four fold through repairs and sealing plus the installation of an excellent storm window without altering their historic character. This strategy also protects the original window and gives it new life and functionality. In many cases, old windows can be saved while raising the overall efficiency of a home, improving its comfort, and retaining its aesthetic charm.

When combined with appropriate insulation and high-quality air sealing (of envelopes as well as duct systems), using window systems such as these would open the way to improvements of 60% to 80% over historic buildings that are leaky, have little insulation, and are equipped with wood-framed, single-glazed windows.

1. INTRODUCTION

This report summarizes the results of a research project aimed at gaining a better understanding of the efficiency implications associated with the application of practical techniques for improving the energy performance of window systems commonly found in historic homes in Colorado and in other states. The study evaluated the energy-related effects of various efficiency treatments including reparation, replacement, and supplement (such as storm windows). The work was funded by the Colorado State Historical Fund (SHF), Alpen Energy Group, Phoenix Window Restoration, and the City of Boulder's Community Planning and Sustainability Office. The research was accomplished by an interdisciplinary team representing the Center for ReSource Conservation, the Synertech Systems Corporation, and Phoenix Window Systems. All members of the team contributed substantial labor as well as tools and materials in support of the aims of the project.

Historic windows are widely viewed as key features of historic structures that are essential in retaining a building's historic integrity. Accordingly, restoration versus replacement of historic windows has become a prominent issue in the Rocky Mountain West and throughout the US. Windows can be the source of considerable energy waste and associated discomfort, particularly in older homes which have not benefited from recent advancements in window technology. While replacing inefficient, single-glazed windows can save considerable energy, the benefit of replacing historic windows must be weighed in the light of energy and resource costs and environmental impacts associated with materials use as well as the societal value of historic structures.

Owners of historic homes, local regulatory bodies, and the preservation and conservation communities need unbiased information based on empirical data to help guide historic preservation policy development and energy saving decisions. The driving hypothesis of the team's work is that better decision-making in the historic window area is likely to flow from accurate data representing a range of practical options.

In preparation for the study, the team reviewed existing studies of historic window efficiency treatments conducted over the past 25 years and found only limited evidence of measured data (see Annotated Bibliography, Appendix A). Those that have attempted to measure window performance in existing structures have been unable to overcome the common barrier that makes such a study immensely difficult -- that is measuring heat transfer and air leakage through a window system while accurately accounting for on-site conditions that can skew study results. It is difficult to assign cause and effect associated with a given window (or even a set of them) since many variables unrelated to windows can overwhelm moderate changes in window leakiness, insulating properties, and heat gain or loss. Accordingly, the study team set out to overcome these limitations by using a test chamber to assess window systems in a controlled environment.

The efficiency of a window is the product of multiple factors. The amount of radiation transmitted through a window's glazing, expressed as solar heat gain coefficient; heat transfer, measured n terms of U-factor; and leakiness, or the amount of air passing through the window system all effect the window's energy performance. The visual light that flows through a window, known as visual transmittance, also affects daylighting, which may impact the home's energy use as a whole. Developing practical schemes for measuring these factors in both the field and the laboratory to the degree possible in each was a central aim of this work.

The Study Team theorized that certain retrofit options would enable achieving energy efficiency gains that would nearly match the gains available by replacing window systems with good-quality, commercially-available windows. To test this theory, the study team conducted empirical testing on a range of alternative window efficiency treatments utilizing three distinct testing approaches and calibrating the results to arrive at a reasonable quantitative metric by which efficiency alternatives may be measured against each other and with respect to the option of replacement. Each of these methodologies plays a valuable role in understanding how historic windows perform in a variety of conditions. The methodologies included:

1) Field testing within an historic home. This process began with a thorough energy audit to assess baseline conditions. The study team then applied of a series of efficiency treatments to windows on the north and south side of the home and measured the effects of each on the window's solar heat gain and visual transmittance.

2) Testing within a special chamber designed, fabricated, instrumented, and calibrated specifically for the project. More than 200 tests for heat transfer (U-value) were run in the test chamber with an average length of 26 hours. Scores of tests for air leakage were conducted as well. In addition, a number of infrared scans were conducted to identify areas of conductive and convective losses. Tests for solar heat gain and visual transmittance were also conducted at the window testing facility.

3) Computer modeling. The study team used RESFEN, widely considered to be the best software currently available to analyze residential fenestration systems, to evaluate window performance. RESFEN was developed by Lawrence Berkeley National Laboratory (LBNL) and other national labs; it incorporates weather data from the National Oceanic and Atmospheric Administration (NOAA) to estimate window performance in different climate zones and for hundreds of cities all over the U.S. The use of RESFEN combined with data gathered in the laboratory and field allowed the team to extrapolate energy and economic performance to any location where historic weather data and utility cost information are available.

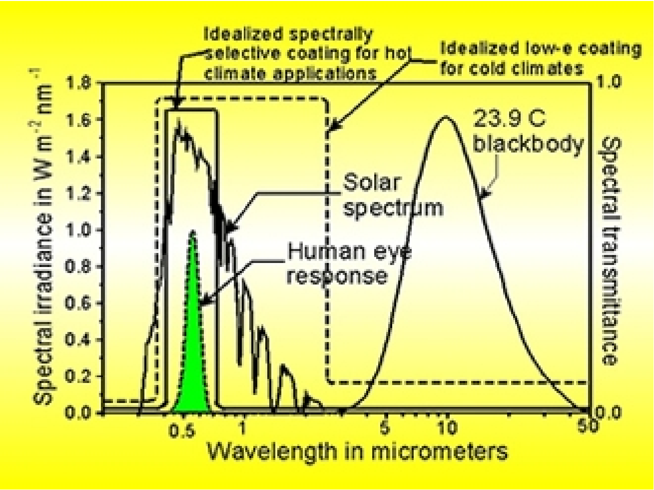
The sections of this report that follow provide details on these methodologies, results of the testing, and analyses undertaken as part of this effort. The study team is hopeful that the results will provide useful data to owners of historic dwellings, preservationists, environmentalists, and local regulators to inform decision-making on energy matters in a variety of historic structures.

2. METHODOLOGY

2.1 Window Energy Performance

Windows transfer energy by radiation, conduction, and convection. Under many conditions, radiation predominates. Our eyes see only a narrow range of wavelengths, slightly less than half of the solar spectrum. Figure 2-1 depicts the irradiance from the sun as a function of wavelength after it has been filtered by passing through the atmosphere. Note that the peak of our eye's sensitivity curve (a wavelength of around 0.6 micrometers which we call yellow) corresponds closely with the peak of the sun's output.

Figure 2-1. Irradiance of the Sun Versus Wavelength



Source: Ross McCluney, Florida Solar Energy Center

2.1.1 Thin Films

Over the last several decades, manufacturers have developed the means to produce windows that selectively filter and reflect different portions of the spectrum. The technique involves depositing very thin layers of metal on a surface of glass or plastic substrate. First generation systems resulted in "low-E" coatings or films that let through most of the sun's shorter wavelength radiation, but reflect longer-wavelength radiation away from room temperature sources (75ºF is represented in the figure, with dashed lines illustrating the filtering action of low-E coatings). The result is good window performance in the wintertime since it transmits most of the spectrum of solar radiation yet reflects longer wavelength radiation from objects at room temperature. Newer, second generation window technology can be much more carefully tuned to filter just the wavelengths desired. For example, it is possible to filter only the infrared and ultraviolet portions of the spectrum while allowing most of the visible portions to be transmitted. This "spectrally selective" property is illustrated by the solid line in Figure 2-1. The resulting window performance is much better adapted to warmer climates where cooling concerns are primary. This style of window keeps out a large portion of the radiation that would heat up a room and increase air conditioner use, while allowing unobstructed viewing and substantial daylight to pass through the window.

Under most circumstances, radiation plays a much larger role in window energy transfer than leakage. The effects of radiant heat transfer properties of a window system are expressed as solar heat gain coefficient and visual transmittance.

Solar heat gain coefficient (SHGC) is the fraction of solar heat transmitted through a window system (plus absorbed energy that ends up supplying heat inside) compared to the amount of solar heat that would flow through an unimpeded opening of the same size. SHGC is a dimensionless number that can range between 0 and 1. SHGC's of clear single and double-glazed window systems run from 0.7 to 0.9, whereas windows with spectrally-selective glazing typically run from 0.2 to 0.5.

Visual transmittance (Vt) is the fraction of visible light transmitted through a window system with respect to the amount of visible light that would flow through an unimpeded opening of the same size. It is also a dimensionless number that can range between 0 and 1. The Vt of clear single and double-glazed glass runs from 0.8 to 0.9, whereas heavily-tinted glass can have a Vt of 0.1 or even lower. Double-glazed spectrally-selective glazing typically runs from 0.4 to 0.7 Vt

2.1.2 Conduction and Convection

Windows also lose energy by conduction and convection. Insulation performance in walls and ceilings, for example, is usually given as an R-value, which is a measure of the resistance to heat flow that occurs because of the temperature difference across a wall or window and the thermal characteristics of the material in between them. During cold weather, windows with high insulation values are significantly warmer on the inside surface than are windows with low insulation values. This provides several benefits: moisture from condensation is reduced or eliminated, occupant comfort is increased, thermostat set-points can be lowered, the home's heating system may be downsized, and costs for space conditioning are reduced. During the summer, well-insulated windows (particularly those that also have low SHGCs) are more comfortable when outside air temperatures exceed indoor air temperatures thereby allowing for higher thermostat set points and downsizing of the cooling system.

The conductivity of a window system is measured in terms of its **U-factor**. Under most circumstances, a lower U-factor equates to higher efficiency. The U-factor is the reciprocal of R-value and is the rate of heat loss through a window *system* (which includes its frame) measured in Btu per hour per square foot, per degree Fahrenheit (Btu/h-ft^2-°F). **U-value** is measured in the same units, but refers to the conductivity through the center of glass only. Unlike the ratings for insulation products and other building sections, window U-factors and U-values include the insulating effects of indoor and outdoor films.

Glass itself is a fairly good conductor (a bad insulator), so its U-factor is quite high and R-value is low. The R-value of a single-glazed window system is a product of the still air layer immediately next to the pane on the inside and the not-so-still air on the outside. (R-values of 0.68 for inside surfaces and 0.15 for outside surfaces are frequently attributed to air films.)

Adding more layers of glazing (or suspended film) adds more still air spaces. Substituting an inert gas for air lowers the U-factor of the space even more. In general, tactics that lower U-values in insulating glass units lower SHGC as well. This tends to be good news during summer months on all facades of a building, but not-so-good-news during winter months, particularly for south-facing facades, because passive solar gain is attenuated.

2.1.3 IGUs

Insulated glass units (IGUs) have multiple glazings (lites) and sometimes films, either suspended between other elements or adhered to them. They frequently include an inert gas that enhances R-value. Of important energy consequence, they use spacers around their edges to hold the IGU together and to ensure that the spacing between elements is maintained evenly. Generally, spacer material is made of thin, roll-formed metal that is strong enough to ensure good mechanical properties yet small enough to keep edge-of-glass conductive losses relatively low. However, as IGU techniques in achieving high center-of-glass R-values improve (R-values of over 10 are now achievable), edge-of-glass losses represent an increasing portion of overall losses through IGUs. Since spacers tend to be the same size for IGUs of all sizes, **edge losses are substantially more pronounced for smaller IGUs than for larger ones**. Not surprisingly, the industry is working to develop edge materials that have lower conductive losses with excellent strength. The problem is complicated by the fact that coefficients of linear expansion with temperature of glass tend to be much lower than expansion coefficients of plastics and other materials of low conductivity, thereby increasing the risk of IGU leakage under conditions of large temperature swings.

Historic windows usually include three properties that contribute to inefficiency: counter weights, wood frames, and single glazing.

2.1.4 Counter Weights

Unlike newer windows, older double-hung window systems routinely use counter weights to aid opening and closing the window. Counter weights are heavy solid iron castings attached to ropes that run through pulleys then attach to the edges of window frames. These weights slide up and down in uninsulated vertical boxes on each side of the window. The result is counter-balancing forces that aid in opening the windows and holding them open to the degree desired. The counter-weight boxes constitute a large portion of the fixed part of the window frames. A combination of visual inspection, blower door testing, and infrared scans reveal that these boxes are frequently the source of substantial convective and conductive energy losses in both summer and (especially) winter.

Figure 2-2. Counterweights common to many historic window systems

2.1.5 Wood Frames and Single-glazing

Frames are typically made of wood; glazing is typically single. An inch of dry white pine has an R-value of one (1/Btu/ft2/F). The R-value of single glazing is approximately the same due primarily to a dead air space close to the surface on the inside whose R-value is 0.68 and an air space on the outside that varies with wind speed. Accordingly, **when both the frame and glazing have roughly the same R-value** (in the case of older single-glazed windows with wood frames), **conductive losses do not change much with the ratio of the cross sectional area of glazing to frame**.

Older double hung windows with counter-weight boxes can have fixed plus moveable frames with about the same cross section area as the glazing. In such a case, if the single glazing is replaced by, for example, a double glazed IGU with low-E hard coat with a U-value of 0.36 (R =

2.8), the overall window system is improved from R-1 to only 1.46. Indeed, if an R-10 IGU is combined with an R1 frame whose area is half of the window system, improvement to the system is from R-1 to only R-1.8. In such cases, frames constitute thermal short circuits – a potent cause of inefficiency in windows.

2.2 Data Gathering

To assess and quantify energy and heat loss through window systems, the study team determined five testing parameters:

Window size, framing and glazing individually and their sum. This measurement was accomplished in both the field and the lab using a tape measure.

Visual transmittance (Vt). This measurement was accomplished in both the field and the lab using a digital light meter. Visual transmittance is not used in calculations of thermal energy performance but is important for daylighting and related considerations.

Solar Heat Gain Coefficient (SHGC). This measurement was accomplished in both field and the lab using a pyranometer with modeled corrections to account for gains associated with net heat transfer through frames. Local shading factors were also estimated in the case of field measurements.

Heat transfer coefficient of the window system, including frame (U-factor). This measurement was accomplished in the lab only.

Leakiness or air flow in cubic feet per minute. This was measured (a) in the field using a blower door to test individual rooms containing single sample windows and (b) in the lab using a factory-calibrated duct blaster.

2.2.1 Treatments Tested

Using these measured parameters as inputs into RESFEN software, the team estimated the seasonal energy performance of common and innovative options to restore or increase the efficiency of historic wood windows, including:

1. Adding removable films to windows such as those commonly found at home improvement stores and can be applied easily by a homeowner using scissors and a squeegee.

2. Installing aluminum-framed exterior storm windows. Such storm windows have been in widespread use for many decades. While the design and manufacture of these types of storm windows have evolved and improved over time, the study team evaluated an older type of triple-track storm window that had been in use at the field study home.

3. Repairing and air sealing historic wood-framed windows using state-of-the art historic window restoration techniques. This work was performed by the team of Phoenix Window Restoration on the six historic windows selected for the study. The Phoenix team's work included silicone compression bulb weather-stripping on the horizontal rails, felt pile weather-stripping on the vertical parting bead and both interior and exterior sash stops, and sealing and insulating open window frame pockets using a methodology that involves replacing the rope and pulley systems with a hidden spring and stuffing the box with fiberglass insulation. Replacement of counterweight systems with spring systems should not be undertaken in properties listed in the National Register of Historic Places

as this technique does not comply with the Secretary of the Interior's Standards for the Treatment of Historic Properties. An alternative approach to sealing and insulating counterweight pockets, which does comply with the Standard, was also performed in the home (described below and with greater detail in Appendix D of this report).

4. Replacing single glazing with an insulating glass unit containing a low emissivity surface and krypton gas in an existing historic wooden sash. All original glass, wood sash and wood frames were maintained in the test home, with the exception of one window on the south elevation.[3] This window received the same weatherization treatment as described above; however, the single pane glass was replaced with an insulated Low E IGU.

5. Sealing and insulating open window frame pockets using a methodology that retains the use of original weight and pulley systems. As mentioned, counterweights in open pockets can be a potent source of air leakage and conductive losses. The study team used a novel technique to insulate and air seal counterweight pockets while retaining their original functionality and the appearance of the window. The technique involves taking out the sashes and opening the pocket, then enclosing the counter weights in thin wall PVC pipe, whose inside diameter is slightly greater than the outside diameter of the counter weights. Next, after blocking off the top and bottom of each PVC pipe, urethane insulation/sealant is applied to the back of the pocket, the PVC tube is nested in the freshly applied urethane, and more urethane is sprayed on top and secured in the pocket. This technique is described more fully in Appendix D.

6. Installing custom-made, wood-framed, historically-appropriate exterior storm windows. It was reasoned that well-designed storm windows could extend the lifetime of the original windows by protecting them from weather while upgrading the efficiency and comfort of the resulting fenestration system. These exterior energy-efficient storm windows were custom designed and built specifically for the study. They may be used in conjunction with original windows, whether repaired or not. A key consideration was the importance of largely emulating the appearance of the less-efficient storm windows of yesteryear while nonetheless achieving good energy performance and long life.

7. Installing new windows. Fiberglass and vinyl frames are both becoming more widespread than wood or aluminum in new windows. Of the two, fiberglass is much longer lasting and has a lower coefficient of linear expansion than does vinyl. However it is somewhat more expensive. The manufacture of vinyl also entails additional adverse environmental consequences. Both have R-values of around 3. When laced with urethanes or other high-quality insulators, frame R-values can be improved somewhat from R-3, though how much was not explored under this project. The study team removed two historic windows from the study home temporarily and replaced one with a typical double-paned, low-E window of the same size and design.[4]

   This allowed the team to 1) test the efficiency of the new window in the field using the same field testing techniques used for other applications and 2) test the efficiency of the

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[3] This glazing of this window was not original to the home and therefore was selected for field testing the application of new glass in the existing frame.

[4] Jeld Wen window. National Fenestration Rating Council certified: U-factor .34; SHGC 0.36 and a visual transmittance 0.60

removed historic windows in the test chamber. Following these tests, the original historic window was replaced in the home.

The team tested each of the energy efficiency treatments to the extent practical in a test home and in the laboratory chamber. Then, using RESFEN Software, the team was able to predict each treatment's energy performance at any orientation (north, east, south and west) at any location for which historic weather data is available. Results of this analysis for Atlanta, Anchorage, Denver, Boston, Minneapolis, Sacramento, and Phoenix are included in Section 4.

Testing techniques are described in more detail below.

2.2.2 Field Testing Procedures

The team examined several historic homes and interviewed homeowners in Boulder, Colorado before identifying an appropriate home for the study. It is a charming 2700 square foot brick home built in 1902. The home has many original single-glazed windows, most covered by triple-track aluminum storm windows. It is heated by a wood stove in a chimney plus a natural gas-fired boiler that provides hot water to conventional radiators. Since heating energy from the boiler is circulated through pipes, the only duct work of consequence provides supply air from a roof-mounted evaporative cooler that pushes cooled air through the home towards partially-open windows.

Figure 2-3. West Elevation of Vintage 1902 Test Home

Figure 2-4. Northwest Elevation (The closest 3 windows were chosen for retrofit)

Figure 2-5. Sample window on south elevation

The study team identified three window systems on the north and three on the south of the home to be studied (see Figures 2-4 and 2-5). The three windows of interest on the south side of the home are each associated with single rooms. The team was able to largely isolate two of these from the rest of the dwelling for testing (the third cannot be fully isolated from a foyer in the front of the home).

The windows on the north are part of large open areas that cannot be isolated from the rest of the dwelling; however, with the blower door depressurizing the home in the post-retrofit period, no leakage whatever was felt from these windows. Since these are in all practical aspects identical to the windows that were tested in the lab—same construction, materials, size, etc—and were treated to the same comprehensive retrofit procedures, it's likely that their energy-related parameters are within several percent of those of the windows that were tested.

An energy audit of the home was conducted to gather and document baseline conditions and to explore any variables that would likely impact the study (see Appendix C). Overall convective losses were quantified using a blower door and the windows were evaluated to assess their circumstances and identify repairs needed.

After taking measurements for both SHGC and Vt to assess the performance of the windows systems, a blower door was set up in the doorways associated with each of the three windows on the south side and the main doorways of the home were opened. The study team used a Model 3 Minneapolis Blower Door produced by the Energy Conservatory. This is the most widely-used instrument in the industry; tens of thousands are in use to assess the leakiness of buildings and measure the degree of success achieved in air sealing. In this project, the team took measurements of the whole house and in the three rooms housing the test windows before and after window retrofits were installed.

Figure 2-6. Blower Door Installed in Bathroom Doorway

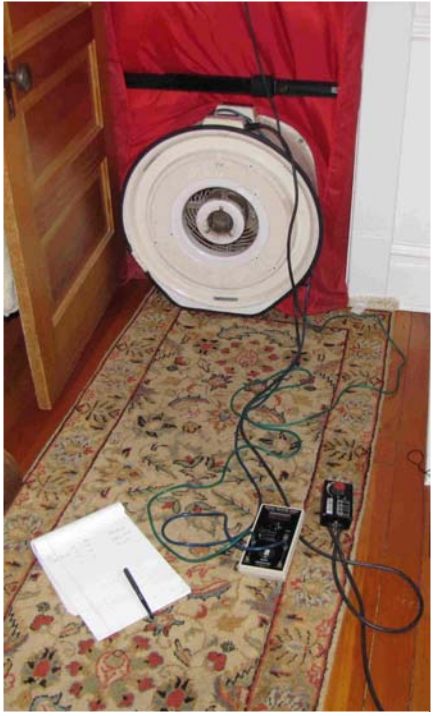

Figure 2-7. Blower Door Installed in Bedroom
(Speed control on floor on right; digital manometer in center)

A blower door consists of a calibrated, variable-speed fan mounted in a shroud that is tightly fitted into a doorway. Running the fan depressurizes the home, allowing a technician to readily find leakage areas with the back of a hand or by observing the movement of artificial smoke. Those skilled in the craft of weatherization use blower doors not only to find leakage areas, but also to estimate the degree to which subsequent air sealing work has been effective. Photos of the blower door installed in interior doorways are shown in Figures 2-6 and 2-7.

Since the areas associated with the study windows were small, a low-flow plate was employed on the blower door to maximize its sensitivity to small flow rates. The result was a measure of all leakage areas in the depressurized room, those associated with the window, plus all others. A second test taken after installing air sealing measures on the window should in principle, reveal changes due only to air sealing the window. Thus, although it is not possible to ascertain ***absolute*** leakage associated with the window work by this field method, the study team was able to measure the value of the ***change*** in air leakage due to retrofit work.

As discussed in Section 2.2.3, the study team employed a similar method for determining leakage in the test chamber using a calibrated duct blaster. An important difference is that ***absolute*** leakage can be more precisely estimated with the chamber technique because the chamber itself is extremely tight.

The study team identified insulation voids associated with the counterweight pockets surrounding the window frames as significant leakage areas; we explored these using the blower door to identify major air leaks and a single-axis infrared sensor to explore conductive losses. The primary aim of these measurements was to identify the *in-situ* thermal losses of the windows and their frames. This baseline data provided the basis for comparison to similar measurements taken post-retrofit to quantify savings.

2.2.3 Laboratory Testing Procedures

The study team designed and constructed a super-insulated, tightly-sealed 390 cubic foot test cell using six inch thick, urethane-based structurally insulated panels (SIPs) on all six sides. It is capable of testing window system samples of up to 20 cubic feet. The cell is heated with electric resistance radiant panels, controlled to maintain a constant warm temperature within a tenth of a degree F (e.g., 122ºF). The test cell can be rolled into and out of a cold chamber built into the inside corner of a building. The cold chamber, which is insulated with 2 inches of polyisocyanurate and 3.5 inches of fiberglass (R-22), is accessed through a 280-pound door, weather sealed and insulated to R-25. The door opens and closes by means of a winch and pulley system suspended from steel roof rafters. The chamber is cooled by a modified room air conditioner to approximately 52F, thereby exposing fenestration samples to a temperature difference of 70 F. Figures 2-8 and 2-9 show the test cell and chamber during construction.

Figure 2-8. Test cell after first day of assembly

Figure 2-9. Completed test cell; outer chamber work nearing completion

The testing laboratory includes a controller designed and built by the project team (see Figure 2-10). The controller employs a WNB Series WattNode electric energy meter manufactured by Continental Control Systems, which produces pulses whose count per unit time is proportional to true watt hours used by the heaters in the chamber. It is calibrated to produce 53,333 pulses per kWh, 0.01875 watt hours per pulse. The electronics also measure temperature and control heaters in the test cell using an Omega Model CNi32 Temperature and Process Controller.

This industrial thermostat is used to operate a relay, which controls a pair of infrared heaters on either side of the test cell that can radiate up to 800 watts if needed, although a phase controller set at approximately 500 watts produces adequate heating for most fenestration system testing. The thermostat is set to have a zero dead band and upon reaching steady state routinely keeps the chamber to within a tenth of a degree F. A pair of EZ-8 data loggers manufactured by Simplified, Inc. is used to monitor eight temperature sensors inside and outside the test cell. These are sampled hundreds of times per minute and produce a time series data record that includes the average temperature of each sensor in the prior minute and the total watt hours of electrical energy used in the previous minute. As a check, the data loggers also record the number of times the heaters were actuated in the previous minute, and the duration of their “on” time.

Figure 2-10. Controller, top view

Appendix B discusses the fabrication of the test chamber in more detail.

2.2.3.1 Determining Heat Transfer Coefficients

The heat transfer coefficient of the test cell as a whole (U-factor) is given by U = Q/AΔT, where U is in units of Btu/hour*ft2*F, Q is the quantity of energy in Btu/hour, A is the area of the chamber in square feet, and ΔT is the inside/outside temperature difference in degrees F. Electric energy used by the heater is gathered in watt hours by the data logger and converted to Btu at the rate of 3.412 Btu/watt hour. The area A is measured with a tape measure. ΔT is the average indoor air temperature differences over a measured time interval, less the average outdoor temperature differences over the same interval.

The team calibrated temperature sensors before setting up the chamber and periodically during its operation using an ice bath in a thermos bottle. Once a window is installed in the test cell, a plug made of the same material as the chamber is installed in the test sample space and is thoroughly sealed. Figure 2-11 shows the test cell with a window and plug installed; the plug is shown in blue. Finally, the doors are closed, the inner chamber is heated and the outer chamber is cooled prior to beginning a calibration run.

Typical calibration runs were conducted for 48 hours. The study team used a spread sheet to display and analyze one-minute data from the data loggers. The spreadsheet also calculates the U-value at the end of each 60 minute interval throughout the test. The analyst looks at the data after a run and notes when temperatures approach steady state and energy use is close to constant. This can take up to 12 hours since all of the mass associated with the chambers must come to temperature. Even if the chamber is already at steady state, the analyst routinely discards the first and last hour's U-value calculation, then takes an average of the remaining computations for U-value and calculates the standard deviation of the distribution. Three to four decimal place repetitions in standard deviations are frequently achieved by this method and U-values for a given sample run are routinely within one percent of results achieved in subsequent runs. Particularly when a given sample being tested is subjected to retrofit, then tested again, such repetition gives confidence that ***changes*** in U-values by virtue of the retrofit can be determined with good accuracy.

The chamber is calibrated with a given plug via three runs of 24 to 48 hours each, which results in the overall U-value of the chamber with the particular plug installed. (The difference between the U-value of one plug and another is typically less than one percent.) A given plug is then used to "house" window samples, beginning with smaller window samples if practical. Under this circumstance, the energy required to maintain the chamber at a given delta T is the sum of (1) the known U-value of the chamber times the area of the chamber minus that of the sample and (2) the unknown U-value of the window sample times its area. Thus determining the U-value of the sample involves measuring its area carefully and ensuring it is completely sealed to the plug, then making another chamber run to gather temperature and energy consumption information.

Figure 2-11. Test cell configured to test small double hung window

2.2.3.2 Measuring Leakiness

The chamber was built to be extremely tight (see Appendix B), so leakage is very close to zero. The test cell has one access door (itself carefully weather-stripped and insulated to R-35) and the aforementioned 20 square foot opening for testing windows into which calibration plugs or plugs with sample windows are inserted. Two additional holes accommodate leakage testing (both of which are insulated with tight-fitting plugs of 7 inches of urethane and air sealed when not conducting leakage tests). Leakiness was measured using a custom-calibrated the duct blaster and two digital pressure gauges from the Energy Conservatory. One 12 inch diameter hole accommodates the duct blaster and allows for precise leakage measurement. The other hole is used to introduce leakage air of a known area (3.14 square inches) via a 2 inch diameter hole. This allows the fan to operate in the "sweet area" of its calibration curve to maximize accuracy.

Figure 2-12. Duct blaster with manometer

When a sample window is installed, the duct blaster is used to pressurize the chamber, taking data points of inside/outside chamber pressure difference versus fan flow. In addition, the technician uses his hand to feel for leaks associated with fenestration system being tested. Then he depressurizes the chamber, again taking data. An analyst examines this data to quantify effective leakage area (ELA) using TECTITE 3.2 software by the Energy Conservatory, and then subtracts the measured leakage areas of the calibration hole and chamber as a whole with a calibration plug in place. The result is ELA in square inches of the sample window system under test. Figure 2-15 shows a screen shot of a plot of flow versus pressure difference.

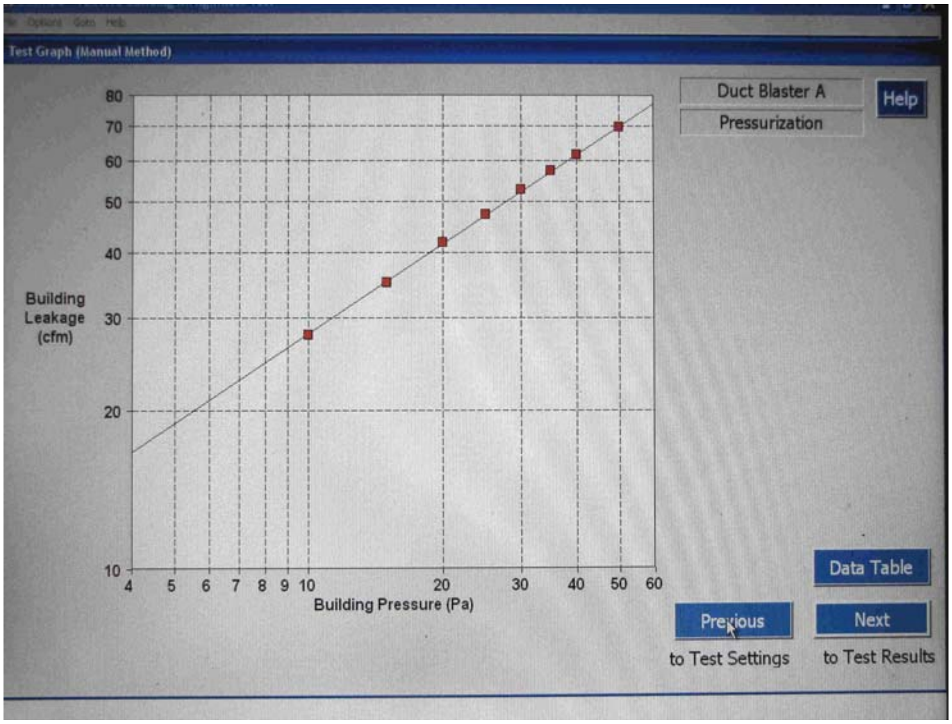

Figure 2-13. Screen shot of eight data points of leakage flow versus pressure difference.

As a final check before finalizing the analyses for this report, the team put a second calibration hole of 3.76 square inches into the chamber, then installed a new plug in the window-testing area and sealed the chamber tight, employing the same techniques used throughout the project. We then used the duct blaster to pressurize the chamber to 50 pascals to check for any leakage. Finally, we took a series of tests at five-pascal pressure increments while measuring flow to estimate the ELA of the chamber under conditions of different hole areas.

The deviation of data points from the regression line is expressed by a correlation coefficient, where perfect agreement results in a correlation coefficient of 1. All of the data taken to produce the calculations resulting in Table 2-1 had correlation coefficients of greater than 0.999. Table 2-1 shows results of the tests.

Figure 2-14. Drilling second calibration hole

2-1. Calculations of Effective Leakage Area

Mode	Physical hole size (in2)	Duct blaster measurement ELA (in2)	Difference (in2)	Difference (%)	Equivalent CFM@ 50 PA
Pressurizing	3.14	3.50	0.36	-11.4%	55
Pressurizing	5.02	4.80	-0.22	4.4%	73
Pressurizing	6.90	6.70	-0.20	2.9%	97
Average			0.0	-1.4%	
Depressurizing	3.14	4.90	1.76	-56.0%	71
Depressurizing	5.02	6.10	1.08	-21.5%	88
Depressurizing	6.90	7.70	0.80	-11.6%	110
Average			1.21	-29.7%	

Note that in pressurizing the chamber, the calculations of effective leakage area are remarkably close to the actual leakage area measured with a ruler, the difference being an average of 1.4 percent. This strongly suggests that: (1) the chamber is indeed quite tight, and (2) computations of ELA when pressurizing the chamber are close to the physical hole cross sectional areas. Accordingly, when testing a fenestration system with only the left calibration hole open, the technique of simply subtracting its actual area from the ELA as measured by the duct blaster when pressurizing the chamber appears sound.

When depressurizing, the difference between actual hole size and ELA is greater, particularly when calibration hole sizes are smaller. Given the accuracy of measured the data, it is possible to develop a calibration curve that produces a correction factor for measuring ELA when depressurizing. However, given both the absence of a clear physical explanation for deviations in the depressurized chamber and the excellence of results from pressurization, we elected to rely on pressurization tests for estimating leakage of the fenestration systems tested on this project.

2.2.3.3 Measuring Solar Heat Gain Coefficient

SHGC is the fraction of solar radiation admitted through a window that is directly transmitted and absorbed, and subsequently released inward. In this project, the team used a factory calibrated LICOR LI200S pyranometer and Keithley 485 digital picoammeter to take readings. The portion of SHGC directly transmitted is measured with a pyranometer that is responsive to the solar spectrum, both visible and invisible. A series of measurements is taken first with the pyranometer looking at the sky directly, then with the pyranometer looking at the sky through the glazing of the window being tested. The resulting ratio, a dimensionless number between 0 and 1, is multiplied by the glazing area portion of the whole window, including its frame. Then a factor is added that represents the portion of solar energy absorbed by the glazing and frame and subsequently released inward. By measuring SHGC and the size of the window, and using solar radiation data throughout a typical meteorological year, it is possible to determine the amount of radiant heat provided to a building through its windows.

2.2.3.4 Measuring Visual Transmittance

Vt is the fraction of visible radiation admitted through a window. The portion of visible light directly transmitted is measured with a digital light meter responsive to the visual specturm. In this project, the team used a United Detector 351 digital light meter. A series of measurements is taken first with the light meter looking at the sky directly, then with the light meter looking at the sky through the glazing of the window being tested. The resulting ratio, a dimensionless number between 0 and 1, is multiplied by the glazing area portion of the whole window, including its frame. Visual transmittance is useful in estimating the daylighting performance of fenestration systems, but in the current project, no analytical use was made of the measurements.

2.2.4 Computer Modeling Procedures

Computer modeling is routinely used to evaluate window performance, particularly for new units. Most modeling techniques flow from engineering principles described in the Fenestration chapter of the *ASHRAE Handbook of Fundamentals*. This handbook was written by members of the American Society of Heating, Refrigeration, and Air Conditioning Engineers and is revised every four years.

Most window modeling software incorporates historic weather data available from NOAA to estimate window performance in different climate zones. Other parametric data for modeling comes both from the ASHRAE Handbook and its extensive library of technical literature, as well as national laboratories, universities, and other laboratories primarily associated with window manufacturers.[5]

The study team used RESFEN (for “Residential Fenestration”), a widely-used energy simulation modeling tool developed by the Lawrence Berkeley National Laboratory with funding the Department of Energy as part of a major performance simulation tool, DOE II. RESFEN is generally considered the most advanced windows simulation and modeling tool available for residential fenestration systems.

The RESFEN model includes historical weather data from over one hundred American cities. It runs a detailed hour-by-hour analysis of the energy flow through windows throughout a typical meteorological year to quantify heating and cooling energy and costs by façade. Key inputs, provided through field and lab testing, include window size, leakage, U-value, and SHGC. The team used RESFEN to predict with good precision the performance of the window systems (1) on the test home in Boulder (using TMY data from Denver, 30 miles distant) and (2) in a sample of cities in other climate zones, including Minneapolis, Anchorage Boston, Atlanta, Phoenix, and Sacramento.

RESFEN stores typical radiant flux and direction of the sun for each hour of the year at a given location. For each hour, this is multiplied times a factor expressive of the angle the sun makes with the window, a factor reflective of the shading on the window, and the SHGC to determine the radiant heat transfer through a window for a season, for example. The sum of radiant gains and conductive losses yields total heat loss/gain for the winter.

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[5] The Windows and Daylighting Group at the Lawrence Berkeley National Laboratory has a number of useful software tools available for free download. These include RESFEN for the analysis of residential fenestration systems and the International Glazing Database (IGDB) which contains spectral data used by other Optics and WINDOW programs. Users may register at **http://windows.lbl.gov/software/registration/register.asp**

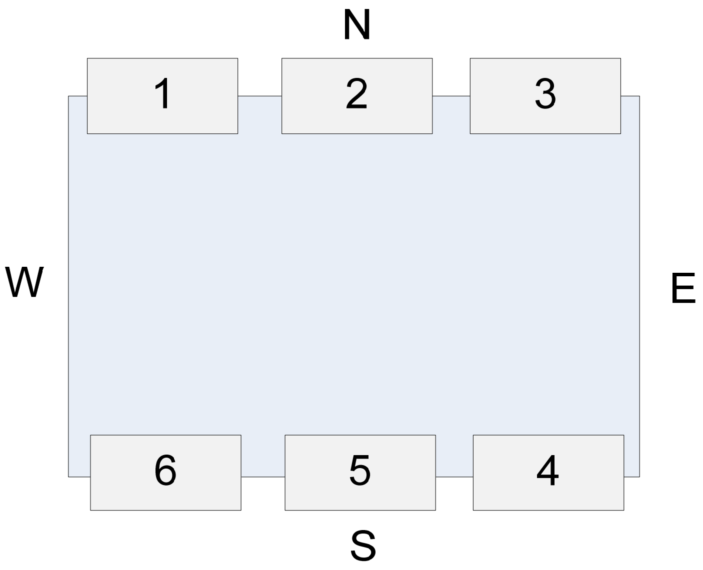
3. TESTING AND RESULTS

3.1 Field Work at Test Home

3.1.1 Initial Window Measurements

Three of the six windows studied in the test home are located on the north side; the other three are on the south. For the purposes of the analysis and reporting, the six windows are numbered clockwise, beginning on the west end of the north side and ending on the west end of the south side, as shown in Figure 3-1.

Figure 3-1. Orientation/numbering of study windows



Information on the test window sizes, SHGCs and Vts is provided in Tables 3-1 through 3-3.

Table 3-1. Window dimensions

Window	Window Height (in)	Window width (in)	Window area (ft2)	Glaz 1 h (in)	Glaz 1 w (in)	Glaz 2 h (in)	Glaz 2 w (in)	Glazed area (ft2)	Portion glazed
1	70.25	44.19	21.56	31.56	39.56	31.50	39.56	17.33	0.80
2	69.81	44.19	21.42	31.56	39.69	31.56	39.56	17.37	0.81
3	46.13	28.25	9.05	19.63	23.63	19.63	23.63	6.44	0.71
4	46.13	28.25	9.05	19.63	23.63	19.63	23.63	6.44	0.71
5	70.25	32.25	15.73	31.75	27.69	31.69	27.69	12.20	0.78
6	70.25	32.25	15.73	31.75	27.75	31.75	27.75	12.24	0.78

Note: Glazing 1 refers to upper and Glazing 2 refers to lower lite height and width

Table 3-2. Solar Heat Gain Coefficients

	Window alone		Storm alone		Screen alone		Window with Storm & Screen	
Window	Raw SHGC	Net SHGC	Raw SHGC	Net SHGC	Raw SHGC	Net SHGC	Raw SHGC	Net SHGC
1	0.81	0.73	0.884	0.92	0.62	0.64	0.58	0.55
2	0.81	0.74	0.884	0.92	0.62	0.64	0.58	0.56
3	0.81	0.68	0.884	0.96	0.62	0.64	0.58	0.53
4	0.81	0.68	0.884	0.96	0.62	0.64	0.58	0.53
5	0.81	0.73	0.884	0.98	0.62	0.64	0.58	0.58
6	0.81	0.73	0.884	0.98	0.62	0.64	0.58	0.58

Note: Raw SHGC refers to the fraction of solar heat transmitted through the center of a window immediately before any absorption or transfer takes place. Net SHGC includes absorbed energy that supplies heat inside.

Table 3-3. Visual Transmittance

	Window alone		Storm alone		Screen alone		Window with Storm & Screen	
Window	Raw Vt	Net Vt	Raw Vt	Net Vt	Raw Vt	Net Vt	Raw Vt	Net Vt
1	0.84	0.67	0.91	0.84	0.66	0.62	0.63	0.46
2	0.84	0.68	0.91	0.84	0.66	0.62	0.63	0.46
3	0.84	0.60	0.91	0.84	0.66	0.62	0.63	0.40
4	0.84	0.60	0.91	0.84	0.66	0.62	0.63	0.40
5	0.84	0.66	0.91	0.84	0.66	0.62	0.63	0.44
6	0.84	0.66	0.91	0.84	0.66	0.62	0.63	0.44

Note that the size and characteristics of windows 1 and 2, 3 and 4, and 5 and 6 are almost identical. These pairings facilitate measurements.

Second, all of the primary windows on the home appeared to be original as deduced by style of construction and (especially), the presence of wavy single glazing (save for Window 5). However they also had triple-track aluminum storm windows installed, whose glazing lites and screens could be moved up and down. Of course, the screen has a deleterious effect on both visual transmittance and SHGC, but it never covers more than half of the window. That fact was taken into account in calculating estimates of net SHGC and net Vt when all three elements are in place.

3.1 Window Retrofit

Following the audit, a team of craftsmen from Phoenix Window Restoration repaired the home's windows. Each of the energy efficiency treatments noted above were then applied to windows on the north and south elevations of the home, isolated from external influences to the extent possible and new measurements were taken to quantify SHGC, Vt, and leakage using the same methodologies[6].

Retrofit work on the home was carefully coordinated so that windows slated to be measured in the chamber could be removed, tested in an "as is" condition in the chamber, then be retrofitted, tested again, and finally returned to the home.

Figure 3-2. Phoenix window's fully-equipped portable shop

Windows 1 through 3 and 5 and 6 each had weights removed from their pockets, the pockets air sealed and insulated, and spring systems installed to retain window functionality and replace counterweights. In addition, all six windows were carefully rebuilt to the extent necessary. This included removing layers of old paint, filling holes and cracks, repriming and sealing wood surfaces, installing new weather stripping, reglazing the windows, preparing fixed surfaces of the frame for the newly-retrofitted windows, and re-installing the windows.

In addition, a new window was designed and installed in the number 4 slot (the small window above the tub in the bathroom was deteriorated beyond repair), and a pair of energy efficient storm windows was installed in the areas formally occupied by triple track aluminum storm windows outside of the recently-repaired primary windows in slots 5 and 6.

Figure 3-2 shows the portable shop used by Phoenix for window retrofit work. Figures 3-3 through 3-7 show a sample of photos of retrofit work at the test home.

Figure 3-3. Starting work

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[6] Although the size and characteristics of each of the pairs of windows on the north and south of the home are nearly identical, their in situ conditions differ. The simulations in Section 4, however, envision that the windows that were tested in both the home and the lab were on all four facades of homes exposed to the weather conditions discussed there. When leakage approaches zero, radiant and conductive heat transfer in windows predominate in determining their energy performance, as mentioned in the report.

Figure 3-4. Sanding the window

Figure 3-5. Repairing rope system

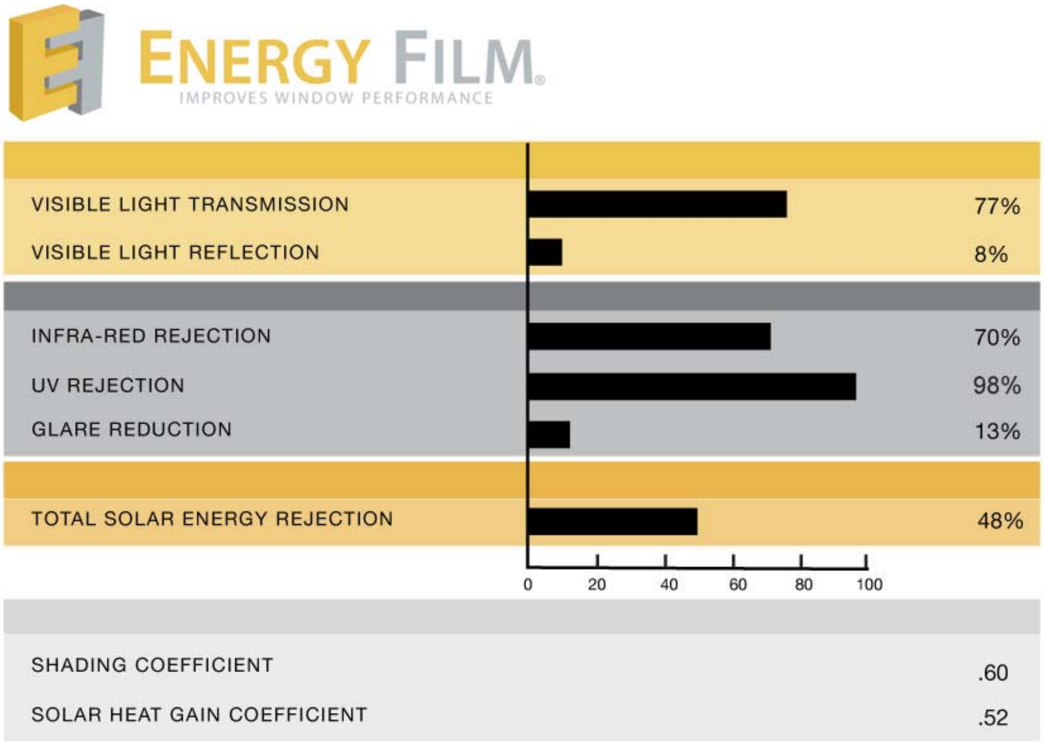
Figure 3-6. Installing spring

Figure 3-7. Retrofit of parting rail with weather strip

3.1.1 Energy Film Testing

Window films, which are adhered to existing glazing as a retrofit measure, are designed to improve window energy performance, enhance comfort, reduce glare, and diminish the fading effects of radiation in the ultraviolet spectrum. Some employ techniques that selectively transmit less of one band of radiant energy than another. For example, *Energy Film* has several products that substantially limit the amount of radiant energy from the sun in both the ultraviolet and infrared regions, while limiting visual transmittance only marginally. Figure 3-8, from *Energy Film's* web site gives information on one of the company's film products.

Figure 3-8. Characteristics of Energy Film



Source: www.energy-film.com

Energy Film's website states that their films improve energy performance in both the summer and the winter.

"Spectrophotometer tests prove in summer, both films block near infrared solar heat wavelengths at the window. This means solar heat rays that normally enter the room and heat its contents are stopped at the window and radiated back outside, reducing air conditioning costs. Laboratory chamber testing indicates in winter, both films allow the room to heat up faster and stay warm longer, reducing winter heating costs."

The team tested the heat transfer coefficient (U-value) of two types of Energy Film, a clear and a darker version, in relation to the U-value of a clear, single-glazed storm window. First, we installed the single-glazed storm window in the chamber with a wood frame. Its overall size is 15.89 SF and glazing area 12.93 SF, representing 81.4% of the window. We then ran a 24 hour test for U-value.

Figure 3-9. Energy Film installation

Figure 3-10. View of window with dark film installed from outside the chamber.

Next, we installed the darker film on the inside of the window without disturbing any other aspects of the window's configuration. (As shown in Figure 3-9, installation involves using water with several drops of liquid soap; then a squeegee is used to eliminate bubbles.) We then ran a pair of back-to-back 24 hour tests for U-value. Finally, we removed the darker film (a simple task since the film peels off from the corner), replaced it with the lighter film, and ran a 24 hour test on this film.

As shown in Table 3-4, the differences in measured U-values are only a quarter of a percent in the case of the dark film and less than one percent in the case of the light film. This is well within instrument error and it is safe to conclude that the differences are effectively zero. Of course, this tells us only that the film has no measurable effect on conductive and convective heat transfer as determined by testing in the chamber.

Nonetheless, there is a complex relationship between the actions of the film, the glazing, and the sun that a test of U-values does not reveal. Whenever radiation strikes a surface, some is transmitted, some is absorbed, and some is reflected. When radiation from the sun strikes a single-glazed clear window, almost 90 percent of it is transmitted. The result is that interior surfaces are heated, good news in the winter, not in the summer. A few percent of the sun's radiation is reflected into the exterior world and a few is absorbed by the glazing, raising its temperature. By virtue of this very slight extra heat, the window will radiate a bit more energy in the long IR wavelengths both to the outside and the inside. It will also heat the air by a modest amount on both the inside and outside.

Table 3-4. Results of chamber testing of U-value for three test cases

Description	*Number of test runs*	*Total test hours counted in calcs*	*Standard Deviation of hourly U-value*	*Weighted Average (U-value)*	*Weighted Average (R-value)*	*Increase in U-value from non-film case (%)*
Single glazed storm, wooden frame	1	18	0.00084	0.737	1.36	0.00%
Same single glazed storm, dark film	2	30	0.0008	0.739	1.35	0.27%
Same single glazed storm, clear film	1	14	0.0007	0.744	1.34	0.94%

If a film is mounted directly behind a single-glazed window, it will reflect, absorb and transmit some of the short wave radiation from the sun as well as some of the long wave radiation from the glazing. The energy it absorbs will raise its temperature, heating the air next to it (on both sides) and radiating in the longer wavelengths on both sides. That which goes inward helps during the heating season but not in the cooling season. That which goes outward is mostly transmitted by the single-glazed surface to which it is attached, but some of it is absorbed and thereby raises its temperature.

The sum of all of this is the effective solar heat gain coefficient of the glazing and film. We could not determine this with high accuracy with the instruments available. However, the film tested does not transmit very much radiation (our measurements indicate that approximately 48% is directly transmitted by the glass-plus-clear-film combination and 18% of the glass-plus-dark-film combination). Further, it does not reflect very much energy. Figure 3-8 indicates 8% reflection in the visible, which represents roughly half of all of the solar energy that strikes a surface after passing through the atmosphere. Accordingly, a substantial portion of solar energy is absorbed, particularly by the darker film. Around half of that ends up within the building's conditioned envelope where it tends to lower heating energy costs (though less so than glazing without film) and raise cooling costs (though less so than bare glazing).

We conclude that the retrofit of films is likely to be more cost effective in cooling-dominated climates that elsewhere. However, shading direct solar radiation outside the envelope is likely to be a better choice when practical.

3.1.2 Leakage Measurements

An initial energy audit of the home included depressurizing it to a canonical pressure difference of 50 pascals, approximately 0.2 of an inch of water pressure. This simulates the effect of a wind of about 22 miles per hour blowing on the home from every direction. The home was configured for winter and the blower door was placed in the front door. The flow was 3000 cubic feet per minute at 50 pascals, somewhat leaky for a 2700 square foot brick dwelling. After window work on the six windows in the study, the overall number dropped to 2884 cfm50, an improvement in overall house leakage of 3.9 percent.

Before and after window retrofit measurements were also taken of the three rooms associated with windows 4, 5, and 6 on the south side of the dwelling. Table 3-5 shows results.

Table 3-5. Blower door flow measurements before and after retrofit

Test Room #	*Retrofit*	*Configuration*	*Pressure (Pa)*	*Flow (cfm)*	*Pre-Post (cfm)*	*Heating savings (therms/yr)*
4	pre	storm only	50	427		
4	post	storm only	50	447	-20	
4	pre	primary only	50	421		
4	post	primary only	50	366	55	
4	pre	both	50	410		
4	post	both	50	366	44	3.92
5	pre	storm only	50	589		
5	post	storm only	50	513	76	
5	pre	primary only	50	502		
5	post	primary only	50	419	83	
5	pre	both	50	499		
5	post	both	50	415	84	7.48
6	pre	storm only	50	991		
6	post	storm only	50	972	19	
6	pre	primary only	50	991		

Test Room #	Retrofit	Configuration	Pressure (Pa)	Flow (cfm)	Pre-Post (cfm)	Heating savings (therms/yr)
6	post	primary only	50	923	68	6.06
6	pre	both	50	987		
6	post	both	40	914	73	

It is interesting to note that when storm windows only are closed in spaces 5 and 6, the post-retrofit blower-door-measured leakage diminishes in spite of no retrofit work on the storm window. This is likely to be due to air sealing work on the counter weight pockets. Weights were removed and the pocket areas were stuffed with fiberglass to high density. This retrofit was not performed on window 4 because the window was rebuilt and replaced.

Second, for window 6, the post-retrofit blower door reading was only 40 pascals of pressure difference, so it cannot be compared with the pre-retrofit flow since it was determined at 50 pascals of pressure difference. Accordingly, estimates of annual savings were made using the difference between readings looking at the primary window only. Accordingly, the estimate of convective savings for window 6 is likely to be conservative.

Third, the pre-post reading of the storm window by itself indicates that the post measurement is slightly higher than the pre measurement by 20 cfm, a modest number. The team did not apply any treatment to this window since it was not original to the home, it was in extremely poor condition, and was slated for removal. There is very little that can be done with such windows shy of permanently air sealing them, which is inconsistent with emergency egress. In the interest of the research project, the team elected to measure the storm by itself but in practice such window are routinely used only in conjunction with primary windows. The reading was anomalous but may have resulted because rust or other debris was disturbed in the process of opening and closing it in order to take other readings, thereby allowing slightly more air to pass through. The research team did not regard it as significant to the overall results.

The estimates of savings due only to lowering convective losses for the winter season assume that the heating degree days in Boulder are 5,500 and that the overall system efficiency of the natural gas-fired hydronic heating system at the test home is 80 percent. Annual savings of heating energy (natural gas) are by virtue of convective improvements alone.

3.2 Chamber Testing

The team tested various combinations of fenestration systems in the laboratory chamber, including windows removed from the test home and several other historic windows acquired from a salvage yard. A “test run” on a given fenestration system consists of configuring a calibrated plug to accept the unit and carefully air sealing its perimeter. After installation, the technical team used a duct blaster in the pressurization mode to test leakiness and to double check that the outer frame of the fenestration system is tightly sealed to the plug. This is accomplished by sliding a hand over all of the crack area with the chamber being pressurized to 25 pascals. Even tiny cracks can be detected because the Bernoulli effect causes small openings under high pressures to yield high velocity air flow. Finally, the team takes measurements with a duct blaster and records the results. Only fenestration systems with double hung or other moveable features showed leakage.

Next, the team removes the duct blaster, seals its hole and the calibration hole, and closes the main door to the chamber. The interior chamber continues to be heated and the exterior chamber cooled so that the masses in both do not drift very far from thermostatically set values. This shortens the time for the chamber to return to a steady-state condition where U-values from hour to hour are nearly uniform.

At this point, the technician leaves the automated equipment to heat the inner chamber and cool the outer chamber to maintain a constant difference in temperature of about 70F while electronic equipment gathers data on energy consumption and temperatures, writing time series data records each minute.

Roughly 24 to 50 hours later, an analyst downloads the data gathered by the data loggers onto a laptop computer, makes an entry into a log book of present circumstances, clears the data from the loggers, and initiates another run. The raw data is later put into an Excel spread sheet for analysis. After entering details on the fenestration system's characteristics, the technical team is able to produce graphs of temperatures and energy use at one minute intervals and calculations of U-values at hourly intervals. The analyst averages U-values over a continuous set of hours beginning with the hour after the chamber has reached steady state and ending an hour before the last computation of U-values. He then calculates a standard deviation of the set of U-values and records all data as shown in Table 3-6.

Table 3-6. Measurements of U and R-values

Description	Number of test runs	Total test hours counted in calcs	Standard Deviation of hourly U-value	Weighted Average (U)	Weighted Average (R-value)	Wind adjusted R	Wind adjusted U
Old double hung from window 5	4	102	0.000872	0.78	1.29	0.79	1.27
Single glazed original alum storm	2	39	0.000872	0.97	1.03	0.53	1.88
New Storm w/o insulated frame	2	32	0.00132	0.27	3.65	3.15	0.32
New Storm w insulated frame	1	16	0.00077	0.24	4.11	3.61	0.28
New Storm single glazed	2	40	0.001045	0.76	1.31	0.81	1.23
Old DH from 5 + new storm w/o Ins	2	39	0.000908	0.21	4.87	4.37	0.23
Old DH from 5 + new Storm w/ Ins	1	42	0.001054	0.19	5.18	4.68	0.21
Retrofitted double hung from wind 5	1	24	0.000862	0.48	2.07	1.57	0.64
Ret DH from 5 + new storm w/o ins	2	39	0.000958	0.19	5.32	4.82	0.21
Ret DH from 5 + new storm w/ ins	3	91	0.000958	0.17	5.83	5.33	0.19
Ret DH from 5 + sg wood storm w/o ins	3	116	0.000926	0.33	3.00	2.50	0.40
New Vinyl Window	3	110	0.000926	0.36	2.75	2.25	0.45

When several runs have been completed, weighted averages of U-values are calculated depending on the number of hours counted in each run. As shown in the table above, an R-value is also calculated (it is simply the inverse of the U-value). Since our chamber is not capable of producing a 15 mph wind across the outside of the sample, we subtracted a factor of R = 0.5 from the R-values to be consistent with canonical procedure from the Fenestration chapter of the ASHRAE Handbook, which counts the outside air film on a vertical window in 15 mph wind as having an R-value of 0.15. Still air has an R-value of 0.68, a differenced of 0.53. Since the flow from the air conditioner fan on the outside chamber produces a modest amount of air movement, we rounded to 0.5 in estimating the wind-adjusted R, and then took the inverse to produce the wind-adjusted U-values shown in the last two columns of Table 3-6. Table 3-7 shows results of duct blaster depressurization testing of the same fenestration configurations as those shown in Table 3-6.

Table 3-7. Effective leakage area estimates

Description	*Depress ELA*	*Net ELA*
Old double hung from window 5	5.2	2.06
Single glazed original alum storm	9.4	6.26
New Storm w/o insulated frame	5.2	2.06
New Storm w insulated frame	5.1	1.96
New Storm single glazed	4.9	1.76
Old DH from 5 + new storm w/o Ins	4.1	0.96
Old DH from 5 + new Storm w/ Ins	3.9	0.76
Retrofitted double hung from wind 5	4.7	1.56
Ret DH from 5 + new storm w/o ins	4.3	1.16
Ret DH from 5 + new storm w/ ins	4.3	1.16
Ret DH from 5 + sg wood storm w/o ins	4.5	1.36
New Vinyl Window	4.8	1.66

These tests were taken with the 3.14 square inch calibration hole open, so the net ELA reflects subtracting that known cross sectional area. In all cases save for the single-glazed aluminum storm window, the net ELA is small and within instrument error bands. The aluminum storm window was carefully sealed in the chamber, yet shows a high net ELA because of ill fitting lites in their tracks and a visible space where they should meet in the middle. In all events, the measurement of U-values reflects convective as well as conductive and radiative losses. Accordingly, computations of U-values are used in the comparisons shown in Section 4.

To further refine testing and confirm results, the study team removed a few of the windows from the test home for corroborative testing in the lab. This helped limit the number of difficult-to-measure variables, however; absolute numbers are more difficult to determine than relative numbers. There may be errors associated with a given measure of U-value (although a number of chamber tests of a standard window product were within a few percent of data listed on National Fenestration Rating Council labels.) However, measurements may be repeated with very small errors, typically less than one percent. Very small standard deviations were routinely achieved when looking at a set of hourly U-value measurements (based on one minute time series data records, themselves made up of averages of thousands of temperature measurements each minute). Thus, measuring a given window, then retrofitting it and measuring it again yields dependable (and often quite useful) relative changes, expressed as a percent change in U-value from the earlier configuration.

The team also used the test chamber to measure the performance of a number of historic and new windows, with various treatments applied, to provide a range of comparative data for the study. First, the study team obtained several used/recycled historic windows from a building materials recycling yard. These windows were of varying types and configurations, including the small double-hung window used in testing the efficacy of the “column” method of air sealing and insulating counter weight pockets (see Appendix D).

Second, we temporarily removed two windows from the historic test home, and installed them in the test chamber. Following baseline testing, the team applied window films, aluminum storm windows and new custom made, high-performance storm windows, measuring the same parameters following each application. More than 200 tests for heat transfer (U-value) were run in the test chamber with an average length of 26 hours. Scores of tests for air leakage and a number of infrared scans were also conducted to identify areas of conductive and convective losses.

Finally, the team installed a new, high efficiency, double hung window to be able to compare the results of the various treatments applied to historic windows to the performance of a standard model new window. The new windows tested included a model with double glazing, interior film, and argon fill whose center of glass U-value is below 0.2 and whose SHGC is below 0.4; and another whose U-value is below 0.2 and SHGC is above 0.6.

4. ANALYSIS AND CONCLUSIONS

4.1 Window Performance in Seven American Cities

Using key tested parameters associated with ten of the window scenarios described in Section 3, the study team estimated energy and cost consequences in seven American cities: Anchorage, Minneapolis, Phoenix, Boston, Denver, Atlanta and Sacramento. Each city's weather patterns and energy costs differ from the others.

For purposes of the RESFEN-based simulation, we assume a 2700 square foot existing brick home with gas-fired heating, the circumstance of the test home. We further assume 100 square feet of window area for each system examined on each of four facades facing north, east, south, and west. This amounts to a window area that is 14.8% of the floor area. In addition to being close to the average total window area of a broad variety of housing stock, choosing 100 square feet per façade facilitates comparing modeled facades with facades of different areas by simply dividing the desired square footage by 100 and multiplying the result by the appropriate values in Tables 4-2 through 4-8. We also assume conventional electric powered compressor-based air conditioning for the modeled homes because this is far more common than is the evaporative cooler associated with the test home.

Almost all homes are shaded on some of their facades some of the time, which diminishes solar heat gain. Reductions in radiant energy entering the dwelling result from blinds, shades, screens, overhangs, and shadowing from fences, neighboring buildings, trees, and the like. Of course, it is important to take this shading into account in simulating window performance in both summer and winter. RESFEN software defines "typical" shading for generic dwellings as follows:

> *Typical…includes: Interior shades (seasonal SHGC multiplier, summer value = 0.80, winter value = 0.90); 1' overhang; a 67% transmitting same-height obstruction 20' away intended to represent adjacent buildings. To account for other sources of solar heat gain reduction (insect screens, trees, dirt, building & window self-shading) the SHGC multiplier was further reduced by 0.1. This results in a final winter SHGC multiplier of 0.8 and a final summer SHGC multiplier of 0.7.*
>
> *These assumptions are intended to represent the average solar heat gain reduction for a large sample of houses. A one-foot overhang is assumed on all four orientations in order to represent the average of a two-foot overhang and no overhang. A 67% transmitting obstruction 20 feet away on all four orientations represents the average of obstructions (such as neighboring buildings and trees) 20 feet away on one-third of the total windows and no obstructions in front of the remaining two-thirds of windows. An interior shade is assumed to have a Solar Heat Gain Coefficient multiplier of 0.9 during the winter and 0.8 during the summer. To account for solar heat gain reducing effects from other sources such as screens, trees, dirt, and self-shading of the building, the SHGC multiplier was further reduced by 0.1 throughout the year. This amounts to a 12.5% decrease in the summer and an 11.1% decrease in the winter. The final SHGC multipliers (0.8 in the*

> *winter and 0.7 in the summer) thus reflect the combined effects of shading devices and other sources.*[7]

Given these considerations, Table 4-1 expresses U-values, SHGCs, SHGCs with typical shading in winter and SHGCs with typical shading in summer for each of the ten fenestration scenarios simulated.

Table 4-1. Key parameters modeled for each fenestration scenario

Window	U-value	SHGC	Typical Winter SHGC	Typical Summer SHGC
Old double hung	1.27	0.73	0.58	0.51
Old storm	1.88	0.98	0.78	0.69
Old double hung +old storm	0.76	0.58	0.46	0.41
New single-glazed storm	1.23	0.73	0.58	0.51
New low U storm	0.28	0.33	0.26	0.23
Old double hung with low U storm	0.21	0.27	0.22	0.19
Retrofit double hung	0.64	0.61	0.49	0.43
Retrofit double hung with single-glazed storm	0.4	0.55	0.44	0.39
Retrofit double hung with low U storm	0.19	0.25	0.20	0.18
New vinyl	0.45	0.43	0.34	0.30

4.1.1 Data

Tables 4-2 through 4-8 show results of seasonal costs in US dollars associated with energy gains and losses through each of these window systems. Results in energy units are expressed in therms of gas for heating and kilowatt hours (kWh) of electricity for cooling, with the total a common unit of a million British thermal units (MBtu). A therm has the energy equivalent of 100,000 Btus, so ten therms = 1 MBtu. A kWh of electricity is the equivalent of 3,412 Btu, so 293 kWh = 1 MBtu. A million Btus is the energy equivalent of about a person year of labor. In Colorado, one MBtu of natural gas costs residential utility customers about $10 while a MBtu of electricity costs $29.30.

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[7] Page 6-3, Program Description of RESFEN 3.1, LBNL-40682 Rev August 1999.

Table 4-2. Energy performance of ten fenestration scenarios in Anchorage (Gas cost $0.440/therm; electricity cost $0.116/kWh)

Window	North heat (therms)	East heat (therms)	South heat (therms)	West heat (therms)	Total heat (therms)	Total heat ($)	North cool (kWh)	East cool (kWh)	South cool (kWh)	West cool (kWh)	Total cool (kWh)	Total cool ($)	Total annual energy (MBtu)	Total annual energy ($)
Old DH	290	238	180	243	951	$419	2	4	6	5	17	$2	95.2	$421
Old Storm	380	312	236	320	1248	$550	3	7	10	12	32	$4	124.9	$554
Old DH+Old Storm	195	154	107	156	612	$270	1	2	2	2	7	$1	61.2	$271
New Sing Glaz Storm	282	230	172	235	919	$405	2	4	6	5	17	$2	92.0	$407
New Lo U Storm	83	60	32	60	235	$104	0	0	0	0	0	$0	23.5	$104
Old DH w Lo U Storm	65	45	23	46	179	$79	0	0	0	0	0	$0	17.9	$79
Retrofit DH	165	122	73	125	485	$214	2	4	4	4	14	$2	48.5	$216
Retro DH w sing gl St	105	67	22	69	263	$116	2	3	3	3	11	$1	26.3	$117
Retro DH w Lo U St	59	41	20	42	162	$71	0	0	0	0	0	$0	16.2	$71
New Vinyl	127	96	60	97	380	$168	0	0	0	0	0	$0	38.0	$168

Table 4-3. Energy performance of ten fenestration scenarios in Minneapolis (Gas cost $1.00 /therm; electricity cost $0.10/kWh)

Window	North heat (therms)	East heat (therms)	South heat (therms)	West heat (therms)	Total heat (therms)	Total heat ($)	North cool (kWh)	East cool (kWh)	South cool (kWh)	West cool (kWh)	Total cool (kWh)	Total cool ($)	Total annual energy (MBtu)	Total annual energy ($)
Old DH	242	178	104	192	716	$716	138	278	241	327	984	$98	75.0	$814
Old Storm	324	239	140	261	964	$964	206	424	375	486	1491	$149	101.5	$1,113
Old DH+Old Storm	158	108	48	117	431	$431	105	206	178	242	731	$73	45.6	$504
New Sing Glaze Storm	234	172	97	185	688	$688	138	279	242	328	987	$99	72.2	$787
New Lo U Storm	63	37	2	40	142	$142	49	90	79	107	325	$33	15.3	$175
Old DH w Lo U Storm	50	27	-2	30	105	$105	36	64	57	77	234	$23	11.3	$128
Retrofit DH	132	82	18	90	322	$322	115	230	198	269	812	$81	35.0	$403
Retro DH w sing gl Stor	83	38	-21	44	144	$144	105	205	176	239	725	$73	16.9	$217
Retro DH w Lo U Storm	46	24	-3	27	94	$94	32	56	50	68	206	$21	10.1	$115
New Vinyl	101	64	18	69	252	$252	69	133	115	158	475	$48	26.8	$300

Table 4-4. Energy performance of ten fenestration scenarios in Phoenix (Gas cost $1.43 /therm; electricity cost $0.11/kWh)

Window	North heat (therms)	East heat (therms)	South heat (therms)	West heat (therms)	Total heat (therms)	Total heat ($)	North cool (kWh)	East cool (kWh)	South cool (kWh)	West cool (kWh)	Total cool (kWh)	Total cool ($)	Total annual energy (MBtu)	Total annual energy ($)
Old DH	37	13	-24	24	50	$72	804	1553	1337	1730	5424	$597	23.5	$668
Old Storm	48	19	-23	34	78	$112	1111	2135	1865	2377	7488	$824	33.4	$935
Old DH+Old Storm	25	5	-27	13	16	$23	616	1203	1022	1341	4182	$460	15.9	$483
New Sing Glaze Storm	37	12	-24	23	48	$69	800	1546	1330	1724	5400	$594	23.2	$663
New Lo U Storm	9	-3	-24	1	-17	-$24	333	662	542	735	2272	$250	6.1	$226
Old DH w Lo U Storm	7	-4	-21	0	-18	-$26	269	537	438	599	1843	$203	4.5	$177
Retrofit DH	20	0	-32	8	-4	-$6	619	1242	1052	1381	4294	$472	14.3	$467
Retro DH w sing gl Stor	12	-6	-34	1	-27	-$39	533	1097	921	1220	3771	$415	10.2	$376
Retro DH w Lo U Storm	7	-3	-20	0	-16	-$23	249	496	403	553	1701	$187	4.2	$164
New Vinyl	16	0	-26	6	-4	-$6	450	883	732	979	3044	$335	10.0	$329

Table 4-5. Energy performance of ten fenestration scenarios in Boston (Gas cost $1.51 /therm; electricity cost $0.17/kWh)

Window	North heat (therms)	East heat (therms)	South heat (therms)	West heat (therms)	Total heat (therms)	Total heat ($)	North cool (kWh)	East cool (kWh)	South cool (kWh)	West cool (kWh)	Total cool (kWh)	Total cool ($)	Total annual energy (MBtu)	Total annual energy ($)
Old DH	191	128	58	145	522	$788	106	226	184	228	744	$126	54.7	$915
Old Storm	261	174	82	201	718	$1,084	163	347	287	379	1176	$200	75.8	$1,284
Old DH+Old Storm	121	73	16	83	293	$442	82	167	136	186	571	$97	31.2	$540
New Sing Glaze Storm	185	122	52	139	498	$752	107	227	184	248	766	$130	52.4	$882
New Lo U Storm	47	20	-13	24	78	$118	37	73	59	82	251	$43	8.7	$160
Old DH w Lo U Storm	36	13	-14	16	51	$77	28	54	44	61	187	$32	5.7	$109
Retrofit DH	100	51	-9	60	202	$305	92	189	151	204	636	$108	22.4	$413
Retro DH w sing gl Stor	59	17	-38	23	61	$92	83	170	137	183	573	$97	8.1	$190
Retro DH w Lo U Storm	33	12	-13	15	47	$71	23	46	37	53	159	$27	5.2	$98
New Vinyl	75	39	-3	46	157	$237	58	111	92	123	384	$65	17.0	$302

Table 4-6. Energy performance of ten fenestration scenarios in Denver (Gas cost $1.00 /therm; electricity cost $0.10/kWh)

Window	North heat (therms)	East heat (therms)	South heat (therms)	West heat (therms)	Total heat (therms)	Total heat ($)	North cool (kWh)	East cool (kWh)	South cool (kWh)	West cool (kWh)	Total cool (kWh)	Total cool ($)	Total annual energy (MBtu)	Total annual energy ($)
Old DH	173	89	15	117	394	$394	132	318	230	303	983	$98	42.8	$492
Old Storm	228	119	21	158	526	$526	194	483	356	450	1483	$148	57.7	$674
Old DH+Old Storm	114	46	-1	68	227	$227	98	233	165	220	716	$72	25.1	$299
New Sing Glaze Storm	168	84	10	112	374	$374	131	318	230	302	981	$98	40.7	$472
New Lo U Storm	46	5	-3	18	66	$66	46	105	71	96	318	$32	7.7	$98
Old DH w Lo U Storm	35	1	-3	11	44	$44	34	79	54	73	240	$24	5.2	$68
Retrofit DH	94	25	-39	46	126	$126	107	258	183	242	790	$79	15.3	$205
Retro DH w sing gl Stor	57	-6	-64	13	0	$0	99	230	161	213	703	$70	2.4	$70
Retro DH w Lo U Storm	32	1	-26	10	17	$17	30	70	48	66	214	$21	2.4	$38
New Vinyl	72	21	-25	36	104	$104	66	153	105	142	466	$47	12.0	$151

Table 4-7. Energy performance of ten fenestration scenarios in Atlanta (Gas cost $1.196 /therm; electricity cost $0.071/kWh)

Window	North heat (therms)	East heat (therms)	South heat (therms)	West heat (therms)	Total heat (therms)	Total heat ($)	North cool (kWh)	East cool (kWh)	South cool (kWh)	West cool (kWh)	Total cool (kWh)	Total cool ($)	Total annual energy (MBtu)	Total annual energy ($)
Old DH	85	40	-11	50	164	$196	283	607	409	627	1926	$137	23.0	$333
Old Storm	113	56	-9	71	231	$276	397	847	581	879	2704	$192	32.3	$468
Old DH+Old Storm	54	18	-24	26	74	$89	230	483	321	501	1535	$109	12.6	$197
New Sing Glaze Storm	82	38	-13	48	155	$185	289	608	410	628	1935	$137	22.1	$323
New Lo U Storm	20	-2	-27	2	-7	-$8	136	271	177	280	864	$61	2.2	$53
Old DH w Lo U Storm	15	-3	-24	0	-12	-$14	111	221	144	228	704	$50	1.2	$36
Retrofit DH	43	7	-36	15	29	$35	253	522	353	534	1662	$118	8.6	$153
Retro DH w sing gl Stor	24	-9	-47	-2	-34	-$41	240	485	327	496	1548	$110	1.9	$69
Retro DH w Lo U Storm	14	-3	-23	-1	-13	-$16	104	204	133	210	651	$46	0.9	$31
New Vinyl	33	6	-27	11	23	$28	174	354	232	364	1124	$80	6.1	$107

Table 4-8. Energy performance of ten fenestration scenarios in Sacramento (Gas cost $0.917 /therm; electricity cost $0.122/kWh)

Window	North heat (therms)	East heat (therms)	South heat (therms)	West heat (therms)	Total heat (therms)	Total heat ($)	North cool (kWh)	East cool (kWh)	South cool (kWh)	West cool (kWh)	Total cool (kWh)	Total cool ($)	Total annual energy (MBtu)	Total annual energy ($)
Old DH	81	36	-8	46	155	$142	225	529	437	663	1854	$226	21.8	$368
Old Storm	107	50	-5	65	217	$199	319	762	637	946	2664	$325	30.8	$524
Old DH+Old Storm	53	16	-21	22	70	$64	173	409	330	511	1423	$174	11.9	$238
New Sing Glaze Storm	79	34	-10	43	146	$134	224	530	436	663	1853	$226	20.9	$360
New Lo U Storm	20	-3	-25	0	-8	-$7	91	209	160	265	725	$88	1.7	$81
Old DH w Lo U Storm	15	-4	-23	-2	-14	-$13	76	167	125	210	578	$71	0.6	$58
Retrofit DH	42	5	-34	11	24	$22	188	443	360	549	1540	$188	7.7	$210
Retro DH w sing gl Stor	23	-10	-46	-5	-38	-$35	174	406	325	494	1399	$171	1.0	$136
Retro DH w Lo U Storm	13	-5	-22	-3	-17	-$16	70	151	116	191	528	$64	0.1	$49
New Vinyl	33	4	-25	8	20	$18	128	289	229	365	1011	$123	5.5	$142

4.1.2 Discussion

Note that in Anchorage (Table 4-2) the weather is quite cold with almost no cooling load while Phoenix (Table 4-4) has very hot weather and very little heating. The cost of gas in Phoenix is 3.24 times that of gas in Anchorage. Nonetheless, double-hung windows with aluminum storms on all four facades in Anchorage result in window energy consumption of 61.2 MBtu, 3.8 times the consumption in Phoenix. The retrofit double hung plus Low U storm window in Anchorage lowers window energy use to 16.2 MBtu, a 3.78 factor of savings over the original system, and about the same relative percentage savings achieved in Phoenix. However, absolute savings (in millions of Btus) in Anchorage is greater by a factor of four.

Minneapolis (Table 4-3) has substantial heating and moderate cooling loads with middling energy costs for both gas and electricity. In this case, upgrading the original window and adding a low U storm results in an overall energy savings of four and a half fold, an annual energy savings of 35.5 MBtu and a cost savings of $389.

Boston's (Table 4-5) heating and cooling loads are typical of New England with energy costs for both gas and electricity well above national averages. Although storm windows are rarely employed as the only fenestration, it is instructive to look at the difference between the annual energy costs of a triple track aluminum storm window of the kind that was on the test home and that of the wood-frame low U storm window fabricated for this project. In Boston, the annual energy cost associated with the aluminum storm on its own is $1,284/yr versus $160 for the low U storm, a difference of $1,124. The same comparison in Denver (Table 4-6) yields a difference of $674/yr for the aluminum versus $98 for the wood-frame low U storm, a savings of $576. In Boston, the difference in energy performance of these two storm window systems amount to 67.1 MBtu, in Denver, 50.0 MBtu.

This illustrates that the cost of fossil-fuel-based energy used for space conditioning in most American homes remains quite modest, a fact that militates against short payback periods for many conservation measures. Where costs of energy are higher, savings associated with conservation retrofits are more attractive.

This point is made clearer by the comparisons shown in Tables 4-9 through 4-11 (which make use of the results shown in Tables 4-2 through 4-8). These illustrate savings from several different window treatments in each of the seven cities modeled. Absolute energy savings in MBtu per year and relative savings (percentage) are shown as well as annual dollar savings and costs of retrofitting 400 square feet of window area (100 square feet on each of four facades), and simple payback. Savings and payback calculations assume a retrofit cost of $25 per square foot. In practice, this number can vary widely depending on the condition of the existing windows and the customer's desires[8]. Labor tends to be the key element in most extensive window retrofit work.

Table 4-9 compares the double-hung historic window as found versus the same window after retrofit (including insulating and sealing, retrofitting counterweight pockets and replacing single glazing with an IGU).

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[8] Typical thorough retrofit practices are described and illustrated in Section 3.1 of this report.

Table 4-9. Savings from retrofitting existing double-hung windows

City	Old DH (MBtu/yr)	Retrofit DH (MBtu/yr)	Absolute Savings (MBtu/yr)	Relative Savings (%)	Savings ($/yr)	Retrofit Cost ($)*	Simple Payback (years)
Anchorage	95.2	48.5	46.6	49.0%	$206	$10,000	48.6
Atlanta	23.0	8.6	14.4	62.7%	$180	$10,000	55.5
Boston	54.7	22.4	32.4	59.1%	$502	$10,000	19.9
Denver	42.8	15.3	27.5	64.2%	$287	$10,000	34.8
Minneapolis	75.0	35.0	40.0	53.3%	$411	$10,000	24.3
Phoenix	23.5	14.3	9.3	39.4%	$202	$10,000	49.6
Sacramento	21.8	7.7	14.2	64.9%	$158	$10,000	63.1
Averages	48.0	21.7	26.3	54.8%	$278	$10,000	36.0

* Retrofit cost is based on $25 per square foot for 100 square feet of window area on each of four facades for a total of 400 square feet (400 x $25 = $10,000).

Average savings resulting from retrofit is 26.3 MBtu per year and 54.8%. However even though savings in Anchorage are twice as much as the average, paybacks are over twice as long than in both Boston and Minneapolis because natural gas costs in Anchorage are so low. Second, savings in this case are counted only from the change in U-value as measured in the test chamber which did not include leakage savings from sealing the weight pockets, but only from installing weather stripping in the parting rail between the upper and lower lites and the edges of the window frame.

Table 4-10 is analogous to Table 4-9 but compares the existing double-hung window with a new mid-grade vinyl window installed by a do-it-yourselfer. Savings and payback calculations assume a cost of $10 per square foot.

Table 4-10. Savings from replacing double-hung window with a new vinyl window

City	Old DH (MBtu/yr)	New Vinyl (MBtu/yr)	Absolute Savings (MBtu/yr)	Relative Savings (%)	Savings ($/yr)	Retrofit window cost ($)*	Simple payback (years)
Anchorage	95.2	38.0	57.2	60.1%	$254	$4,000	15.8
Atlanta	26.4	8.1	18.3	69.2%	$226	$4,000	17.7
Boston	56.1	17.7	38.4	68.4%	$612	$4,000	6.5
Denver	44.5	12.8	31.7	71.2%	$342	$4,000	11.7
Minneapolis	76.7	27.7	49.0	63.9%	$515	$4,000	7.8
Phoenix	33.1	15.4	17.7	53.6%	$339	$4,000	11.8
Sacramento	25.1	7.2	17.9	71.2%	$227	$4,000	17.6
Averages	51.0	18.1	32.9	64.5%	$359	$4,000	11.1

* Retrofit cost is based on $10 per square foot for 100 square feet of window area on each of four facades for a total of 400 square feet (400 x $10 = $4,000).

Here both average and relative savings are slightly higher and costs of the retrofit are lower, so paybacks are shorter than the other efficiency options evaluated for this study. However, the team used a relatively low-cost window of the type available in most home improvement stores for this test. A higher quality window, installed by professional technicians would likely cost considerably more. Again, although absolute energy savings are three times higher than those achieved in Phoenix, paybacks are longer than in all cities save Atlanta.

Table 4-11 compares the existing double-hung window with the same window that has been supplemented with a low-U storm window. Savings assume a cost of $25 per square foot for the new storm window and 100 square feet of the fenestration systems installed on each of four facades.

Table 4-11. Savings from retrofitting double-hung window with new Low U-value storm

City	Old DH (MBtu/yr)	Old DH + New Lo U Storm (MBtu/yr)	Absolute Savings (MBtu/yr)	Relative Savings (%)	Savings ($/yr)	Retrofit window cost ($)*	Simple payback (years)
Anchorage	95.2	17.9	77.3	81.2%	$342	$10,000	29.2
Atlanta	26.4	1.2	25.2	95.4%	$297	$10,000	33.6
Boston	56.1	5.7	50.3	89.8%	$806	$10,000	12.4
Denver	44.5	5.2	39.3	88.3%	$424	$10,000	23.6
Minneapolis	76.7	11.3	65.4	85.3%	$686	$10,000	14.6
Phoenix	33.1	4.5	28.6	86.4%	$491	$10,000	20.4
Sacramento	25.1	0.6	24.5	97.7%	$311	$10,000	32.2
Averages	51.0	6.6	44.4	87.0%	$480	$10,000	20.8

* Retrofit cost is based on $25 per square foot for 100 square feet of window area on each of four facades for a total of 400 square feet (400 x $24 = $9600).

In this case, savings average 44.4 MBtu and 87%. Dollar savings are over $800 per year in Boston and average $480 overall. The savings in Anchorage are the energy equivalent of 77 person years of labor, yet paybacks are 28 years.

It is useful to note in the above analyses that:

- The assumed cost of a highly-energy-efficient storm window reflects no economies of scale and assumes a wood frame, which is labor intensive to manufacture and has an R-value that is three times less than that of fiberglass or vinyl.
- No local, state, federal, or utility incentives are taken into account.
- The analysis does not account for such benefits as increased comfort, yet many consumers count this factor as primary in decisions concerning their windows.
- There are many circumstances in the real world in which useful lifetimes of various window treatments may be less than payback periods. These factors are notoriously difficult to quantify and therefore have not been considered in payback calculations.
- The analysis does not account for the likely increase in the lifetime of the primary window resulting from either retrofit or adding an energy-efficient exterior storm window.
- Cost-benefit calculations assume the rate of inflation in energy costs is identical to the overall inflation rate. Accordingly, the analysis is likely to be conservative.

4.2 The Influence of Frame Size and Material on Window Efficiency

Before drawing inferences from the above findings, it is useful to note the key role played by frames in determining window energy performance. Historic window frames are typically made of wood; glazing is typically single. An inch of dry white pine has an R-value of one (1/Btu/ft2/F). Single glazing also has an R-value of approximately one owing primarily to a dead air space close to the surface of the inside whose R-value is 0.68 and an air space on the outside that varies with wind speed, but is conventionally assigned an R-value of 0.15, corresponding to a wind speed of 15 miles per hour. Accordingly, **when both the frame and glazing have roughly the same R-value** (the case of older single-glazed windows with wood frames), **conductive losses do not change much with the ratio of the cross sectional area of glazing to frame**.

IGUs have multiple glazings and sometimes films, either suspended between other elements or adhered to them. They frequently include an inert gas that enhances R-value. Of important energy consequence, they use spacers around their edges to hold the IGU together and ensure that the spacing between elements is maintained evenly. Generally, spacer material is made of thin, roll-formed metal that is strong enough to ensure good mechanical properties yet small enough to keep edge-of-glass conductive losses relatively low. However, as IGU techniques in achieving high center-of-glass R-values improve (R-values of over 10 are now readily achievable), edge-of-glass losses represent an increasing portion of overall losses through IGUs. Since spacers tend to be the same size for IGUs of all sizes, **edge losses are substantially more pronounced for smaller IGUs than for larger ones**. The window industry is working to develop edge materials that have lower conductive losses along with excellent strength. The problem is complicated by the fact that coefficients of linear expansion with temperature of glass tend to be much lower than expansion coefficients of plastics and other low conductivity materials, thereby increasing the risk of IGU leakage under conditions of large temperature swings.

Moderate size older double-hung windows with counter-weight boxes can have fixed plus moveable frame areas that are about the same cross section area as the glazed area. In such cases, if for example, the single glazing is replaced by a double glazed IGU with low-E hard coat and a U-value of 0.36 (R = 2.8), the overall window system is improved over single glazing from R-1 to only 1.46. Indeed, if an R-10 IGU is combined with an R1 frame whose area is half of the window system, improvement to the system is from R-1 to only R-1.8.

Frames made of either vinyl or fiberglass have R-values in the area of 3 per inch. The addition of urethane or related materials of substantially higher R-value can increase this value. (Urethane used as an insulation product has an R-value ranging from 7 to 11 depending on density.) In addition, adding even 25% of Styrofoam (R = 5 per inch) to cavities routed out from the inside of wooden frames can raise the overall R-values of window systems by 5 to 15%.

To illustrate the effects of frame material and percentage of window area on the U- and R-values of windows, Table 4-12 explores several combinations of frame and IGU R-values on windows with a glazing-to-total window area from 0.5 to 0.87 as a function of frame U-values of 1 and 0.33 with window U-values of 1 to 0.1.

Table 4-12. U-values and R-values on various glazing to window area ratios

Ratio glazing/ total window area	U frame	R frame	U glazing	R glazing	Total net U	Total net R
0.50	1	1.00	1	1.0	1.00	1.00
0.50	1	1.00	0.5	2.0	0.75	1.33
0.50	1	1.00	0.36	2.8	0.68	1.46
0.50	1	1.00	0.2	5.0	0.60	1.66
0.50	1	1.00	0.1	10.0	0.55	1.80
0.50	0.33	3.03	1	1.0	0.66	1.51
0.50	0.33	3.03	0.5	2.0	0.41	2.41
0.50	0.33	3.03	0.36	2.8	0.34	2.90
0.50	0.33	3.03	0.2	5.0	0.27	3.76
0.50	0.33	3.03	0.1	10.0	0.22	4.63
0.75	1	1.00	1	1.0	1.00	1.00
0.75	1	1.00	0.5	2.0	0.63	1.60
0.75	1	1.00	0.36	2.8	0.52	1.92
0.75	1	1.00	0.2	5.0	0.40	2.49
0.75	1	1.00	0.1	10.0	0.33	3.06
0.75	0.33	3.03	1	1.0	0.83	1.20
0.75	0.33	3.03	0.5	2.0	0.46	2.19
0.75	0.33	3.03	0.36	2.8	0.35	2.84
0.75	0.33	3.03	0.2	5.0	0.23	4.30
0.75	0.33	3.03	0.1	10.0	0.16	6.33
0.87	1	1.00	1	1.0	1.00	1.00
0.87	1	1.00	0.5	2.0	0.56	1.78
0.87	1	1.00	0.36	2.8	0.44	2.27
0.87	1	1.00	0.2	5.0	0.30	3.32
0.87	1	1.00	0.1	10.0	0.21	4.68
0.87	0.33	3.03	1	1.0	0.92	1.09
0.87	0.33	3.03	0.5	2.0	0.48	2.09
0.87	0.33	3.03	0.36	2.8	0.36	2.81
0.87	0.33	3.03	0.2	5.0	0.22	4.62
0.87	0.33	3.03	0.1	10.0	0.13	7.75

The above analysis results in a number of useful observations.

- Improving the R-value of frames is highly important. In particular, improving the R-value of a substantial portion of the fixed part of the frame of an older double hung window--like the counter weight box--can be very effective.
- Raising the glazing-to-frame ratio of any window system whose frames have an R-value of one or less makes good sense.
- Investing in high R-value IGUs is increasingly cost effective as frame portions become smaller and frame R-values higher.
- Retrofit storm windows with high R-value glazing are increasingly cost effective when frames are small and have good R-values.

4.3 Storm Windows for Historic and Other Homes

The strategy of adding an energy-efficient storm window to an existing fenestration system in an historic dwelling showed promising results. Even before upgrading the existing double hung window, the combination of a wood frame with a modern insulated glazing unit (IGU) and krypton gas resulted in an overall U value of 0.21 (SHGC 0.27). However, given the above discussion of the relative efficiency of wood versus vinyl or fiberglass frames, it is useful to estimate the storm window's energy performance if the wooden frame were replaced by fiberglass (retaining the same IGU).

Although PVC plastic is in wide use in windows and its insulating value is close to that of fiberglass (about R-3 per inch), we elected not to examine this option because of several shortcomings associated with vinyl. First, its coefficient of linear expansion with temperature is about 16 times that of fiberglass, so it tends to shift with temperature changes, which can weaken joints over time and result in leakage of both air and water. Second, even with the addition of ultraviolet inhibitors to the plastic during the extrusion process, the lifetime of vinyl windows is typically shorter than that of fiberglass or even well-maintained wood. The rate of deterioration is a direct function of the magnitude of long-term exposure to direct sunlight, so south-facing windows are more vulnerable to UV degradation than are those on other elevations. Lifetimes tend to be particularly short in sunny, high altitude regions like Colorado where clear skies and less atmosphere scatter the sun's direct beam UV radiation.

In addition, fiberglass is structurally much stronger than either wood or vinyl, so frames can be of smaller cross sectional areas than is possible with either of those materials. Since in this case, the IGU is even more insulative than fiberglass, the result of a smaller frame is a more energy-efficient window. This affords greater viewing area and solar heat gain, exposing more of the window's historic characteristics (while avoiding exposing it to the ravages of weather). Finally, pultruded fiberglass frames may be fabricated to closely resemble wooden frames.

Given these considerations, we analyzed results assuming a fiberglass frame. First, we took the chamber-measured U values of the low-U storm window with a wooden frame built for this project, as well as that of the old double hung before retrofit, and the combination of the two. We assumed an R value of 0.8 (U = 1.25) for the wooden frame which is 1.96 inches wide and an inch thick. (This is slightly less than the canonical R = 1 per inch because the frame houses the IGU whose R value at the edge is considerably less than at center of glass.) The net R value of the glazing was R = 5.33, U = 0.186. Next, we assumed a fiberglass frame that is an inch wide and de-rated the fiberglass from R= 3 to R = 2.4 to account for the glazing's edge effects. This allowed the study team to compare assumed conditions identical to those measured in the chamber, to examine specifically the effects of the fiberglass frame. The R value for the storm window estimated by this procedure is 5.05, U = 0.198. With the old double hung, the R value of the fenestration system is 6.l25, U value 0.16. Owing to the larger opening (yet low secondary heat effect due to the better insulated frame) we increased the estimate of SHGC from 0.27 to 0.28. Finally, we ran RESFEN with this window system making the same assumptions that were made in producing the analyses shown in Tables 4-2 through 4-8.

The results by city are shown in Table 4-13.

Table 4-13. Energy Performance of Double Hung window with Low U, Fiberglass Frame Storm Window (U = 0.16; SHGC = 0.28)

City	*North heat (therms)*	*East heat (therms)*	*South heat (therms)*	*West heat (therms)*	*Total heat (therms)*	*Total heat ($)*	*North cool (kWh)*	*East cool (kWh)*	*South cool (kWh)*	*West cool (kWh)*	*Total cool (kWh)*	*Total cool ($)*	*Total annual energy (MBtu)*	*Total annual energy ($)*
Denver	23	-11	-41	-1	-30	$(30)	36	83	56	77	252	$25	-2.1	$(5)
Boston	24	1	-27	4	2	$3	31	63	52	71	217	$37	0.9	$40
Minneapolis	35	11	-19	14	41	$41	43	79	68	96	286	$29	5.1	$70
Phoenix	4	-7	-24	-3	-30	$(43)	268	546	443	609	1866	$205	3.4	$162
Atlanta	9	-9	-31	-7	-38	$(45)	119	234	153	239	745	$91	-1.3	$45
Sacramento	8	-11	-30	-9	-42	$(39)	76	167	126	209	578	$58	-2.2	$19
Anchorage	46	26	3	26	101	$45	0	0	0	0	0	$0	10.1	$45
Averages	21	0	-24	3	1	$(10)	82	167	128	186	563	$64	2	$54

4.3.1 Discussion

Note that in all cases, the system using a fiberglass frame saves substantial energy over a wood-framed window system; the average across seven cities modeled is 70%.

The product modeled for the study is not yet available in the marketplace, so estimating costs to the consumer is inexact. However, by applying the costs of energy-efficient IGOs and fiberglass pultrusions, which are increasingly widespread in the window industry, we are able to estimate costs to the end user with the following assumptions:

- Economies of scale. Manufacturing windows in batches is substantially more cost effective than building individual windows to precise measurements. Thus, we assume that “bulk” purchases are defined as orders of 20 units or more.
- The costs of taking window measurements, installation, and shipping are not included in the cost estimates.

Given these considerations, we estimate costs of $14 to $18 per square foot for a fiberglass frame, low U storm window discussed above. In the case of the relatively large (15.73 square feet) windows in the historic home that is the subject of this report, the cost would be about $236 per window.

Table 4-14 assumes a cost of $15 per square foot for purposes of calculating paybacks.

Table 4-14. Double Hung with Fiberglass Low U Storm @ $15/ft2

City	*Old DH (MBtu/yr)*	*Old DH + New Lo U Fiberglass Frame Storm (MBtu/yr)*	*Absolute Energy Savings (MBtu/yr)*	*Relative Energy Savings (%)*	*Savings ($/yr)*	*Retrofit window cost ($)*	*Simple payback (years)*
Anchorage	95.2	10.1	85.1	89.4%	$377	$6,000	15.9
Atlanta	26.4	-1.3	27.6	104.8%	$287	$6,000	20.9
Boston	56.1	0.9	55.1	98.3%	$875	$6,000	6.9
Denver	44.5	-2.1	46.6	104.8%	$497	$6,000	12.1
Minneapolis	76.7	5.1	71.6	93.4%	$745	$6,000	8.1
Phoenix	33.1	3.4	29.7	89.8%	$506	$6,000	11.9
Sacramento	25.1	-2.2	27.3	108.9%	$349	$6,000	17.2
Averages	51.0	2.0	49.0	96.1%	$519	$6,000	11.6

The table reflects 100 square feet of window area on each of four facades for the cities analyzed. Note that in three cities savings are over 100%. This means that the window systems become net producers of energy on a full-year basis.

4.4 Final Conclusions

Tightening windows helps lower convective losses and contributes to improving energy performance and comfort, but if leakage is modest to begin with, savings are likely to be small. Of course, if work is being done on the weight box, it makes sense to undertake tightening, sealing, and other improvements on existing windows at the same time. Painting and adjustments, plus good hardware also improve comfort and extend lifetimes. The level of improvement achievable is a function of how leaky windows were before the retrofit.

The work of carefully rebuilding old windows is practiced primarily by professional craftsmen who work with specialized tools and equipment. Some, like Phoenix Windows, employ a portable shop which they bring on site to enable rebuilding multiple windows in several days time. This process can breathe new life into old windows and dramatically improve comfort and energy efficiency. However, because the work is painstakingly conducted by a skilled craftsman, the cost is very different from window systems manufactured off site and left to a homeowner or local technician to install.

Adding a more efficient IGU to windows in combination with air sealing and insulating the existing window and its weight pocket showed good improvements in this study. Empirical data from chamber measurements were consistent with the computations in Table 4-12. In particular, if a wooden frame dominates a window, the only way to achieve excellent savings while retaining the historic window is to install an energy-efficient storm window.

Adding storm windows was quite successful and has aesthetic advantages as well as significant thermal ones. Even with a wooden frame (whose proportions were modest while being consistent with traditional historic aesthetics), energy efficiency was on the order to four times that of the original window. Switching to an energy-efficient fiberglass frame would improve the performance a great deal, probably raising the overall efficiency of the window system by a factor of six or more over an existing single-glazed wooden window. It is possible to fabricate fiberglass frames to appear to be virtually identical to wooden frames. This would result in a storm window that could be manufactured at a lower cost than a wooden storm window. It would also achieve better comfort, longer life, and greater energy savings than wood. This type of frame is not currently commercially available; however, a mass-produced, semi-custom fiberglass frame solution may find strong commercial demand among historic homeowners and others. Because storm windows are modular and removable, it is assumed that such a product would pass muster with most historic preservation communities.

In a recent look at the prices of storm window produced by four manufacturers offering bulk purchase pricing, the study team found that canonical 10 square foot storm windows may be purchased in bulk (20 or more windows) for $10 (i.e., for storm windows with aluminum frames and single glazing) to $28 per square foot (i.e., storm windows with a vinyl frame, double glazing and a low-E coating on an interior surface). Based on current window technology, bulk purchases of similar-size storm windows with fiberglass frames and lower U value glazing than any storm windows currently available could cost from $14 to $18 per square foot. Assuming a cost of $15 per square foot, such a product would lower paybacks to an average of 11 years for most of the areas of the country examined in this report and last considerably longer than any other storm windows now available. This simple payback is similar to that achievable by a new low-end vinyl window, although lifetime and aesthetic considerations highly favor the storm window approach.

Along with appropriate insulation and high-quality air sealing (of envelopes as well as duct systems), using window systems such as these would open the way to improvements of 60% to

80% over historic buildings that are leaky, have little insulation, and are equipped with wood-framed windows with single glazing.

In general, improvements in U-value result in lower SHGC. Sometimes this is desirable, particularly in cooling-dominated climates, especially on west and east elevations. When designing appropriate storm windows for historic buildings, matching U-values and SHGC to facades is quite important. In Boulder and other climates with good sunlight for much of the year but also substantial heating loads, ensuring high SHGC for south-facing window systems that are not substantially shaded is much more important than achieving the lowest possible U.

Adding window film that adheres to existing glazing had no effect on U-value but did lower radiant heat transfer from the sun. However, since the film is mostly absorptive rather than reflective, glazings are heated by the film, causing them to transmit more heat (to both the inside and outside of the envelope) via the heat transfer mechanisms of long-wave radiation, convection, and conduction.

The most important conclusion flowing from this research is that it is possible to improve the overall energy performance of existing window systems by over four fold without altering their historic character through repairs, sealing, and the installation of an excellent storm window. This retrofit will also raise comfort substantially. The cost impacts of such measures vary depending on climate, materials used, and local fuel and labor rates. While the cost and payback of good quality retrofit work and storm windows exceeds the cost of new windows, in many areas replacing historic windows is not permitted under historic and landmark rules. Accordingly, such measures offer the only viable option for homeowners seeking greater comfort and efficiency from their windows.

Air temperature on the inside surface of a single-glazed window on a cold and windy day can be 40F or even lower. Assuming the efficient storm window retrofit developed in this project, applied in a climate akin to Boulder’s, and an indoor room air temperature of 70F, the window surface exposed to the inside will rarely drop below 65F. This halves mean radiant temperature losses from human beings through windows, thereby improving comfort dramatically.

The result also protects the original window, improves its functionality, and likely provides for another century of life while retaining the home’s aesthetic charm.

APPENDIX A. ANNOTATED BIBLIOGRAPHY

ASHRAE 2005 Handbook of Fundamentals, Chapter 31 on Fenestration, 69 pp.

The ASHRAE 2005 Handbook includes a bibliography of 200 + technical papers on recent research in window technology. It is broadly considered the definitive text of currently-known energy science associated with fenestration.

Carmody, J., S. Selkowitz and L. Heshong. _Residential Windows: A Guide to New Technologies and Energy Performance_. W.W. Norton & Company. 1996.

This book is a useful primer on modern window technology, how specularly-selective surfaces work to optimize glazing performance in different climate zones, and educated projections on what the future holds for the development of more effective fenestration systems.

Fisher, Charles. _"Installing Insulating Glass in Existing Wooden Sash Incorporating the Historic Glass."_ Preservation Tech Notes: Windows No. 3. Historic Preservation Education Foundation. 1985.

In this case study, Charles Fisher examines alternatives to upgrading 102 wooden windows in an historic Chicago office building. While the windows were in relatively good condition, there was considerable air leakage due to lack of weatherstripping, cracked putty seals around the glass, and shrinkage and cracks in the caulk around the outside frame. As part of the rehabilitation of the building, the windows were repaired, weatherstripped and retrofitted with an additional sheet of glazing using a technique that permitted creation of sealed insulating units in each sash. No alternative techniques to achieving efficiency gains were evaluated as part of this project and actual energy savings were not evaluated.

James, Brad, Andrew Shapiro, Steve Flanders, and Dr. David Hemenway. _"Testing the Energy Performance of Wood Windows in Cold Climates."_ Report to The State of Vermont Division of Historic Preservation Agency of Commerce and Community Development. August 30, 1996.

This study, conducted by energy and environmental engineers, was undertaken to test the assumption that historic windows can be retained and upgraded to approach the thermal efficiency of replacement sash or window inserts. In the study, non-infiltrative losses (conduction, convection and radiation) were modeled using a computer simulation of thermal fenestration performance. Infiltration was measured by field testing 151 windows in various stages of repair, mostly in Vermont. The results were used to model three window infiltration scenarios: typical, tight and loose. Estimated annual energy costs of these assumed windows were used to estimate energy cost savings associated with various efficiency treatments. This study revealed several interesting results – among them the multitude of environmental and site specific factors that can impact energy savings results associated with a given treatment. Because the authors evaluated a large sample of windows in different stages of upgrade, rather than measuring the “before” and “after” efficiency gains of renovated windows, their results required a high degree of “normalizing” the data to achieve anecdotal results.

Kinney, Larry. "Windows and Window Treatments," Prepared for the USDOE's Building America Program. September 2004.

This report details a study of energy efficient window options with an orientation to the Southwest. It defines a number of technical terms in layperson language and discusses window system applications in new and retrofitted residential structures in a six state region that includes Colorado. It includes an extensive discussion of the importance of matching window characteristics to facades to optimize energy performance. Results of simulations using RESFEN software are given in both tabular and graphic form.

McGrew, Dr. Jay L., David P. McGrew and George P. Yeagle. *"Integrated Heat Flow in Windows."* A report to the Energy Research Foundation. July 1978.

This study, conducted in Denver Colorado, looks at the heat flow characteristics of historic windows. The study authors argue that evaluation of U-value – the primary element of structural heat flow evaluated in studies up to that time – offered a poor estimate of heat flow in most cases. They sought to develop a more theoretically sound and accurate estimation of heat flow. Towards this end, the study authors developed a computer model that considers the transient nature of window heat flow, and includes all relevant variables such as geographical location, window orientation, geometry, eave overhang, and environmental effects such as sun, wind and cloud cover as well as the component temperatures. The authors' research compared the heat flow properties of single pane versus double pane windows, (add comma) and used experimental measurements to verify their theoretical model. Finding that the two did not match, they made corrections to compensate in the model. This study was quite innovative for its time, however its relevance today is limited. The study relies entirely on computer modeling circa 1978, which may well have been a precursor to today's RESFEN, which is based on DOE2 models, but with less sophistication, a smaller range of potential variables and a lower degree of accuracy. Additionally, the study does not utilize residential site measurements in historic structures or isolated laboratory measurements to verify and refine the models findings. Finally, the study looks only at the addition of a pane of glazing as an alternative efficiency scenario and ignores other possible treatments such as various coatings that may provide valuable solutions for historic structures.

Park, Sharon C. *"Thermal Retrofit of Historic Wooden Sash Using Interior Piggyback Storm Panels."* Preservation Tech Notes: Windows No. 8. Historic Preservation Education Foundation. 1980.

This report, by architect Sharon C. Park, AIA, is a case study that looks at several alternatives to improving the energy performance of 506 windows in an historic office building in downtown Oklahoma City. The following approaches were investigated: 1. Repairing the existing windows; 2. Adding weather stripping to the existing units; 3. Adding a second layer of glazing to the existing windows, either as a separate storm window or as applied storm panels; 4. Replacing the existing windows with new double-glazed thermal windows. The need to maintain the visual integrity of the historic structure and to stay within budget eliminated two of the four options, as reported in the case study:

> "The need to seek a cost-effective and yet compatible solution quickly eliminated two common options. The first was the use of an exterior storm window since it would have altered the deep setback which was a character-defining feature of

> the building. The second alternative was the use of a modern replacement window. The cost of replicating 507 double-hung windows out of wood and installing thermal glazing was beyond the budget of the owner. A much less expensive solution, which was investigated, involved the replacement of all windows with a metal frame, fixed sash and solar grey heat absorbing insulating glass. While the cost estimate of $300 per unit was within the budget, the architect felt that such a solution was unacceptable since it would have drastically changed the building's historic appearance.”

After careful evaluation, the decision was made to fit a new storm panel to the existing sash in a manner that was cost-effective and also preserved the window's distinctive qualities. The project resulted in a cost-effective solution for the building owner, however, this study did not involve any direct measurement of the resulting thermal gains of the applied window treatments.

Sedovic, Walter and Jill H. Gotthelf. *“What Replacement Windows Can’t Replace: The Real Cost of Removing Historic Windows.”* APT Bulletin: Journal of Preservation Technology. 36:4, 2005.

Mr. Sedovic and Ms. Gotthelf argue that replacing historic windows is inherently less sustainable that preserving them. This conclusion is based on several arguments: 1. the embodied energy associated with materials used in most replacement windows is high, 2. since restoration relies on labor more than materials, restoration contributes to local economies, supporting economic sustainability, 3. the materials used in most window replacements degrade and are difficult to reuse or recycle while historic windows can last up to 100 years with minimal maintenance, 4. window manufacturers’ efficiency claims are often skewed or misrepresented, and 5. addressing the primary sources of energy waste in historic homes, namely air leakage and insufficient insulation can be cost-effectively accomplished without replacing windows. While many of these arguments are valid, Mr. Sedovic and Ms. Gotthelf make several massive generalizations that are patently designed to influence the reader toward their opinions with no data provided to back up their claims.

Trissler, Wayne and Charles Fisher. *"Exterior Storm Windows: Casement Design Wooden Storm Sash."* Preservation Tech Notes: Windows No. 3. Historic Preservation Education Foundation. 1984.

This case study looks at efforts to upgrade the efficiency of historic windows in a two-story historic gatehouse in New York. The windows are prominent features of the building, and although in good condition were energy inefficient. Although careful consideration was given to restoration methodology and the need to meet specific historic considerations, design and energy efficiency goals, no consideration was given to alternative approaches to achieving these goals. The windows on this structure were fitted with custom-made exterior storm windows that meet specified performance criteria and yet minimize both damage and visual obstruction to the historic windows.

APPENDIX B. WINDOW TEST FACILITY CONSTRUCTION

In order to isolate and study the efficiency properties of window units, the study team constructed a super-insulated, tightly-air-sealed window test facility chamber. The facility was calibrated with no windows in place, which allowed the team to determine the chamber's heat transfer coefficient (U factor) with an insulated plug in place of a sample window. Then, when a window is tested, the difference in U can be assigned to the window. Once U factor is known, heat loss (Q) can be determined for any difference in temperature or cross sectional area of the window. So, for example, if one has data for a typical meteorological year for a given locus, one can calculate winter heat losses by summing up hourly heat losses.

For this project, we used techniques that are sound but cost effective. A considerable amount of labor, materials, and instrumentation were donated to help the study achieve its goals.

The following pictorial depiction follows construction and testing of the chamber.

The test cell was constructed using structural insulated panels composed of oriented strand board on either side of urethane insulation. The photo on the left shows the first corner of the test cell being set into place.

Each joint was sealed using urethane foam insulation and caulk to ensure joints were well sealed. The team used clamp hooks to snug the walls together. Then, wheels were installed to roll the test cell in and out of the chamber. The photo below shows the constructed test cell following a day's work.

Fourteen tubes of caulk were applied to the post-assembly test cell. Three coats of vapor barrier paint were then applied inside and out to ensure well-sealed construction.

The chamber was framed into the corner of a warehouse. The existing walls were first covered in two inches of polyisocyanurate (R-13).

The photo on the left shows three walls of the chamber completed with the test cell inside. The outer chamber, likewise well insulated and sealed, is cooled while the test cell is heated to test U values.

The technical team constructed a 380 pound door (see photo at left), insulated with both fiberglass and polyisocyanurate to R-25. The photos below show a winch and pulley system, suspended from steel roof rafters, used to open and close the chamber door.

APPENDIX C. FIELD WORK DETAILS

Part of the process of preparing this research design included examining approximately ten potential homes and interviewing homeowners. The result of this process was the selection of a 108 year home in a historic district in Boulder owned by Gretchen Lang and Michael Wilkins. The Synertech team performed an extensive energy audit of the home on January 4, 2008. This appendix consists of a selection from the 75 photographs taken during the audit.

The following are exterior views of the home and its windows.

West elevation/front of home

East elevation/back of home

South elevation

North elevation

Exterior window/storm detail

Blower door test

The two-story 2700 square foot home is quite leaky; the blower door reading showed 3500 cfm of leakage when the conditioned envelope was depressurized to 50 pascals of pressure. (Between the audit and the retrofit of the home, the homeowners undertook a number of air sealing measures—none of which had to do with windows—which resulted in lowering the blower door reading to 3000 cfm at 50 pascals. As reported in Section 3, the window work resulted in bringing the leakage down to 2860 cfm at 50 pascals.)

In spite of spotty insulation in the attic (see photos at left and below) and none in the walls of the old portion of the home (there's a newer addition on the back—east—façade of the home), air leakage accounts for approximately half of the heating load on the home. Such leakage causes energy waste and discomfort, and can shorten the lifetime of beautiful old homes like this one.

Multi-zone heating system

The home is heated by a multi-zoned, gas-fired boiler expertly installed by the homeowner. One zone, controlled by an aquastat, heats water in a “side arm” tank which supplies the home’s needs for domestic hot water.

Domestic hot water tank

Antique radiator supplies heat to the interior

In addition, a good deal of the heating load is met by a wood-burning stove mounted in front of a chimney centrally located in the home’s living room. The modest cooling load is met by an evaporative cooler on the roof. Of consequence to the window retrofit, distribution of cool air from the evaporative cooler involves opening a number of windows to direct cool air to spaces that need it.

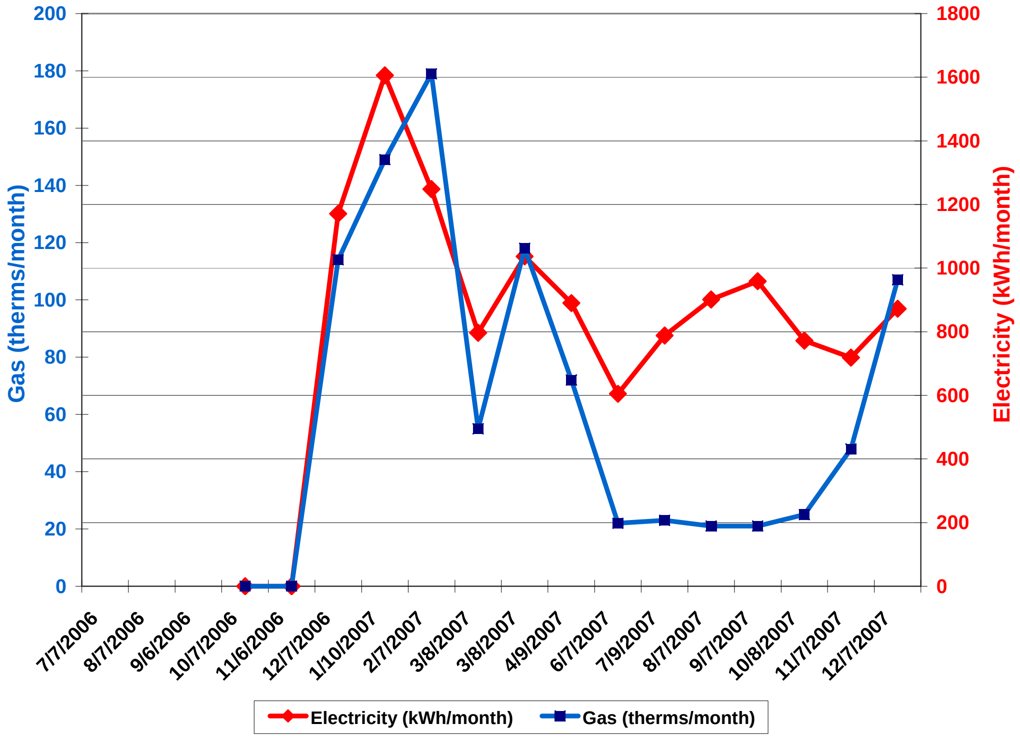
Wood stove vents into existing chimney

Table C-1 summarizes the use of gas and electricity in the home broken down by baseload, heating and cooling. Heating energy is normalized to home size and weather. Figure C-1 shows fossil fuel energy consumption by month.

Table C-1. Annual Energy Consumption

Annual Energy	Total	Heating	Cooling	Baseload	Air leakage
Gas (therms/yr)	840	677.5	na	162.5	341.7
Gas ($/yr)	$781	$630	na	$151	$318
Electricity (kWh/yr)	11,194	1,591	248	9,356	922
Electricity ($/yr)	$896	$127	$20	$748	$74
Total (MMBtu/yr)	122.2	73.2	0.8	48.2	36.9
Total ($/yr)	$1,677	$757	$20	$900	$392
Estimated portion of heating and cooling costs due to air leakage					50%
Normalized annual consumption (Btu/ft^2/heating degree day)					3.8

Figure C-1. Gas and Electric Consumption by Month



APPENDIX D. ALTERNATIVE APPROACH TO AIR SEALING AND INSULATING COUNTERWEIGHT POCKETS

Introduction

Unlike newer windows, older double-hung window systems routinely include un-insulated boxes on their sides that contain iron weights, ropes, and pulleys. The ropes connect weights to the frames of moveable lites of the window systems, thereby providing counter-balancing forces that aid in opening the windows. Such boxes constitute a large portion of the fixed part of the window frames. A combination of visual inspection, blower door testing, and infrared scanning reveal that these boxes are frequently the source of substantial convective and conductive energy losses in summer and (especially) winter. Thus, the combination of large cross sectional area and thermal leakiness of the frame means that even if glazing is replaced with excellent insulating glass, the overall performance of the window system is doomed to be modest at best.

Old window with closed counter weight pockets

The study team explored two options for retrofitting counter-weight pockets. What we call “the spring solution” eliminates the function of the box, replacing its weights with a spring mechanism and stuffing the box with fiberglass insulation. This solution was employed on the test home, as illustrated in Section 3. What we call “the column solution” retains the function of the box and its weights, replaces old rope with new, inserts a plastic column inside of which the weights may slide, and adds urethane foam to the remaining spaces within the box. In both cases, air sealing and insulating are achieved. If carefully done, finished retrofits are invisible to the naked eye.

This appendix consists of an annotated set of photographs aimed at illustrating the problem and showing details of the column approaches to solving it.

Open pocket with counter weight

The problem

Counter weights are heavy solid iron cylinders attached to the windows via ropes. These weights slide up and down in uninsulated vertical boxes on each side of the window. These boxes are frequently leaky to the outsides of homes. Cold air can enter the home through pulley holes and other cracks. Both conductive and convective energy waste are the unhappy results (along with discomfort).

Ropes connected to these weights pass over pulleys and down the inside edge of the window frame and sash. The sash is usually equipped with a hole drilled in both its vertical outer edges to accept a knot tied in the ends of the ropes thereby securing the weights to the sash.

With the column solution, the aim is to retain the virtues of the old counter weights without suffering their problems.

First, we tested the window "as is" in the test chamber. A 4 x 5 foot insulated plug was adapted to fit the window. The plug was fitted in the chamber and tested for air leakiness, then U value.

Window in the test chamber

The column solution

Inserting a plastic pipe, whose inside diameter is just larger than the outside diameter of a counter weight is the key to the solution. The weight slides inside the pipe while the rest of the open space in the counter weight box is sealed with expanding foam insulation such as urethane.

Sliding counter weight into PVC tube

New weight ropes are installed and cardboard and packing tape is used to seal up both ends of the PVC tubes to prevent urethane from penetrating the area where the weight slides.

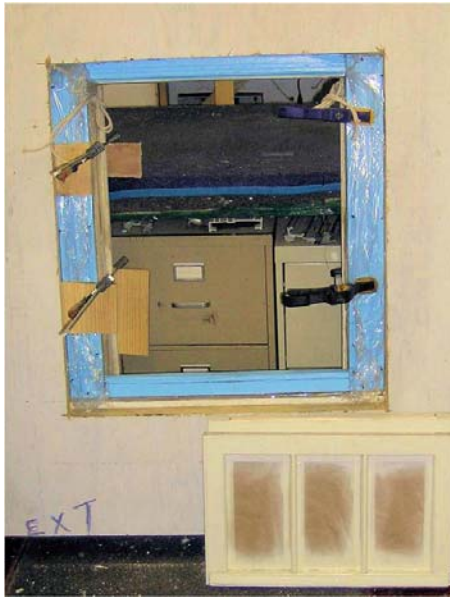
Cardboard in place over PVC tube

Urethane is applied in layers to ensure weight tubes are completely surrounded – foam (shown), 1st tube inserted, foam, second tube, and still more foam. Foam expands several fold while curing.

Adding urethane to pocket

Urethane sticks to almost everything, but not plastic sheeting. Technicians wrap boards covering the box in plastic to facilitate post-cure inspection, then clamp them down and test the movement of the ropes.

Cure is complete in a few hours. Clamps are removed, rope functionality is verified, and the cracks are sealed.



Everything in place to cure.

Post-retrofit testing indicates an eight percent improvement in window performance. No doubt it would be more under windy conditions.

APPENDIX E KEY MEMBERS OF THE PROJECT TEAM

Amy Ellsworth, Project Manager. Ms. Ellsworth has 17 years of project management and practical experience in the energy efficiency, renewable energy, and climate change arenas. Her experience includes a broad range of project analysis, program design, and policy work. Currently a Senior Associate with the Cadmus Group, Ms. Ellsworth works with utilities and local governments to design energy efficiency, demand reduction and conservation programs. Ms. Ellsworth provided broad oversight for the project and led reporting and facilitation between the technical team, historic homeowners, funding partners, and stakeholders.

Larry Kinney, Technical Team Leader. Larry is the cofounder and president of Synertech Systems Corporation, a Boulder-based energy efficiency research and development firm founded in 1984. Active in energy conservation research for over 35 years, he has broad experience in weatherization program operations, fenestration systems, lighting and daylighting technologies, energy-efficient refrigeration, air handling and conditioning systems, and controls. He did undergraduate work in Physics and Philosophy at Davidson and Rhodes colleges and holds a PhD in Philosophy from Syracuse University. Larry has authored over 200 publications and reports to clients and is the co-holder of three patents in the daylighting area. He led the technical research of the present study and is the principal author of this report.

Gerald (Gary) Cler, Technical Team. Gary is an independent consultant specializing in energy efficiency, daylighting, renewable energy, and combined heat and power (CHP) applications. He did undergraduate work in Mechanical Engineering at the University of Illinois and holds a Masters Degree in Mechanical Engineering from Colorado State University. Gary was the principal designer and assembler of the window test lab, developed the analytical spreadsheet, and played key roles in laboratory testing and data analysis.

In addition to these team members, the study benefitted greatly from volunteer labor that contributed both expertise and enthusiasm to the work of the project.