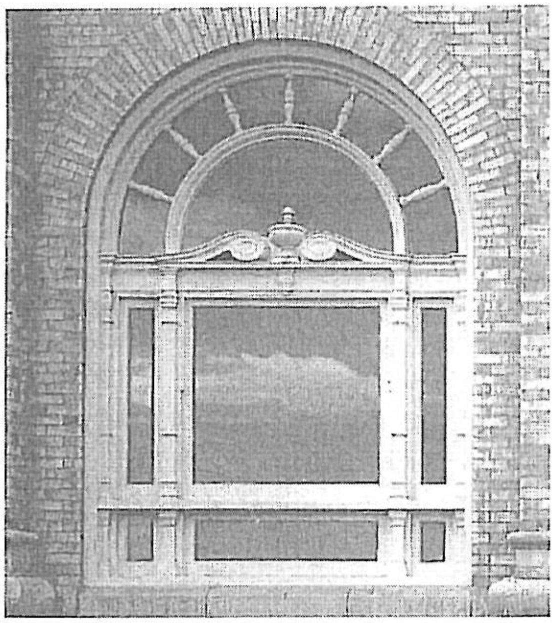

Window Rehabilitation Guide for Historic Buildings

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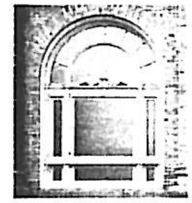
RETAIN OR RETIRE? A FIELD STUDY OF THE ENERGY IMPACTS OF WINDOW REHAB CHOICES



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Executive Summary

The goal of retaining historic windows during building rehabilitation is often challenged by those who would prefer to replace them with modern windows. Concern for long-term energy conservation is one of the many important factors encouraging replacement rather than rehabilitation of wood windows. Few test data exist, however, that quantify the actual energy performance of existing and rehabilitated historic wood windows.

This study has performed over 150 in-place and several laboratory air leakage rate tests of pre- and post-rehabilitation historic wood windows. In these tests, heating season natural air infiltration and non-infiltration heat losses were modeled. These energy losses were subsequently summed and translated into annual heating season energy costs in order to estimate savings and to compare savings to costs.

Major results of this study include the following:

- Both retention and replacement strategies can result in high levels of energy performance, depending on the specific option selected and the quality of its execution.
- Decisions about window upgrade methods should be based primarily on decisions other than energy. However, once a general rehabilitation strategy is chosen, energy performance should be optimized, based on cost-effectiveness criteria appropriate to the project.
- The cost-effectiveness of upgrading the energy efficiency of windows is highly dependent on the performance of the existing windows. Little improvement can be expected from upgrading windows that already have low air leakage rates and that include a second layer of glass.
- Diagnostic whole-building air leakage testing should be used as part of a total building energy analysis to prioritize window air leakage treatment appropriately.
- Window heat loss accounts for approximately 20 percent of the total heat load for the typical building studied. Efforts to upgrade energy efficiency of windows should be placed in that context.

The project was funded by a grant from the National Park Service through the National Center for Preservation Technology and Training to the Vermont Division of Historic Preservation. The project team included the Vermont Energy Investment Corporation, the University of Vermont School of Civil and Environmental Engineering, and the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Introduction

When historic buildings are renovated, the question of how to treat the windows is inevitably raised. The desire to retain the historic character and the actual historic material of the windows is often seen as competing with the desire to improve energy performance. This discussion is multifaceted, including factors such as the historic character of the windows, ease of operation, maintenance costs, lead abatement, window longevity, occupant comfort and energy conservation. In northern climates, energy conservation can take a prominent role in the discussion, particularly in renovation of affordable housing, where long term energy costs can be more important than in other contexts.

To date, there has been little data that quantifies the impact on energy costs of either window renovation or replacement, or data that compares the estimated value of conserved energy to the installed cost for various retrofits or replacements. In 1995 the Vermont Division of Historic Preservation commissioned a study to investigate the energy performance of historic windows, before and after a variety of energy improvement retrofits. This study, funded by the National Center for Preservation Technology and Training, was designed to test the assumption that historic windows can be retained and upgraded to approach the thermal efficiency of replacement sash or window inserts.

Windows tested as part of the study were primarily in residential buildings in Vermont; most of these were in the process of renovation for affordable housing, a segment of the housing stock particularly concerned with long term energy costs. Tested windows were double-hung and generally of average quality when originally built. Approximately half of the windows were counter-weighted sash and half had either pin-type sash or no mechanism for holding one sash open. Their condition when tested varied widely, from very good to falling apart.

Quantifying Heat Losses Through Windows

This study concentrated on heating season energy loss through windows. Window heat loss can be divided into infiltration and non-infiltration losses. Infiltration losses, driven by wind and by the temperature difference between the inside and outside of a building, occur primarily through cracks between the sash, the sash and the frame, and the frame and the rough opening. Non-infiltration losses include heat lost directly through the materials of the window.[1]

Non-infiltration losses are difficult to measure in the field, but have been studied extensively in mobile test facilities and in controlled laboratory conditions. Much of this work was conducted by Lawrence Berkeley Laboratories (LBL) Window Division, which has developed a detailed computer model, Window 4.1, that is now widely accepted as highly reliable for determination of non-infiltration heat transfer through overall window assemblies. Window 4.1 was used in this study to model these losses, which vary little between windows with similar numbers of layers of clear glass and similar frame materials. In contrast, infiltration losses vary significantly from one window to the next. The American Society for Testing and Materials (ASTM) has developed a test to evaluate air leakage rates in the field, ASTM E783-91. This test results in an air leakage rate at a specific pressure across the window. In order to correlate such test data with an average heating season natural infiltration rate, a model of natural infiltration developed at LBL, the Sherman-Grimsrud model, was used.[2] The infiltration and non-infiltration heat loss rates were added together to obtain the total average heat loss rate.[3]

Data were normalized to a typical 36 inch wide by 60 inch high window size. A standard ASHRAE heat loss model was used to develop the first year heating load from the heat loss rate, and Burlington, Vermont, climate data and typical heating fuel cost and efficiencies were used to calculate the first year cost for heat for a window (Figure 1).

Infiltration Testing Method

The infiltration test method was modeled on ASTM E783-91. Two air leakage tests were performed on each window configuration. A plastic sheet was first taped onto the inside trim of the window, with an air hose and pressure tap attached (Figure 2). Air was drawn through the window and the flow rate, in cubic feet per minute (CFM), was measured at various pressure differentials across the sheet. This test result was called "total leakage." A second sheet was then attached to the exterior of the window and the test repeated. This test result was called "extraneous leakage." The difference between these two values is called "sash leakage." Sash leakage at a specified pressure is the value reported in window manufacturers' literature for the air leakage rate (Figure 3).

Sash leakage is often understood by building designers to include all the air leakage due to the window. However, leakage between the sash and rough opening can make a significant contribution to overall air leakage. In order to estimate the contribution of rough opening leakage, temperature measurements were made of the indoor air, outdoor air, and the air being drawn through the window during the extraneous leakage test. On average, the temperature of the air drawn through the window was approximately 30 percent cooler than the indoor air, compared to the outside air, indicating that roughly 30 percent of the extraneous leakage was coming from outside. While this method is far from exact, it served to give a value

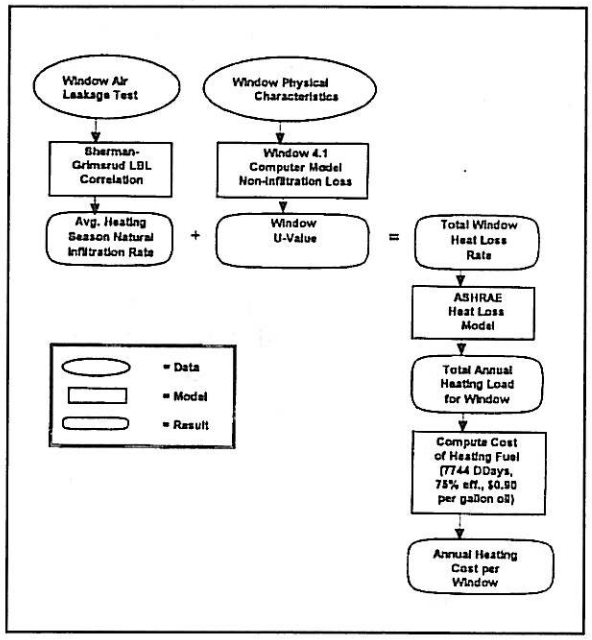


Figure 1. Window Energy Performance Flow of Data and Analysis.

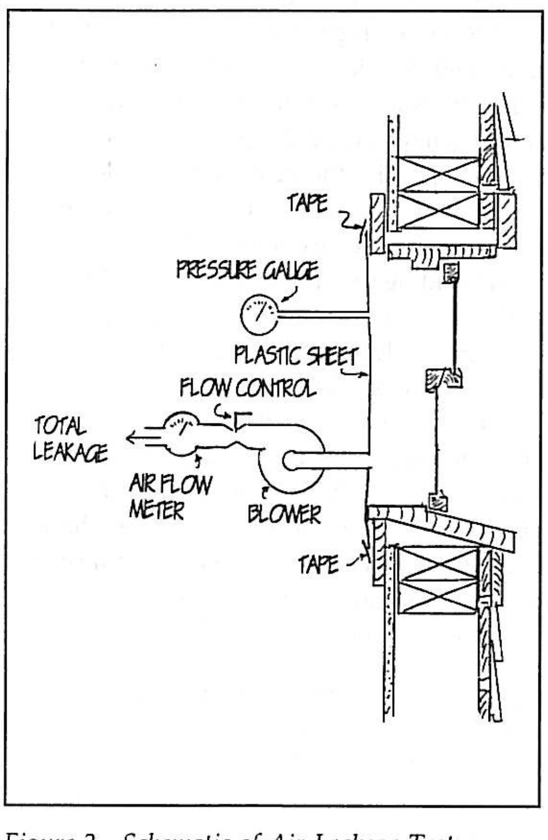


Figure 2. Schematic of Air Leakage Test.

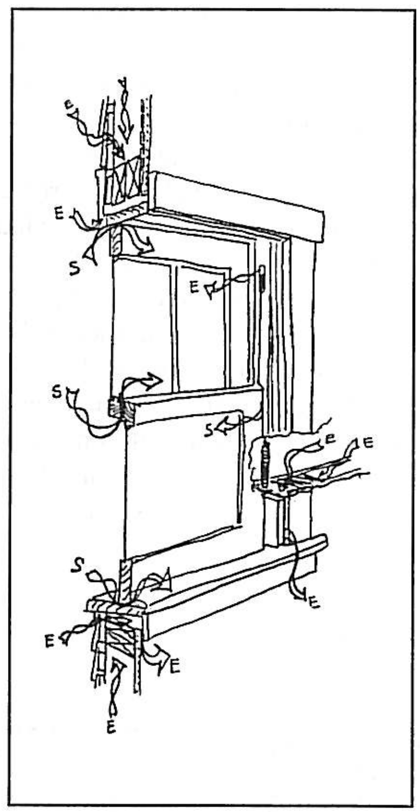


Figure 3. Typical Air Leakage Sites, with Sash Leakage, S, and Extraneous Leakage, E.

that could be used during analysis to 1) indicate that this leakage is recognized as contributing to the heating load, and 2) approximate the magnitude of the contribution to the heating load of air leakage through the rough opening. Total leakage from the exterior is then estimated as sash leakage plus 30 percent of extraneous leakage.

In addition to air leakage testing, physical measurements were made of the windows, including materials types, sizes and dimensions. Various visual parameters were recorded, in an attempt to correlate the results of a visual inspection with air leakage rate. Cost estimates for window upgrades were based on interviews with the housing developers and/or builders, and were normalized to a $20 per hour labor rate.

Windows tested

Windows tested were located primarily in affordable housing projects undergoing rehabilitation in Vermont. Test locations were limited by building access and condition of the windows and surrounding surfaces. Pre-treatment windows had to be sufficiently intact that the pressure exerted during the testing would not break glass, and the surrounding surfaces had to be large enough and smooth enough to allow application of masking tape. Sixty-four pre-treatment windows were tested, of which approximately half were windows with sash balances and half were windows with pin-type mechanisms or no mechanism for holding sash open. Eighty-seven post-treatment windows were tested: treatments included a wide variety of improvement strategies. Table 1 summarizes the general upgrade categories tested and the number (n) of each, with some windows falling into two categories. See Figure 4 for schematics of window upgrades tested.

Table 1: Number of windows tested by general upgrade category.

General Window Upgrade Category	n
Retained original sash	62
Replacement sash with vinyl jamb liners	11
Replacement window inserts	12
Whole window replacements	2
Replacement storm windows	17
Double- versus single-glazing replacements	19

Results

Results for original windows. Air leakage rates of original windows ranged widely, due to the large variation in condition of the windows. Inspection of the data indicated that there were no strong correlations between visual parameters and air leakage rates beyond a weak correlation between the fit of the sash at the meeting rail and air leakage, and a weaker correlation between fit of the sash to the frame and air leakage. Whole building air leakage testing, using a blower door and a smoke pencil to identify leakage locations, can be useful in identifying and locating air leakage paths. The spring-loaded interior storm sash, site 10A, had a remarkably low sash leakage rate of 0.05 scfm/lfc (at 0.30 inches water pressure) and the magnetic strip/plexiglass interior storms at site 15 had a sash leakage rate of 0.01 scfm/lfc.

All windows with operable storms were tested with storms both open and closed. A mean air leakage rate was established for all original (pre-treatment) windows that had operable storms in place, called the "Typical" window. The "Tight" window was assumed to have one standard deviation lower leakage rate. The "Loose" window was the average of all original condition (pre-treatment) windows with storms open or missing. This established three baseline windows for comparison with rehabilitated windows, in order to 1) emphasize the variability in air leakage rates of existing windows, and to 2) emphasize that energy performance comparisons for a particular building should be based on the condition of the windows in that building. Table 2 shows the Equivalent Leakage Area (ELA) for the pre-treatment baseline windows based on sash leakage and ELA based on 30 percent of rough opening leakage assumed to come from outside. ELA is the area of a single hole that would have the same air leakage as the aggregate of all the air leakage sites in a window. First year heating cost is shown for infiltration, non-infiltration and the total of these two components of heat loss.

Results for windows retaining original sash. Table 3 lists and describes upgrades that retained the original sash. Figure 5 shows the heating cost due to air leakage for these upgrades. Leakage rates are shown without storm windows to emphasize the differences, which are somewhat

Table 2. ELA for Baseline Windows - Original (Pre-treatment) Condition.

Baseline Window Category (in²)	ELA Sash (in²)	ELA Rough Opening (in²)	ELA Total	First year Cost for Air Leakage	First yr. Cost for Non-Air Leakage	Total Heating Cost
Tight Window	0.27	0.59	0.86	$2.09	$12.31	$14.40
Typical Window	0.89	0.59	1.48	$3.59	$12.31	$15.90
Loose Window	2.19	0.59	2.78	$6.69	$22.21	$28.90

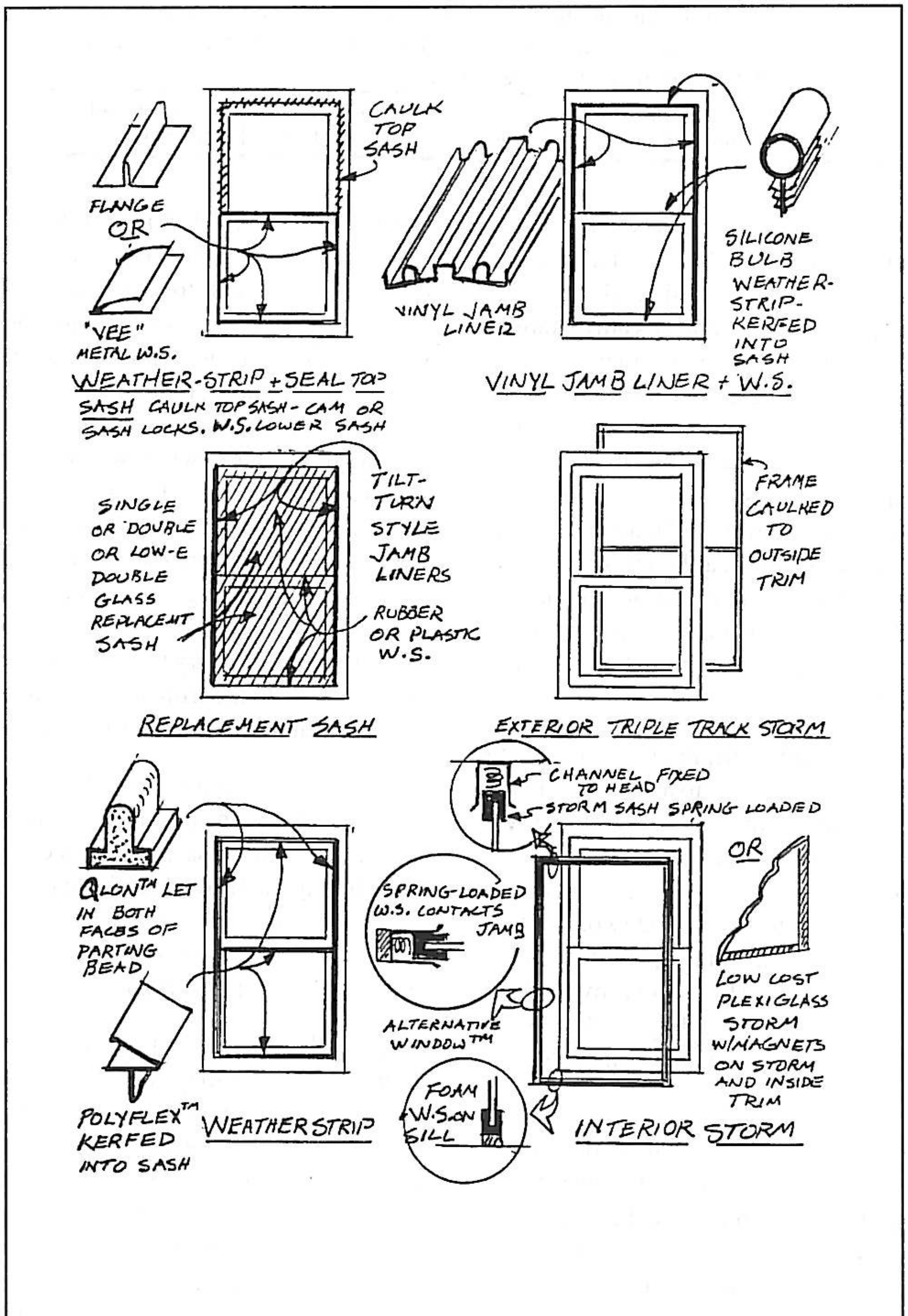


Figure 4. Selected window energy upgrades.

Table 3. Upgrades Retaining Original Sash.

Site ID	n	Upgrade Description
12	7	Vinyl jamb liners; no weather stripping
13	8	Vinyl jamb liners; silicone bulb weatherstripping at sill and head
7	19	Vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail
2	3	Vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail; double-pane insulating glass; new latch at meeting rail (Bi-Glass System)
17	3	Zinc rib-type weatherstripping on lower sash; upper sash painted in place; V-strip weatherstripping at meeting rail; pulley seals; new aluminum triple track storm windows, frames caulked in place
19	2	Bronze V-strip weatherstripping on lower sash, meeting rail, and sill junction; top sash painted in place; existing aluminum triple track storm window caulked in place; no locking mechanism
10	1	Sash weatherstripped with Q-Lon between sash face and parting bead; Polyflex Vee with Tee-slot at sill, head, and meeting rail junctions

masked by the use of storm windows. An extremely wide variation in the cost of air leakage for the first four sites listed — all of which utilized vinyl jamb liners — appears attributable to the role that workmanship plays in the success of jamb liners at reducing air leakage. Jamb liners require a precise fit of the sash to the liner and opening to avoid air leakage around the jamb liner and between liner and sash. Windows where the jamb was out of square were difficult to seal and did not perform well. Also, although sites seven and two incorporated weatherstripping at the meeting rail, an important location, the much lower leakage rate should not be attributed only to that difference.

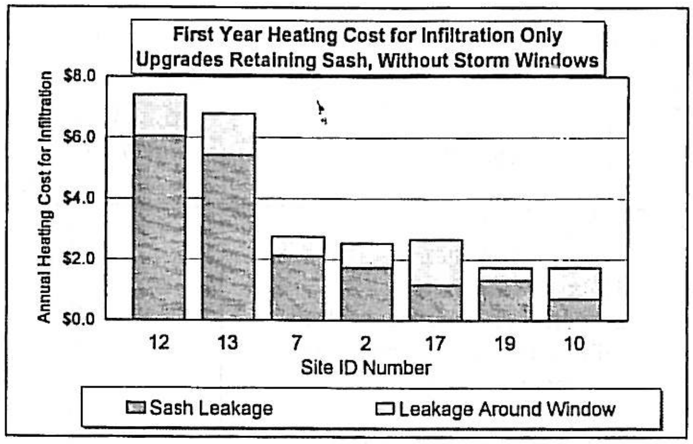
At site 17, metal weatherstripping was fixed to the jamb with a flange that fits into a slot milled in the sash, V-strip at the meeting rail, and caulked upper sash, which resulted in quite low sash leakage. However, the total leakage was approximately the same as sites seven and two, due to high leakage through the rough opening. Similarly, even though site 10 had a very low sash leakage rate, the overall air leakage performance was undermined by the rough opening air leakage.

Figure 6 shows one total first year heating cost for these upgrades, and identifies the costs for sash leakage, rough opening air leakage and non-infiltration losses. It quickly becomes apparent that infiltration is a small part of the heating cost. Nonetheless, differences in infiltration performance result in as much as a $5 per year per window difference in heating costs.

Results for storm windows. Table 4 shows reduction in leakage area due to the installation of new or rehabilitated storm windows. Results for the first four windows demonstrate the wide variability in prime window leakage and the variety in air leakage reduction performance of a variety of storm windows. Site 14, for example, used a type of storm window with a laboratory tested air leakage rate of 0.01 standard cubic feet per minute per linear foot of crack (scfm/lfc), an extremely low leakage rate.[4] This shows the importance of looking for and specifying storm windows with low air leakage rates, based on independent laboratory testing. Caulking exterior storm frames to the trim at site 19 also resulted in lower leakage and should be routinely specified.

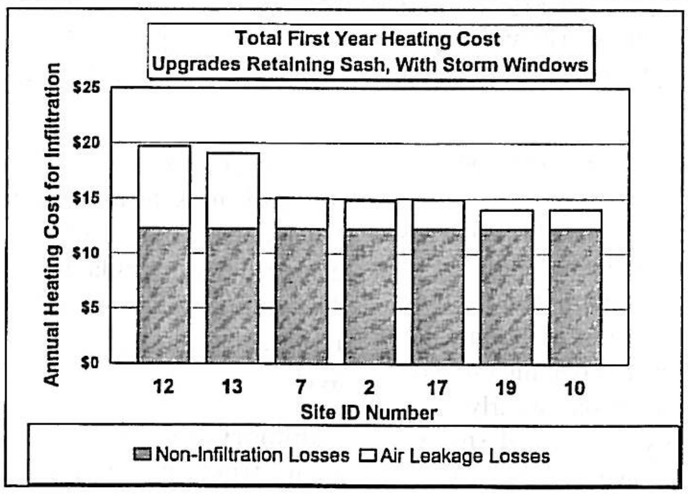
Interior storm windows have the advantage of reducing air leakage through the rough opening as well as through the sash. They accomplish this by reducing the flow of air that can come through the window-weight cavity/rough opening and then through the pulley or other jamb opening to the interior of the prime window.

Figure 7, First Year Heating Cost per Window for Storm Windows Open and Closed, shows the cost for heat losses due to air leakage and those due to non-infiltration losses. In this context it becomes clear that while infiltration is the much smaller component of window heating costs, it can be a significant part of the total costs for windows, particularly those without storm windows. It is also clear that the first year heating costs are similar for all storm window



Site ID	n	Upgrade Description
12	7	Vinyl jamb liners; no weather stripping
13	8	Vinyl jamb liners; silicone bulb weatherstripping at sill and head
7	19	Vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail
2	3	Vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail; double-pane insulating glass; new latch at meeting rail (Bi-Glass System)
17	3	Zinc rib-type weatherstripping on lower sash; upper sash painted in place; V-strip weatherstripping at meeting rail; pulley seals; new aluminum triple track storm windows, frames caulked in place
19	2	Bronze V-strip weatherstripping on lower sash, meeting rail, and sill junction; top sash painted in place; existing aluminum triple track storm window caulked in place; no locking mechanism
10	1	Sash weatherstripped with Q-Lon between sash face and parting bead; Polyflex Vee with Tee-slot at sill, head, and meeting rail junctions

Figure 5. First Year Heating Costs, Infiltration Only, Upgrades Retaining Sash.



Site ID	n	Upgrade Description
12	7	Vinyl jamb liners; no weather stripping
13	8	Vinyl jamb liners; silicone bulb weatherstripping at sill and head
7	19	Vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail
2	3	Vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail; double-pane insulating glass; new latch at meeting rail (Bi-Glass System)
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10	1	Sash weatherstripped with Q-Lon between sash face and parting bead; Polyflex Vee with Tee-slot at sill, head, and meeting rail junctions

Figure 6. Total First Year Heating Cost, Upgrades Retaining Sash.

Table 4. Reduction in Equivalent Leakage Area (ELA) by Storm Window Upgrades.

Storm Location	Site ID	n	Storm Window Type	Total Window ELA		% Reduction
				Storm Open	Storm Closed	
Exterior	10B	1	Triple Track, new	4.6	0.64	86%
	14AD	4	Triple Track, new	1.8	0.43	76%
	17	3	Triple Track, new	1.1	0.91	16%
	19	2	Triple track, existing, caulked	0.7	0.61	16%
	10C	1	Fixed upper, removable lower	4.3	0.86	80%
	7	1	Exterior Wood, new	2.2	1.7	21%
Interior	14EF	2	Triple Track, new	3	0.48	84%
	10A	1	Spring-loaded frame w/ WS	4.3	0.39	91%
	15	3	Plexi w/magnetic strip	2.2	0.22	90%
	10-le	0	Spring-loaded frame w/ WS,low-e	**		

** Not encountered in field. Air leakage data from 10A used.

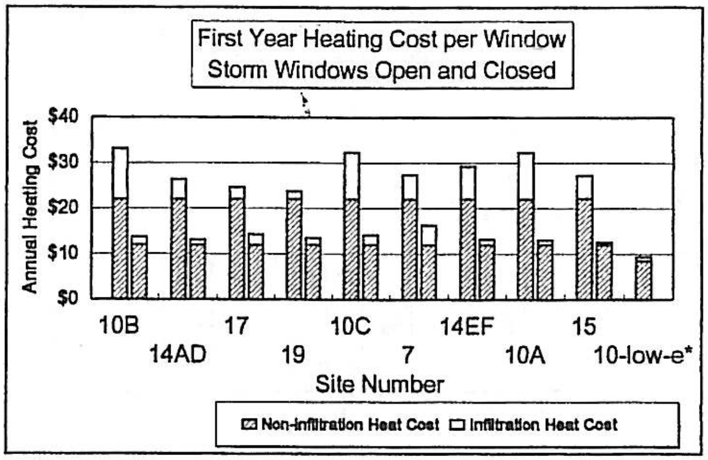
Table 5. First Year Heating Cost for Upgrades that Replace the Original Sash.

Site ID	n	Upgrade Description	First Year Heating Cost		
			Non-Infiltration	Infiltration	Total
6	6	Vinyl Window Insert	$12	$0.37	$12
11	6	Wood Window Insert	$12	$0.70	$13
3BCD,12B	7	Replacement Sash + Storm	$12	$1.68	$14
13I	1	Replacement Sash+Storm, poor fit	$12	$4.83	$17
18	2	Marvin insulated glass Rplcmnt Sash	$12	$0.60	$12
18-le	0	Marvin insulated Low-E Rplcmnt Sash	$8	$0.60	$9

strategies, unless low-e glass[1] is used for the storm, in which case the first year energy use is approximately $5 lower. 10-le uses the same site data as site 10A, but assumes the use of low-e glass. (It should be noted that glass manufacturers have made substantial progress in producing low-e glass that retains its heat reflecting properties while avoiding color distortions of early examples of this technology.) In general, storm windows cut the energy usage of the windows nearly in half.

Results for replacement sash and window inserts. Table 5 lists the sites with either replacement sash or window inserts. Costs for infiltration and non-infiltration losses are shown in this table and in Figure 8. With two exceptions, the first year heating costs are similar, ranging from $12 to $14. Window 13I was poorly installed in a frame that was out of square, resulting in high sash leakage and associated heating costs This example indicates the importance of square-ness of the opening when installing new square sash. Site 18-le uses the air leakage data from site 18, but assumes a non-infiltration loss that would be achieved with a similar window with low-e glass. The savings of low-e glass over other sash replacement strategies is estimated at $3.40 per year.

Summary of results for all treatment types. Figure 9 indicates the infiltration and non-infiltration first year heating costs for groupings of window upgrade types, and for the three baseline windows. It is notable that heating costs are similar for most rehabilitated windows, with the exception of treatments using low-e glass, which have lower heating costs. Further, while infiltration is of secondary importance, it is not insignificant.

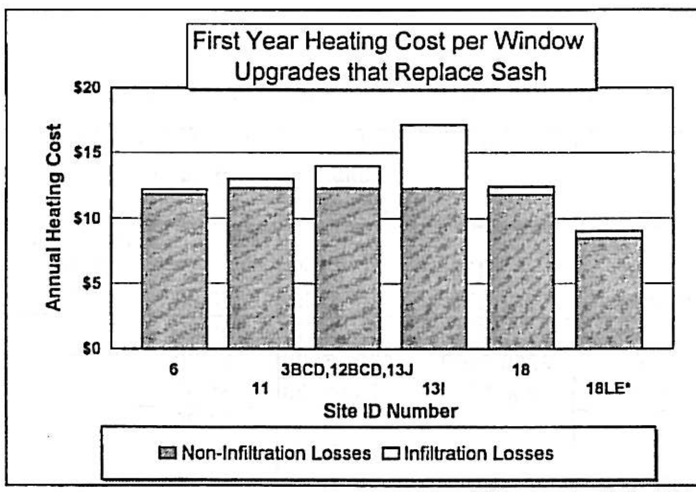


* Not encountered in the field

Site ID	n	Storm Window Type
10B	1	Exterior alum. triple track, replacement
14AD	4	Exterior alum. triple track, replacement
17	3	Exterior alum. triple track, replacement
19	2	Exterior alum. triple track, existing, frame caulked
10C	1	Exterior alum. fixed sash, removable lower sash
7	1	Exterior Wood sash, replacement
14EF	2	Interior mount, aluminum triple track, rplcment
10A	1	Interior storm window, spring-loaded mtl frm
15	3	Interior storm window, plexi w/magnetic strip
10-le*	0	Interior storm window, spring-loaded mtl frm, low-E*

* Not encountered in the field

Figure 7. First Year Heating Cost per Window, Storms Open and Closed.

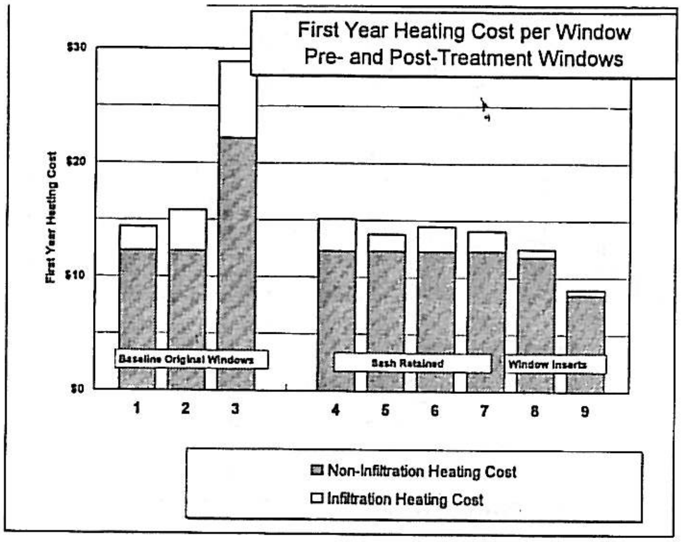


* Not encountered in the field

Site ID	n	Upgrade Description
6	6	Vinyl Window Insert
11	6	Wood Window Insert
3BCD,12BCD,13J	7	Replacement Sash + Storm
13I	1	Replcmnt Sash+Storm,poor fit
18	2	Marvin DG Rplcmnt Sash
18LE	0	Marvin DG Rplcmnt Sash,Low-E *

* Not encountered in the field

Figure 8. First Year Heating Cost per Window, Upgrades that Replace Sash.



Key	Window Category
1	Baseline Original Window, Tight with Storm
2	Baseline Original Window, Typical with Storm
3	Baseline Original Window, Loose, No Storm
4	Vinyl Jamb Liner with Weatherstripping
5	Metal Vee Weatherstripping, seal top sash
6	Metal Flange Weatherstripping, seal top sash
7	Replacement Sash with Vinyl Jamb Liner and WS
8	Window Insert with Insulated Glass
9	Window Insert with Insulated Low-E Glass*

*not encountered in the field

Figure 9. First Year Heating Cost per Window, Pre- and Post-Treatment.

Table 6. Costs and first year heating cost savings for window upgrade categories.

Category	Upgrade *	Cost	Cost with Lead Abatement**	First Year Savings Compared to Baseline Windows****		
				Tight	Typical	Loose
Retain original sash	Vinyl jamb liners	$175	$300	***	$0.80	$14
	Weatherstripping	$75	$200	$0.20	$1.70	$15
Replace Sash	Single glass sash	$200	$200	$0.30	$1.80	$15
	Window inserts	$250-$500	$200-$500	$1.90	$3.40	$16
	Low-E DG inserts	$250-$550	$250-$550	$5.30	$6.80	$20
Storm Windows	New exterior	$100	$225	$1.00	$2.50	$16
	New interior	$115	$240	$1.30	$2.80	$16
	Interior low-E	$155	$280	$4.70	$6.20	$19

* All upgrades retaining original sash and single glass replacement sash include reatining existing storm windows. Costs for replacement sash verage 1/1 and 2/2 windows. Costs for inserts included a range, from medium cost vinyl insert windows to high quality wood inserts.

* * Full sash lead abatement costs of $125 are included for all upgrades retaining existing sash.

* * * No savings realized.

* * * * Savings are based on 7744 degree days, oil heat at $0.90/gallon with 75% overdall heating season efficiency. Note that the samples of most of the upgrades tested were very small, and that, in most cases, these results have very low statistical significance.

Analysis of Results

Comparison of costs and savings. Table 6 compares costs and savings for major groupings of window upgrades. Costs and savings for this table are averages based on a number of upgrades tested in each category. Note that the upgrade assumes the storm window is in place, unless the upgrade includes insulated glass. One immediate conclusion to be drawn from this table is the importance of which components of an upgrade are chosen for comparison with the value of energy savings. Should the whole cost of the upgrade be compared to the savings? Or should part of the costs of upgrades be attributed to maintenance, ease of operation of the window, occupant comfort or other considerations? The answer will depend on the particular circumstance. One approach is to consider the difference between the costs of routine maintenance and the costs for an upgrade that would provide lower heating costs, and to compare this difference to the energy savings. Financing costs, cash flow analysis and life-cycle costing are also important considerations. The costs and value of potential window energy savings relative to other energy conservation measures are also important within the often constrained building rehabilitation budgets. These considerations were beyond the scope of this study.

Table 6 compares heating cost savings to the heating costs associated with a baseline window similar to the windows being considered for upgrade. If the original window already has a low air leakage rate and has a storm window in place (Tight), most upgrades result in very low energy savings. Compared to the Typical baseline, most upgrades result in savings ranging from $1 to $7 in the first year. Compared to the baseline window without a storm window (Loose), savings range from $14 to $20 in the first year.

It is important to consider the costs in context. For example, the costs for upgrading a Loose window with weatherstripping, sealing the top sash, and rehabilitating an existing storm are $75, if no lead abatement is needed, which compares favorably with the first year savings of $15. If lead abatement were needed in addition to weatherstripping, the cost would be $200, similar to the cost for replacement sash, since no lead abatement would be needed in that case. Savings for the replacement sash are similar, but the replacement sash might offer greater ease of operation. A new exterior storm window added to a Loose baseline window has a first year savings of $16 at a cost of $100 (excluding lead abatement), a 16 percent rate of return in the first year. Adding a low-e interior storm saves $19 at a cost of $155, a 12 percent rate of return in the first year. Savings compared to total costs for upgrades of Typical baseline windows offer very low rates of return, and returns are even lower for Tight baseline windows. While some savings are low compared with total costs in many cases, the basis for comparison must be carefully considered.

Energy savings due to increased occupant comfort are not included in this study. These can be significant: if an occupant can lower the air temperature as a result of warmer interior window surface temperatures and decreased drafts due to air leakage, significant heating savings can result. Likely occupant interaction with the window upgrade is also not considered: a significant fraction of storm windows can be found open all winter in some buildings. These considerations emphasize the need for a full energy analysis to put window savings in the proper context of a building rehabilitation project, and to take full and appropriate account for costs and savings.

Decisions related to the upgrade of windows should be made primarily for reasons other than energy savings: for a given set of initial conditions, there is not a large difference between the energy savings for different options. Non-energy rationale for choosing a particular rehabilitation strategy can be based on historic considerations, occupant comfort, long term maintenance costs, lead abatement issues, egress requirements, durability of the energy improvements, total building rehabilitation budget, and matching the type and ease of window operation with the occupant population.

Once the window replacement strategy is chosen, energy should be considered and incremental costs and incremental savings should be compared. For example, purchasing low-e glass in place of clear glass typically has a $17 to $40 incremental cost for a storm window or for double glazing. With savings of approximately \$3.5 in the first year (excluding savings from a lowered thermostat due to warmer mean radiant temperature), this results in a 10 to 20 percent rate of return. Improved treatment of rough opening extraneous leakage can often be accomplished at a low cost, and can result in improved occupant comfort. The value of warmer interior surfaces and fewer drafts can be considered in the context of whole-building energy analysis.

Further Research

Several useful areas for further research became apparent during the course of this study:

- Study a more statistically significant sample, particularly of promising upgrade strategies
- Develop a method to more accurately quantify rough opening leakage
- Develop and field test methods to reduce rough opening leakage
- Develop better methods to correlate visual observation with expected air leakage rate
- Document how energy performance changes over time – durability of various treatments
- Investigate ease of operation of various upgrades
- Investigate storm windows relative to code compliance, particularly egress issues
- Perform controlled laboratory studies on a wider variety of treatments
- Investigate the interaction between infiltration and non-infiltration losses
- Research other rehabilitation strategies
- How often are storm windows REALLY open?
- Investigate applications of low-e glass products that minimize visual impact
- Work collaboratively with product manufacturers and preservationists to improve energy performance of products and applications

Conclusions: A summary of advice for preservationists

Decisions about window upgrade methods should be based primarily on decisions other than energy: Most energy-related window projects, including window retention and window replacement, result in similar post-treatment energy usage.

Once a general rehabilitation strategy is chosen, energy performance of that rehabilitation should be optimized. For example, low-e glass can reduce energy usage below average.

The level of treatment should be matched to the original condition of the window. To priortize window treatment appropriately, diagnostic whole-building air leakage testing should be used to guide air leakage reduction strategies as a part of a total building energy analysis.

"Retain versus retire" is a false dichotomy: window energy rehabilitation encompasses a continuum of possibilities:

1. Retain and repair original material only.

2. Retain and repair original material and add a storm window.

3. Retain and repair original material and add weatherstripping.

4. Retain but modify sash to accommodate vinyl channels and/or let-in weatherstripping.

5. Retain sash, but modify to accommodate double glass (can be low-e), vinyl channels, and let-in weatherstripping.

6. Replace sash with single glass sash, with varying levels of vinyl channels and weatherstripping.

7. Replace sash with double-glazed sash (can be low-e), with varying levels of vinyl channels and weatherstripping.

8. Remove sash and insert a replacement window inside existing jamb, including new jambs.

9. Remove entire window and trim and replace with a new window.

All possibilities can include storm windows, and options 3-8 should include sealing and insulating window weight/rough openings.

Quality of workmanship is a large determinant in final air leakage rate.

The rough opening, as well as the sash and jamb, should be treated to minimize air leakage.

In general, air leakage is the smaller part of the total heat loss of a window with two layers of glass. Lowering non-infiltration losses, by using double glass and low-e glass, results in greater energy savings than lowering air treatment leakage losses. Effective window upgrades reduce both losses.

Storm windows should be specified with low, independently-tested air leakage rates. Exterior storm frames should be caulked to outside trim.

Interior storm windows not only reduce leakage around the sash, but reduce leakage through the rough opening.

Infiltration reduction can significantly improve occupant comfort, which can result in lower thermostat setting and associated heating energy savings not reflected in this study.

Low-e glass, by raising interior glass surface temperatures, increases occupant comfort and can also result in similar savings not reflected in this study. Recent improvements in low-e glass have minimized its visual impact.

Notes

[1] Non-infiltration losses consist of radiation and convection to the interior surfaces of the window from the room, conduction through the materials of the window, and convection and radiation from the exterior surfaces to the outdoors.

[2] This model was developed for estimating natural infiltration rates for buildings based on whole building air leakage testing. Sensitivity analyses performed indicated that application of the model to single window data resulted in very similar results as the difference in modeled whole building natural infiltration rate with and without the window. A 3,000 square foot, two-floor, four-unit apartment building, typical of affordable housing in Vermont, with typical wind shielding, was used for this modeling.

[3] This study used the simplifying assumption that natural infiltration through a window with a storm window and a prime window does not alter the conductive and convective heat transfer in that region. Investigating this interaction was beyond the scope of this project, so it was assumed that these heat loss paths were independent.

[4] This leakage rate was as tight as any window tested in the study. The spring-loaded interior storm sash, site 10A, also had a low sash leakage rate of 0.05 scfm/lfc (at 0.30 inches water pressure.) The magnetic strip/plexiglass interior storms at site 15 had a sash leakage rate of 0.01 scfm/lfc.

[5] Low-emissivity (low-e) glass has a special coating that reduces heat radiation emitted by the surface by as much as 90 percent, improving the U-value of double glass windows by approximately 30 percent.

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