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Testing the Energy Performance of Wood Windows in Cold Climates

A Report to
The State of Vermont Division for Historic Preservation
Agency of Commerce and Community Development

August 30, 1996

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EXECUTIVE SUMMARY

During rehabilitation of historic buildings, the question of how to treat the windows is inevitably raised. The desire to retain the historic character of the windows and the actual historic material of which the windows are made is seen as competing with the desire to improve energy performance and decrease long term window maintenance costs. Replacement of window sash, the use of windows inserted inside existing jambs or whole window replacement is often advocated in the name of energy efficiency, long term maintenance cost reduction, ease of operation, and better assurance of window longevity. Other approaches to improve the energy efficiency of historic windows retain all or part of the existing sash and balance system and typically include exterior triple-track storm window rehabilitation or replacement. Some building renovations only include storm window repair or replacement and prime window maintenance. To date there is little data quantifying the impact on annual heating costs of these varied upgrade options or comparing estimated first year energy savings to installed costs. This study 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.

While upgrades often improved other aspects of windows, including ease of operation, reduction of lead hazard, and occupant comfort, only energy impacts were included in this study. In order to assess energy improvements due to window upgrades, it was necessary to establish first year heating energy costs associated with windows before and after upgrades. Energy costs resulting from thermal losses associated with a window are due to both infiltrative and non-infiltrative losses.

Infiltrative thermal losses through a window arise from air moving around the sash and jamb as well as through any cracks or gaps associated with the window. Thermal losses also occur due to radiation through the glazing, conduction through the window materials, and convection of the air layer next to the window materials. These latter three methods of heat loss (conduction, convection, and radiation) are considered to be non-infiltrative thermal losses and were modeled using WINDOW 4.1, a computer program simulating fenestration thermal performance.

Infiltrative thermal losses were investigated by field testing 151 windows during 1995 and 1996, primarily in northern and central Vermont. Leakage characteristics of these windows were estimated by fan pressurization. Of these 151 windows, 64 were in original condition and 87 were of various upgrades. A percentage of infiltrative exterior air was estimated during field tests based on temperature differences in the test zone during fan pressurization. Exterior air leakage was summed with sash leakage to estimate a whole window total infiltrative thermal loss rate due to infiltration. Total window leakage rates were correlated with heating season infiltration rates by using a computational model established for estimating whole building infiltration rates. Results for the 64 original windows were used to model typical, tight, and loose original condition windows. Estimated annual energy costs of these assumed windows were used to estimate first year energy cost savings for the various upgrade types.

The significance of exterior air infiltration to the total heat load of a window was observed throughout the study. Thermal loss due to exterior air infiltration can cause the thermal performance of a tight window to approach that of a loose window. The importance of reducing exterior air infiltration during any renovation was noted. Interior storm windows effectively reduced exterior air infiltration as well as reducing sash air infiltration. Exterior storm windows in good condition showed significant reductions in sash infiltration when in the closed position.

One issue in assessing energy performance of windows fitted with storms was if the storm was in the closed position during the heating season, a factor which can change the energy performance significantly. This study did not attempt to quantify how many storms were likely to be open or closed. Therefore, the assumed loose window with no storm allowed comparison of upgrades with storm windows open as well as with windows not fitted storm windows.

First year energy savings for window upgrades and estimated annual energy costs of the assumed windows were based on a typical Vermont climate (7744 degree days). Neither cooling cost savings nor changes in solar heat gain due to window improvements were addressed.

Results of testing and analysis were expressed in a number of ways including:

- effective leakage area (ELA), which may be loosely described as the size of a single orifice with similar air flow characteristics as the sum of the cracks of the window tested;
- sash air leakage rate at 0.30 inches of water pressure differential across the window, expressed in standard cubic feet per minute pre linear foot of crack, a standard value given in specifications for new windows, representing a useful point of comparison; and
- first year estimated heating cost savings compared to the three baseline original condition windows described above.

Costs of window upgrades were investigated primarily by interviewing developers of affordable housing in Vermont. Material, installation and mark-up costs are included for the window upgrades studied. Costs for upgrades were considered above those which would be required for routine window maintenance (paint, putty, caulk, and sash balance maintenance). Routine maintenance costs were considered a baseline for any building rehabilitation apart from energy upgrades. Costs for upgrades field tested ranged from a low of $75 to a high of $500. The lower cost option included sealing the top sash, installing bronze V-strip weatherstripping and sash locks, and retaining the existing prime and storm windows. If lead abatement was required for an original sash, an additional cost of $125 was added to the upgrade cost. The larger upgrade cost was for a wood window insert with double-pane insulating glass.

The findings of the study indicated the wide range of window upgrade options and installed

costs resulted in annual heating cost savings that were similar. Within several types of window upgrades tested, there were examples where inappropriate application of an upgrade or an incomplete installation resulted in below average energy performance. However, when installed carefully, virtually all the options studied produced savings in a similar range.

Estimated first year energy savings per window due to field tested upgrades ranged from zero to a high of $3.60 as compared to an assumed typical window and were slightly lower when compared to an assumed tight window. Estimated savings compared to an assumed loose window ranged from $12.40 to $16.60 per window. Estimated savings increased when windows with low-e glazing were modeled using WINDOW 4.1. It should be noted that estimated first year savings as shown should be viewed solely as relative savings when compared to other upgrades within the context of the study and not actual savings realized.

The variability in estimated first year energy savings for all window upgrades was small. A comparison of estimated energy savings per upgrade to costs for upgrade materials and installation revealed energy savings were two orders of magnitude lower than renovative costs. Based on the range of estimated first year energy savings of window upgrades generated by the study as compared to an assumed typical window and those costs associated with upgrade purchase and installation, replacing a window solely due to energy considerations did not appear to be worthwhile. Estimated first year savings of upgrades when compared to an assumed loose window are significantly greater, reflecting the importance of the original window condition in determining first year energy savings. Life-cycle costs of window upgrades were not included as a part of this study and may have a bearing on the decision making process.

As a result of the similarity in savings between upgrade types and the small savings indicated when existing windows were similar in performance to a typical or tight window, the decision to rehabilitate or replace a window generally should be made on the basis of considerations other than energy cost savings. It should be noted that this decision is not clear cut. Some upgrades that retain the original sash make major sash modifications while some replacement upgrades mimic historic windows effectively. There is a continuum between replacing and rehabilitating windows where the developer must find a solution appropriate to the particular context while considering non-energy issues such as maintenance, ease of operation, historic character, and lead abatement.

The population served by the housing is another important variable in an upgrade decision. Tenant populations in rental housing have no financial incentive to close storm windows or may be unable to operate them. In such cases, the value of estimated first year savings of an upgrade may be higher than expected if double-glazing is used in the prime window.

Once the decision to upgrade or replace an existing window is made, it is important to select a strategy that not only meets the needs of the building occupants and owners but also utilizes techniques that achieve the highest levels of energy savings and occupant

comfort justified by the financial constraints and financing mechanisms of the building rehabilitation project. In general:

- Window upgrades using existing sash can achieve performance indistinguishable from replacement sash but economics of the upgrade depend on the leakiness of the original window.
- If the existing window is loose, it can often be cost-effective to address this leakage, including air leakage between the window and rough opening as well as between an exterior storm window and trim. If the window is already in typical or tight condition, an upgrade is unlikely to be cost-effective regardless of the cost-benefit test used.
- If the windows have single glass, it is worthwhile considering installing a second layer, including the options of storm windows, replacement insulated glass units, energy panels and use of low-emissivity glass (low-E).

While it is tempting to compare first year energy savings to the total installed costs of a window upgrade, it should be noted that some window upgrades may be done for reasons other than energy savings. Therefore, a strict comparison of energy costs to total installed costs may not be appropriate in all cases. In addition, the time frame over which savings may be calculated can vary significantly. Developers of affordable housing, which often includes rehabilitation of historic structures, are often concerned with establishing "perpetually affordable" housing which includes decreased long-term maintenance and energy costs.

Within the decision-making process for deciding to replace or renovate an existing window, energy considerations should not be the primary criteria, but should also not be ignored. The resulting window rehabilitation strategy should result in the most comfort and appropriate degree of energy savings.

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Glossary of Terms

Actual cubic feet per minute (acfm) - the volume of air at ambient conditions passing through the fan pressurization device per unit time

Air leakage - induced air flow through a building envelope or window when using fan pressurization. Induced air flow is a measure of building or window tightness.

Effective leakage area (ELA) - the area of a round orifice with a flow coefficient equal to one, allowing an air flow equivalent to the summed gaps around a window

Extraneous air leakage (Q_e) - the volume of air flowing per unit time through the rough opening and test apparatus when under pressurization by the testing device

Humidity ratio - mass of water vapor per mass of dry air. Essentially, the mass of water vapor contained within a volume of air as compared to the mass of that air if it were dry.

Infiltration - uncontrolled air flow through unintentional openings driven by pressure differentials induced by temperature differences and winds

Infiltrative heat load - thermal losses through a window from air moving around the sash and jamb as well as through any cracks or gaps associated with the window.

Linear foot crack (lfc) - the sum of all operable sash perimeter of a window, expressed in feet

Natural infiltration - uncontrolled air flow during the heating season through unintentional openings driven by pressure differentials induced by temperature differences and winds

Non-infiltration heat load - the thermal loss due to convection, conduction, and radiation through a window

R-value - thermal resistance (hr-ft^2-°F/Btu). The steady condition mean temperature difference between two surfaces that induces a unit heat flow rate per unit area. Essentially, a measure of resistance to heat flow. R-value is the inverse of U-value.

Relative humidity - the ratio of the amount of water vapor in the air to the maximum amount of water vapor the air can hold at the ambient temperature.

Rough opening - the opening in a building envelope designed to accept a window

Sash air leakage (Qs) - the volume of air flowing per unit time through the window exclusive of any air from the rough opening during the testing period

Standard cubic feet per minute (scfm) - the volume of air per unit time passing through the fan pressurization device, converted to standard conditions for reference and comparative purposes. Standard conditions for this study were defined as:

- standard temperature - 69.4°F (20.8°C)
- standard pressure - 29.92 inches of mercury (760 mm Hg)

Standard cubic feet per minute per linear foot crack (scfm/lfc) - standardized volume of air per unit time passing through one linear foot crack of operating window perimeter

Total air leakage (Qt) - the volume of air flowing per unit time through the window system when under pressurization by the testing device

U-value - thermal transmittance (Btu/hr-ft^2-°F). The rate of heat flow per unit time per unit area per degree temperature differential. Essentially a measure of thermal transmission through window materials and the boundary air films. U-value is the inverse of R-value.

Window - includes the jamb, sash, associated hardware but excludes the rough opening and any spaces between the jamb and rough opening

Window system - includes the window, any space between the window and rough opening, and framing members that form the rough opening

Nomenclature:

ELA_s/lfc - effective sash air leakage area per linear foot crack (in^2/lfc)
ELA_{ext}/lfc - effective extraneous air leakage area per linear foot crack (in^2/lfc)
ELA_{tot}/lfc -effective whole window leakage area per linear foot crack (in^2/lfc)
ELA_{to}t -effective whole window leakage area (in^2)
Q_{nat} - natural air infiltration rate during the heating season, due to pressure differentials induced by wind speed and direction, as well as interior/exterior temperature differences (scfm)
L_{inf} - whole window infiltrative thermal loss rates (Btu/hr-°F)
L_{non} - non-infiltrative thermal toss rates (Btu/hr-ft^2-°F)
L_u - whole window non-infiltrative thermal loss rates (Btu/hr-°F)
L_{eff} - whole window thermal loss rates; infiltrative and non-infiltrative thermal loss rates combined (Btu/hr-°F)
L_{yr} - annual whole window thermal losses (Btu/yr)
C_{win} - annual energy costs per window ($)
S_{win} - annual savings per upgrade ($)

1. INTRODUCTION

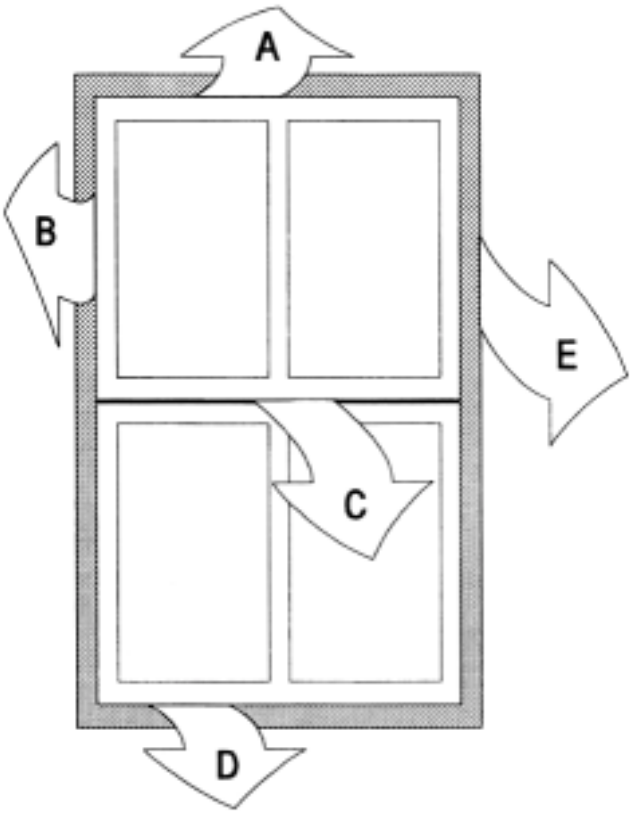
Windows serve a variety of integral roles in buildings, ranging from admitting light and ventilation to an expression of period technology and design. Windows also have a major impact on the energy consumption of a building as any thermal loss through a window must be replaced by the heating system. When historic buildings are to be renovated, the question of the existing historic windows is inevitably raised. The desire to retain the historic character of the windows and the actual historic material of which the windows are made is seen as competing with the desire to improve energy performance and decrease long term window maintenance costs. Replacement of window sash, the use of windows inserted inside existing jambs, or whole window replacement is often advocated in the name of energy efficiency, long term maintenance cost reduction, ease of operation, and better assurance of window longevity. The renovation of historic windows to improve energy efficiency retains all or part of the existing sash and balance system and typically includes exterior triple track storm window rehabilitation or replacement. To date, there is little data that quantifies the impact on estimated first year heating costs of these varied approaches or compares the estimated value of energy saved to installed costs. This study was undertaken to address the assumption that historic windows can be retained and upgraded to approach the thermal efficiency of replacement sash or window inserts. While window upgrades often improved other aspects of windows including ease of operation, reduction of lead hazard, and occupant comfort, only energy impacts were included in this study.

In December 1994, the State of Vermont Division for Historic Preservation (DHP) of the Agency of Commerce and Community Development issued a Request for Proposals to address the energy impacts of the rehabilitation versus replacement issue, based on a grant from the National Park Service and the National Center for Preservation, Technology, and Training. The study was directed toward windows in historically significant buildings, including affordable housing and private residences. Major issues addressed were:

- energy savings attributable to existing window retrofits,
- estimating first year savings in heating costs attributable to field tested window retrofits,
- installation and materials costs for existing window retrofits, and
- the comparison of costs and savings from existing window retrofits to those incurred by replacement windows.

The decision to rehabilitate or replace a window is often based on factors other than long-term energy conservation, including the historical significance of a window, its role in a building's character, occupant comfort, and ease of operation. While some of these factors were often improved during window upgrades, only energy costs associated with reduced thermal losses due to infiltration and non-infiltration were studied. Infiltrative thermal losses are due to exterior air moving through and around the sash and rough opening. Infiltrative

Figure 1: Principle air leakage sites for a typical double-hung window



A - air infiltration through the head junction
B - air infiltration through the sash/jamb junction
C - air infiltration through the meeting rail
D - air infiltration through the sill junction
E - air infiltration through and around the jamb from the rough opening

losses were investigated by field and laboratory pressurization testing. Figure 1 is a schematic diagram of a standard double-hung window, showing typical air leakage sites for that style window. Non-infiltrative losses include conduction, convection, and radiation through the materials of the window and were simulated using a computer model.

While historically significant buildings are found throughout Vermont, few were scheduled for renovations during the time frame of the study. Many affordable housing buildings and private residences in Vermont are of the same nature as historic buildings and were scheduled for, or had undergone renovations during the required time period. Due to building similarities, windows in affordable housing and private residences consequently constituted the majority of field testing with the inclusion of some historical windows renovated during the course of the study.

This report contains the results of the study implemented to determine the effectiveness

of various window rehabilitations in reducing infiltrative and non-infiltrative thermal losses. Those rehabilitations included windows utilizing existing sash as well as several replacement options. The results, gathered from 151 windows at 19 sites, estimate the first year energy impacts of upgrades associated with a reduction in heating cost requirements during an average Vermont heating season. No attempts were made to estimate either the contribution of solar gains during the heating season or energy impacts associated with reductions in cooling requirements due to window upgrades.

While not addressing all issues concerning window performance and operation, the results of this study concerning the energy performance of windows during the heating season will be beneficial to the historical preservation community as well as providers and developers of affordable housing and the general home-owner. This information will allow those organizations and individuals to make better informed choices about window rehabilitation and replacement strategies based on actual data as opposed to anecdotal evidence.

2. BACKGROUND AND SIGNIFICANCE

A literature review was undertaken to determine the nature of previous work and findings relevant to the study.

2a. Whole Building Energy Losses

One of the primary purposes of building renovation is to reduce energy consumption and costs via thermal losses due to air infiltration. A large body of pre- and post-renovation data for whole building energy consumption does not exist. However, a reduction in building energy requirements may be accomplished by reducing air infiltration through sills, walls, basements, attics, doors, and windows. Estimated energy costs associated with air infiltration range from 33% of total building energy costs (Sherman et at., 1986) to as much as 40% (Giesbrecht and Proskiw, 1986). Upon completion of whole building retrofitting, reductions in energy costs attributable to infiltration have been estimated to range from 19% based on a 55 house sample (Jacobsen et at., 1986) to 50% for a single townhouse (Sinden, 1978). Most saving estimates fall between 30-37% (Giesbrecht and Proskiw, 1986; Harrje and Mills, 1980; Nagda et at., 1986). Giesbrecht and Proskiw also found two-story houses showed lower reductions in infiltration after renovations (24.4%) than single-story houses (36.9%), likely due to leakage between floors.

2b. Window Energy Losses

Of concern to this study was the portion of total house leakage attributable to infiltration through and around windows. Estimates of window contribution vary more widely than whole house leakage estimates. Two separate studies found the fraction of window leakage to be approximately 20% of whole house leakage (Tamura, 1975; Persily, 1982). An estimated 37% of the total heat loss from a house may be due to infiltration through windows and doors (Lund and Peterson, 1952), while a 20 house survey showed these sources are unlikely to exceed 25% (Bassett, 1984).

The use of a mathematical model estimated 25% of heat loss through a loose fitting, nonweatherstripped window was attributable to infiltration (Klems 1983). The modeled window was assumed to be typical of windows found in older housing. A reasonably tight double-pane window, typical of new construction, was estimated to have 12% of its thermal losses attributable to infiltration by the same model. Energy costs associated with infiltrative losses became a significant portion of total fenestration energy costs when air leakage rates exceeded 0.5 cubic feet per minute per linear foot crack (cfm/lfc) based on the Residential Fenestration (RESFEN) computer model developed by Lawrence Berkeley Laboratory (LBL), University of California, Berkeley (Kehrli, 1995). Various leakage rates at 0.30 inches of water pressure were modeled with RESFEN, then reduced to total window energy losses at 0.016 inches of water pressure, the assumed average heating season interior/exterior pressure differential. Costs due to infiltration as a percentage of total window energy costs varied from 15% at 0.5 cfm/lfc to 41 % at 2.0 cfm/lfc for a two story house, based on the RESFEN simulation.

2c. Window Weatherstripping

The intent of weatherstripping a window is to reduce the amount of air infiltrating through the sash/jamb junctions and the meeting rails. Infiltrative losses were reduced from 37% to 17% of total house thermal losses when metal rib-type weatherstripping was installed around the windows (Lund and Peterson 1952). This corresponded to an approximate 24% reduction in building energy costs.

2d. Storm Windows

The installation of storm windows, either exterior or interior, presents its own range of advantages and disadvantages. In general, properly installed new storm windows in combination with existing single-glazed windows may achieve U-values comparable to insulating glass and reduce air infiltration while lowering maintenance costs and extending the life of the window (National Park Service, 1986). Thermal transmittance (U-values) refers to the amount of heat a one foot square section of window would lose per hour for every one degree Fahrenheit temperature differential and has units of Btu/ft^2-hr-°F. Lower numerical values for thermal transmittance imply better thermal efficiency.

Disadvantages of exterior storm windows include visual obstruction of an historic window and its attendant details, while interior storm windows may increase condensation and cause moisture related problems to the primary sash. The negative visual effect of exterior storm windows may be reduced by using single lite storm sash. Interior storm windows have avoided the problem of condensation by incorporating vent holes and a sealed fit (Park, 1982). The use of interior storm windows can also reduce infiltration by reducing air movement through the sash or rough opening into the building interior. Whole house energy consumption was reduced by 12% in a test house in England fitted with interior storm windows (Rayment and Morgan, 1985).

2e. Rating New Windows

Many builders, contractors, and individuals purchasing new windows for either new construction or renovation are increasingly aware of energy considerations and choose windows based on rates of sash air leakage and thermal transmittance (U-values) as well as appearance. These ratings are provided by window manufacturers and are the results of independent testing by accredited simulation laboratories. Laboratories are accredited by the National Fenestration Rating Council, with each accredited laboratory having one or more certified simulators. Air leakage tests are conducted according to ASTM E 283-91, *Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen.* Thermal transmittance tests follow ASTM E 1423-91, *Standard Practice for Determining the Steady State Therma/ Transmittance of Fenestration Systems* (Kehrli).

For sash air leakage, test results are generally provided as cubic feet per minute per linear

foot-crack (cfm/lfc) at a differential of 0.30 inches of water pressure. National standards for sash air leakage at 0.30 inches of water allow a maximum sash flow of 0.37 cfm/lfc for new windows in order to be certified (National Wood Window and Door Association, 1996).

ASTM E 1423-91 is both a complex and expensive laboratory testing process, averaging $1200 per test (Kehrli). Researchers at the Lawrence Berkeley Laboratory (LBL), have developed an interactive computer program to calculate the thermal transmittance of windows. This program, WINDOW 4.1, is based on actual window testing following the E 1423-91 method and is consistent with the rating procedure developed by the National Fenestration Rating Council (NFRC 100-91: *Procedure for Determining Fenestration Product Thermal Properties).* Test data listed by window manufacturers are the results of WINDOW 4.1, the LBL computer simulation program. Manufacturers provide a random sample of their higher and lower end window models to the accredited testing laboratories to ensure actual compliance with certifiable specifications (Weidt).

2f. Window Performance

Should a renovation project be designed with replacement windows, it is likely that windows will be chosen based on the results of the manufacturers' data. The maximum 0.37 cfm/lfc allowable sash flow for certification is often exceeded by windows, as shown by both field and production-line testing (Kehrli, 1995). An on-site study of window leakage rates was done in the Minneapolis/St. Paul metropolitan area, comparing listed air leakage rates of 192 windows to actual measured leakage rates after installation in new residential constructions. Window models from sixteen manufacturers were tested, which included both double- and single-hung windows. Of all the window tested, 60% exceeded the manufacturers' listed performance specifications while 40% exceeded the 1979 industry maximum of 0.50 cfm/lfc for certifiable windows. More specifically, 79% of double-hung and 100% of single-hung windows exceeded the manufacturers' lab data. Installation technique, as performed by the various contractors, showed no significant effect on window performance (Weidt, 1979).

The Weidt study also showed double-hung windows had lower air infiltration rates per linear foot crack than did single-hung windows within any manufacturer. Infiltration rates expressed as cfm/lfc may be a misleading statistic when comparing different window types. As an example, a typical double-hung window has approximately 70% more operable linear crack per sash area than a single-hung window of identical size. If the two windows show equal air leakage rates per linear foot crack, more air is actually moving through the double-hung window due to its larger operable linear crack perimeter. When infiltration is expressed as cfm/sash area or cfm/ventilation area, single hung windows outperform double hung windows (Weidt, 1979).

2g. Non-infiltrative versus Infiltrative Thermal Losses

Within the confines of how the predominant energy loss of a window occurs, there is some debate. Those advocating non-infiltrative thermal losses being much greater than

infiltrative losses, recommend all single-glazed sashes be replaced with double-pane insulating glass (Kehrli). Energy losses due to direct heat transmission through a window were observed to be consistently greater than those due to air leakage, regardless of the leakage rate considered (Klems, 1983). In a comparison of energy requirements between a test house and an idendical control, it was estimated that replacing single-glazing with double-glazing reduced losses via thermal transmission such that building space heating requirements were reduced by 9% (Rayment, 1989).

If double-pane insulating glass is to be used and the original sash retained, there must be adequate wood thickness to accommodate the rabbeting necessary to insert thicker, double-pane glass. The wood must also possess the strength to support the extra weight (National Park Service, 1986). This has been done in some old single-lite sash but presents a more complicated problem in multi-lite sash where muntins are present. As compared to a single-lite window, the larger glass/wood edge perimeter of a multi-lite window will reduce the thermal improvements of double-pane insulating glass by allowing more conduction through the edges.

Others believe that air infiltration is a larger contributor to poor energy performance than single-glazing and any steps taken to reduce infiltration are nearly always cost effective (National Park Service, 1986). The Colcord Building in Oklahoma City reduced its space heating costs by 25% when its loose fitting, single glazed windows were renovated. Renovation included reglazing with new putty compound, painting, bronze V-strip spring weatherstripping, and the addition of removable interior acrylic storm panels (Park, 1982). It was undetermined what fraction of heating cost reductions were attributable to the interior storm window and what fraction arose from the other renovations.

The addition of acrylic storm panels in the Colcord Building constituted a second glazing layer which served to decrease non-infiltrative losses through the windows. Acrylic panels were chosen over glass due to weight considerations, but provided the additional benefit of decreasing non-infiltrative losses by 15% as compared to ordinary glass storm panels. Storm windows in general provide a second glazing layer, reducing non-infiltrative thermal losses. Exterior storm windows provide the additional benefit of lowering window maintenance costs as well as prolonging window life by preventing accumulations of moisture (Fisher, 1986).

2h. Air Infiltration through the Rough Opening

A significant source of infiltration may be the gap between the rough opening of the building and the frame of a window unit (Flanders et al, 1982). Estimates of infiltrative contributions through window rough openings range from 12% of whole building energy loads in loose construction (typical of affordable housing stock) to 39% in tighter construction (Proskiw, 1995). Air leaking through the rough opening/frame juncture around an otherwise tight window will adversely affect the overall performance of the window unit (Louis and Nelson, 1995). The conventional method used to seal this gap in new construction is to insert fiberglass insulation between the rough opening and frame, even though fiberglass

insulation is not intended to be an air barrier material. A laboratory study in Winnipeg, Canada, showed the conventional sealing method still allowed significant air leakage through the rough opening (Proskiw, 1995).

The amount of air attributable to leakage through the rough opening was estimated for both loose and tight houses. A loose house was assumed to have 5 ACH_{50} (5 air changes per hour at 50 Pa, or 0.20 in. H_2O), typical of older houses. A tight house was assumed to have 1.5 ACH_{50}. Ratios of rough opening to whole house leakage were based on laboratory results, which gave estimates of 14% rough opening leakage for tight houses and 4% for loose houses. The two most efficient and cost effective methods for sealing rough openings were low expansion urethane foam and casing tape, reducing estimates of rough opening leakage to less than one percent of whole house leakage (Proskiw, 1995). Casing tape is the tape normally used for taping joints between exterior sheets of insulated sheathing.

Older buildings often do not have any barrier between the frame and rough opening, allowing air access to the window unit with little impediment. Proskiw estimated 39% of total house air leakage was from rough openings in a loose house typical of older construction. The most effective means of reducing extraneous leakage require removal of both interior and exterior trim. Trim removal provides exposure and access to the window frame/rough opening junction, allowing thorough sealing. Care must be taken when using expandable foam to prevent overfilling, which could lead to window jamb distortion. It is possible to drill small holes in the jamb to insert foam, but three potential drawbacks exist. Insertion holes may be visible, but more importantly, there is a greater risk of overfilling the cavity with foam, which would cause distortion of the jamb. A complete seal also cannot be ensured without visual inspection. Removal of the trim provides this opportunity.

2i. Air Infiltration and Relative Humidity

Relative humidity plays a significant role in infiltration through old wooden windows by influencing the fit of the sash to the frame. The physical change in wood dimensions as wood absorbs or releases atmospheric moisture affects the gap dimensions between the sash and frame, directly influencing infiltration. Temperature also affects wood dimensions but relative humidity is a more important factor than wood temperature, with cold wood expanding more from absorption of outside moisture than from temperature changes (Lstiburek). While cold air in the winter does not carry a large amount of moisture, its relative humidity is approaching saturation due to the decreased amount of moisture the cold air may hold. This implies that some moisture absorption may occur in the winter with a corresponding degree of swell.

2j. Routine Maintenance

Significant reductions in infiltration may be accomplished by routine maintenance of an existing window while improving its integrity. Routine maintenance includes removing the glass, applying back putty, reinserting the glass, repointing and reglazing. Excess paint

should be removed and any necessary sash or frame repairs done along with the installation of good quality weatherstripping (NPS, 1986). Repainting the sash, frame, and glazing will help provide a good seal against the elements.

2k. Benefits of Renovating Historic Windows

The advantages of renovating existing windows versus replacement in an historic building include saving the historic value and design of the window as well as the interior/exterior appearance. For these reasons, it is advantageous to investigate methods of rehabilitation in an historic building. It has been shown in both the Colcord Building in Oklahoma City (Park, 1982) and the Delaware Building in Chicago (Fisher, 1985) that effective window rehabilitation can be accomplished at a lower cost than replacement windows while still resulting in significant energy savings.

3. ASSUMPTIONS AND TYPICAL PARAMETERS

Excessive natural infiltration may lead to a number of unwanted effects and problems in a building during the heating season. The addition of cold, infiltrative air represents an additional heat load for the building, unnecessarily increasing annual energy costs. Drafts from infiltrating air affect occupant comfort levels near windows or may preclude the use of entire rooms. Older buildings are subject to low relative humidity levels due to excessive infiltrative exterior air during the heating season. Exterior air has a low humidity ratio (mass of water vapor to mass of dry air), even though it has a high relative humidity. When the exterior air is heated, humidity ratio remains constant but relative humidity drops precipitously, giving rise to dry air.

As cold exterior air infiltrates a building during the heating season, warm interior air extiltrates through wall and window openings as it is displaced. As the warm air passes through the building shell, temperature decreases and condensation may occur in insulation or on structural elements. Condensation decreases the insulative value of insulation and may lead to wood rot.

Specific areas this study addressed include the following:

- energy savings attributable to existing window retrofits,
- estimating first year savings in heating costs attributable to field tested window retrofits,
- installation and materials costs for existing window retrofits, and
- the comparison of costs and savings from existing window retrofits to those incurred by replacement windows.

First year energy savings achieved by upgrading existing windows were estimated as the difference between energy costs attributable to an assumed pre-treatment window and those attributable to a window upgrade.

An estimate of typical heating season energy costs had to be made in order to estimate savings realized from any type of window upgrade. This necessitated the definition of a building typical of affordable housing from which a base-line estimate of annual energy costs could be made. The windows in such a defined building were also to be typical of existing window stock. Although the focus of the study was to be residential historical windows, the decision was made to base estimated energy costs on a typical building used for affordable housing. The reasons for the decision were twofold - few historical windows were scheduled for renovation during the period of the study and affordable housing stock was representative of many Vermont residences, including many historical structures.

The relationship between thermal losses through typical windows to total house energy costs was of concern in order to simplify these calculations. If a reduction in thermal loss through a single window due to energy improvements correlated directly to a reduction in whole building annual heating cost due to a window upgrade, then savings could be

modeled for each window upgrade directly. If this were not the case, then a whole building simulation utilizing each upgrade type would be required. This required development of a typical building for the purposes of the study.

Air leakage characteristics through typical windows were based on pressurization field testing of 64 existing windows in older buildings and homes. These data were extrapolated to 0.016 inches of water pressure and correlated to natural infiltration rates using the Lawrence Berkeley Laboratory (LBL) correlation model.

For whole buildings, pressurization data in terms of effective leakage area (ELA) is correlated to natural infiltration by a fluid mechanical model developed by the Lawrence Berkeley Laboratory. The LBL model uses a whole building ELA and a calculated coefficient to determine the seasonal average infiltration rate of a whole house (Grimsrud et al., 1982). This coefficient, specific to both house and climate, is the average heating season infiltration per unit ELA. Knowing the average seasonal infiltration rate, heating degree days for the climate, heating system efficiency, and the cost of fuel allows an estimation of the heating costs attributable to the building.

For the purposes of this study, the use of the LBL model was modified by using data from a single window rather than whole house data. The assumption was made that when using a window ELA, the results of the LBL model would have the same equivalent significance in predicting the average annual heating season natural infiltration rate for a window as the model would have when using a whole building ELA to predict the heating season natural infiltration rate for the building. It is recognized that this was not the intent of the model and as such, none of the derived values should be treated as absolutes. Rather, numbers should be viewed only as relative values and used solely for comparative purposes with other values similarly derived in this study.

A potentially significant source of thermal loss due to air leakage was around the window frame by way of the rough opening. The thermal loss may be of sufficient magnitude to significantly affect the thermal performance of an efficient window. A new test methodology cited in the literature has been proposed to segregate and quantify the amount of extraneous air leaking through the rough opening into test chamber and window surround components (Louis and Nelson, 1995). The proposed methodology does not quantify the exterior air included in the extraneous air volume, but suggests several methods to estimate the exterior air volume.

One of the outcomes of the current study was a field method used to quantify the percentage of exterior air contained in the induced extraneous air during pressurization testing. A simple method of estimating the volume of exterior air passing through the rough opening during fan pressurization is presented, based on temperature differentials. The method, implemented in the spring of 1996, required an interior/exterior temperature differential and could only be applied during the pressurization testing of 33 windows due to a limited number of available interior/exterior temperature differentials.

Once a base-line estimate was established, first year energy costs associated with upgraded existing windows or those associated with replacement sash or window inserts were estimated based on field testing and computer modeling. These estimates were based on the air leakage and thermal transmission characteristics of field tested window upgrades or replacements.

3a. Typical Affordable Housing Parameters

As previously mentioned, a typical affordable housing building was used to estimate energy costs although the focus of the study was on residential historical windows. Affordable housing provided a pool of old windows scheduled for renovation during the time frame of the study and was also representative of many Vermont residences. Affordable housing may be found in all manner of buildings, but in Vermont, these buildings generally are two story structures with both an attic and basement. The following criteria were chosen to characterize a typical, historical affordable housing building:

- 30 by 50 foot rectangular building with a gable roof;
- two heated stories with an unheated attic having R-1 9 insulation;
- uninsulated basement, heated only by losses from the heating system and floor above;
- uninsulated basement walls, exposed 2 feet above grade;
- wood frame 2 x 4 walls, uninsulated;
- eight windows on each 50 foot side, four on each 30 foot side for a total of 24 windows;
- two wooden doors, 3 ft. x 6 ft. 8 in., without storm doors;
- oil-fired heating system, 65% efficient;
- 6,100 cfm infiltration rate at 0.20 in. water pressure (50 Pa), equivalent to an average 1.2 air changes per hour during the heating season; and
- leakage areas equally distributed between the walls, floor, and ceiling.

It was assumed for this study that the building would be renovated at the same time as the windows. Assumed typical post-renovation building parameters are listed below:

- walls insulated with 4 inch cellulose;
- attic floor insulated to 12 inch settled depth (R-38);
- storm doors installed;
- infiltration rate reduced to 2,200 cfm at 0.20 in. H_2O (50 Pa) equivalent to an average 0.41 air changes per hour during the heating season; and
- heating system upgraded to 75% annual efficiency.

3b. Typical Parameters for Existing Windows

Typical windows found in affordable housing buildings were assumed to be double-hung and fitted with aluminum triple track storm windows. These windows were assumed to be single-glazed with dimensions of 36 by 60 inches, yielding 19 perimeter feet of operable

linear crack. Sixty-four original condition windows were field tested for air leakage by a fan pressurization device prior to any retrofits. From these data, air leakage rates for a “typical” original condition window as well as both “loose” and “tight” windows were determine

A typical window was assumed to have an aluminum triple track storm window in the closed position. Air leakage characteristics of the typical window were assumed to be equivalent to the averaged sash leakage of all the original condition windows tested when storm windows were closed. Thermal transmission characteristics were based on wooden sash and single-pane glass. The tight window was also assumed to have a storm window in the closed position but had leakage characteristics equivalent to one standard deviation low than the field test average for windows with storms closed. The loose window was assumed to have no storm in place with leakage characteristics equivalent to the averaged sash leakage for original condition windows with storms in the open position. In all cases, a percentage of the appropriate averaged induced extraneous air was included with the sash leakage to account for the exterior air contribution.

3c. Original Condition Windows and Window Upgrades Field Tested

For the study, 151 windows at 19 sites were field tested, with 87 of those windows being various upgrade types. Sites for pressurization testing were chosen by availability, timing of scheduled renovation, suitability as to window and upgrade type, and window accessibility. Several buildings were not typical of affordable housing, but all field tested windows were representative of windows found in affordable housing throughout Vermont

Table 1 is a site list of windows field tested, showing the number of original condition windows and/or the number of upgrades tested at each site. Not all windows at a given site were tested due to accessibility or weather conditions, nor were all original condition windows retested after renovation. Occupancy and weather precluded retesting windows at some sites, while many other sites did not receive the expected upgrade within the allotted time frame of the study. Renovations sufficiently improved leakage characteristics of windows at several sites to allow a greater number of upgraded windows to be tested Also included in the last column are the number of windows tested prior to and post renovation at relevant sites.

A variety of window upgrades were field tested, ranging from minimal weatherstripping to replacement window inserts. Some windows had new aluminum triple track storm windows installed while others retained the existing storm windows. Still others used interior storm windows as an upgrade option. In two instances, existing wooden storm windows were weatherstripped and retained. Table 2 lists locations and identification numbers of sites where window upgrades were tested as well as the various upgrades encountered.

Table 1: Site locations and ID's, showing numbers of original windows and upgrades tested

Site ID	Location	Original Windows	upgraded Windows	Windows Tested Pre- and Post-Upgrade
1	CVCLT Montpelier, VT	3		
2	40 Nash Street Burlington, VT	3	3	3
3	133 King Street Burlington, VT	9	4	3
4	Congress Street Morrisville, VT	5		
5	204 Pearl Street Burlington, VT	8		
6	101 Fairfield Street St. Albans, VT	4	6	3
7	Sapling House Island Pond, VT	12	20	12
8	127 Mansfield Avenue Burlington, VT	6		
9	6 Raymond Street Lyndonville, VT	6		
10	124 Federal Street Salem, MA	4	4	4
11	76 Pearl Street St Johnsbury, VT		6	
12	12 Summer Street Morrisville, VT		10	
13	George Street Morrisville, VT		10	
14	Kidder Hotel Block Derby, VT		6	
15	4 Occom Ridge Hanover, NH	4	4	4
16	Irasburg Town Hall Irasburg, VT		7	
17	605 Dalton Drive Fort Ethan Allen Colchester VT		3	
18	Brisson Residence South Hero, VT		2	
19	40 Barre Street Montpelier, VT		2	

Table 2: Window Upgrades

ID	Location	Upgrade
2	40 Nash Street Burlington, VT	**Bi-Glass System:** Existing sash routed to accept sealed double-pane insulating glass and vinyl jamb liners. Bulb weatherstripping at meeting rail, head, and sill junctions.
3	133 King Street Burlington, VT	**Broscoe Replacement Sash:** Single glazed, wood replacement sash with vinyl jamb liners. New aluminum triple track storm windows, caulked around frame.
6	101 Fairfield Street St. Albans, VT	**Custom Gard:** Vinyl frame and sash insert with vinyl replacement sash, installed inside existing jamb. Double-pane insulating glass.
7	Sapling House Island Pond, VT	**19 Original Sash Retained:** Sash routed to accept Caldwell DH-100 or 200 vinyl jamb liners. Bulb weatherstripping at meeting rail, head, and sill junctions. **Weather Shield:** One custom Shield replacement window.
10	124 Federal Street Salem, MA	**Storm Windows:** Interior storm; aluminum triple track storm; low-profile, non-track, removable pane storm; new wooden storm window with primary sash weatherstripped.
11	76 Pearl Street St. Johnsbury, VT	**Weather Shield:** custom Shield replacement wood frame and sash insert, installed inside existing jamb. Double-pane insulating glass.
12	12 Summer Street Morrisville, VT	**7 Original Sash Retained:** Sash routed to accept Caldwell DH-100 vinyl jamb liners. **3 Marvin Replacement Sash:** Single-pane, wood replacement sash.
13	George Street Morrisville, VT	**8 Original Sash Retained:** Sash routed to accept Caldwell DH-100 vinyl jamb liners. Bulb weatherstripping at head and sill junctions. **2 Marvin Replacement Sash:** Single-pane, wood replacement sash.
14	Kidder Hotel Block Derby, VT	**Original Sash Retained:** Windows reglazed and painted. New Harvey aluminum triple track storm windows caulked to exterior trim.
15	4 Occom Ridge Hanover, NH	**Original Sash Retained:** Interior plexiglass storm windows held by magnetic strips.
16	Irasburg Town Hall Irasburg, VT	**Original Sash Retained:** Caldwell coiled spring balances; bulb weatherstrip at sill junction. Wooden storm windows felt weatherstripped. **Weather Shield:** One custom Shield replacement window.
17	605 Dalton Drive Fort Ethan Allen Colchester VT	**Original Sash Retained:** Pulley seals; zinc rib-type weatherstripping along jamb; metal V-strip at meeting rail. Top sash painted in place. New aluminum triple track storm windows caulked to exterior trim.
18	Brisson Residence South Hero, VT	**Marvin Tilt Pac:** Double-pane insulating glass replacement sash with vinyl jamb liners utilizing existing frame.
19	40 Barre Street Montpelier, VT	**Original Sash Retained:** Top sash painted in place; bronze V-strip weatherstripping; old aluminum triple track storm window frame caulked in place.

4. METHODOLOGY

Energy costs associated with existing windows in older housing must first be known in order to estimate savings from any type of window retrofit. Thermal losses accounting for these costs are attributable to natural infiltration through and around the window unit and non-infiltrative losses. Field testing and computer simulations were used to estimate associated energy costs due to infiltrative and non-infiltrative thermal losses.

A total of 151 windows at 19 sites were field tested for air leakage. These windows included 64 original condition windows used to determine base estimates for air leakage through assumed typical, tight, and loose windows. The remaining 87 windows consisted of a variety of window upgrades, ranging from minimal weatherstripping of the original window to the addition of new storm windows to total window replacement. Three windows in one location were tested over a period of eight months to investigate the correlation of air infiltration rates to environmental parameters. Laboratory tests were also performed on two original condition windows. Testing was repeated on one laboratory window after routine maintenance and on the other after an upgrade.

4a. Contribution of Window Thermal Losses to Whole House Losses

Energy losses attributable to windows account for approximately 20% of whole house losses according to the literature. One of the goals of this study was to assess a change in whole house energy consumption on a per window basis due to a window upgrade. This required knowledge of how the cost of thermal losses due to windows affected the cost of whole house losses. Calculations of energy savings could be simplified if the relationship was additive such that a decrease in energy costs for a window directly corresponded to an equivalent decrease in total building energy costs. Simplifications would arise from calculating savings based solely on energy cost reductions realized through window upgrades rather than modeling whole building performance for each type of window upgrade. The concept of an additive relationship for thermal loss is supported when leakage rates are expressed in terms of effective leakage area (ELA). Individual building components may be added together as ELA's to estimate a total building leakage area (Proskiw, 1995).

The relationship between window and whole house annual heating costs was investigated by utilizing two models, an ASHRAE static heat load model and REM/Design, a static model that estimates contributions of internal and solar heat gains. Based on surface area, actual blower door test data for both a tight and loose house were scaled to the assumed typical affordable housing building. The assumption was made that air leakage is proportional to surface area as increased surface area should allow for more leakage sites.

Both models were run with typical, tight, and loose windows in both loose and tight building configurations. Values for annual heating energy costs varied between the two models, but the incremental changes between window conditions were similar. Based on the similar

incremental results of the two models, it was assumed that a reduction in energy costs due to window upgrades corresponded to an equivalent reduction in whole house energy loss.

The relative locations of leakage sites may play a large role in determining whether natural infiltration is the primary result of wind or temperature induced infiltration. Wind induced pressures would be the dominant driving force for infiltration if most leakage sites were located in the walls of a building, as opposed to floors or ceilings. If that were the case, solely upgrading the windows to reduce air leakage would transfer a greater percentage of whole house leakage to floors and ceilings. The effect of this change in relative leakage location was investigated by running the Lawrence Berkeley Laboratory (LBL) correlation model, using typical Vermont temperature and wind speed data. Using the blower door data, tests with leakage sites relegated to varying percentage locations in walls, floors, and ceilings were run for loose and tight house configurations, as well as the scaled up buildings. It was found that relative location of leakage sites had little bearing on the results with an extreme case showing a difference of 4%. Distribution of leakage sites prior to modeling a window upgrade were assumed to be even for the purposes of this study (33% ceiling, 33% floor, 34% walls).

4b. Infiltrative Thermal Losses

Losses due to natural infiltration through a window are the result of interior/exterior temperature differentials and wind induced pressure. Natural infiltrative losses were estimated from measurements of air leakage at a set range of pressure differentials. These data were the results of field testing existing window stock based on a modification of ASTM E 763-93, *Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors.* The modification arose from the leakiness of the original window stock. Current industry standards list air leakage rates at 0.30 inches of water pressure, the recommended reference pressure cited in ASTM E 783-93. Many original windows were in poor condition, precluding the attainment of 0.30 inches of water pressure. A range of pressures was systematically employed to characterize the leakiness of the windows according to the flow model:

$$Q = c\Delta P^X$$

where

Q = air flow rate
c = leakage constant
ΔP = pressure differential
x = flow exponent

Linear regression was used to determine the leakage constant (c) and flow exponent (x) for a window, based on leakage results from fan pressurization. These data were used to extrapolate air leakage rates at 0.30 and 0.016 inches of water. The latter pressure (0.016 in. H_2O) was assumed to be the average heating season interior/exterior pressure

differential that drove natural infiltration. The driving force resulted from pressure differences induced by building interior/exterior temperature differentials and those from wind speed and direction. The effective leakage area (ELA) was used to characterize the total air flow moving through all openings and was calculated at 0.016 inches of water (ASTM E 779-87, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization).* The ELA is equivalent to the area of a round orifice with a flow exponent equal to one, allowing the same total air flow as the window under a driving pressure differential of 0.016 inches of water. Using an ELA value allowed air openings in and around a window to be expressed as one total area for comparative purposes.

Pressurization data in terms of effective leakage area (ELA) was correlated to natural infiltration by the fluid mechanical model developed by the Lawrence Berkeley Laboratory. As stated previously, for the purposes of this study use of the LBL model was modified by using data from a single window rather than whole house data. It should be repeated that this modification was not the purpose for which the LBL correlation model was designed and any results should not be viewed as absolutes. Values obtained from this modification should be used only for comparative purposes with other values in this study.

A portable air test unit, manufactured by DeVac, Inc., was used to induce pressure differentials testing. The unit is a self-contained device, consisting of a blower motor capable of producing an approximate air flow of 40 cfm, low (1.2-11.6 cfm) and high (10-80 cfm) volume Ametek flow meters, and a Dwyer slant-tube manometer used to measure pressure differentials. The unit may be used to produce a positive or negative test pressure. An earlier study of 196 houses showed no systematic difference between pressurization and depressurization although significant uncertainty was associated with any individual measurement (Sherman et al., 1986). A negative test pressure was chosen for the purposes of this study, primarily for safety considerations. Any pressure induced glass breakage would have been directed inwards toward the interior plastic sheet.

4b i. Fan Pressurization Test Method Description

Plastic sheeting was taped to the inside trim of a latched window if an operable latch was in place and a series of negative pressures were applied. The amount of air flowing through the window unit was read from a flow meter calibrated in cubic feet per minute. The pressures applied ranged from a low of 0.03 inches of water pressure (equivalent to an approximate 8 mph wind impacting the building) to a high of 0.30 inches of water pressure if attainable (an approximate 25 mph wind). The applied negative pressure was uniform across the entire window so that each square inch was subjected to the same pressure.

The first set of readings represented the total flow (Qt) of air passing through the window unit (through and around the sashes, jambs, and frame). A second sheet of plastic was then taped to the exterior trim of the window and the same pressure range was again applied to the window with corresponding flows recorded. The second set of readings was the extraneous flow (Q_0) and represented the air flow moving through the rough opening,

frame, and jamb as the exterior sheet of plastic had isolated the area of the window within the jamb from any air passage. The difference between these two sets of readings was the sash flow (Q_5) and represented the amount of air passing through the sash area within the jamb (the area referred to in this report as the window):

$$Q_t - Q_e = Q_s$$

If the window was fitted with a working storm window, the procedure was repeated with the storm window in place.

4b ii. Environmental and window parameters recorded

Interior/exterior temperatures and wind direction were recorded on-site for each window as per ASTM E 783-93. Also estimated and recorded on-site were wind speeds based on the Beaufort Wind Scale. Barometric pressures were read and recorded in Burlington, VT. Relative humidities were determined using the on-site interior/exterior temperatures and psychrometric charts. Recorded also were various window dimensions (height, width, sash depth, etc.), window type (double- or single-hung; pulley- or pin-type), condition and location of any locking mechanism, window orientation, and weather conditions for some of the latter tests where exterior air percentages were being determined. Appendix C shows a field data sheet used for each window.

Left- and right-hand side gaps between the lower sash and jamb were measured as well as the distance the lower sash moved forward and backward at the meeting rail. Sash and meeting rail gaps were not measured for all original windows tested, as these measurements were deemed important after field testing began. For existing windows utilizing vinyl jamb liners as an upgrade, the distances between the sash/jamb liner bulb and the sash/jamb liner wall were measured on both sides of the lower sash.

It was an early goal to derive a means of visually examining a window and deciding whether to replace or upgrade without resorting to pressurization testing. As a means towards that end, original windows were characterized by their general physical condition, utilizing a twelve parameter check list (Appendix C). These twelve parameters were reduced to several combination parameters, descriptive of the physical condition of the window. Two individual parameters were also investigated for significant correlations to air leakage. Combination parameters were weighted toward meeting rail and sash fit characteristics rather than glazing condition. It was assumed that any type of window renovation would include repair of existing glazing problems.

Along with the reduced physical descriptive parameter, window type was investigated for potential correlation with air leakage characteristics. Windows were categorized as single or double-hung, and as pin- or pulley-type windows for further clarification.

4b iii. Determination of percent exterior air in Q_e

The method described above and used for this study failed to account for exterior air infiltrating through the rough opening. Infiltration of exterior air not only occurred through the window sash and sash/jamb junction (Q_s), but also through the rough opening (Q_e), adding to the heating load. The amount of exterior air through the rough opening can have a significant effect on the infiltrative heating load of a tight window, where Q_5 alone showed a small heat load. Determination of the amount of exterior air through the rough opening was therefore important.

A rough estimate of the volume of exterior air coming through the rough opening was calculated by knowing the exterior and interior air temperatures as well as the test chamber temperature (the temperature between the two sheets of plastic) while performing the test for extraneous air (Q_e). Knowing these three data points and any measured value of Q_e, a mass balance on temperature and air flow was performed to estimate the volume of exterior air in Q_e. The volume of exterior air in °e was determined by the following formula:

$$Q_{ext} = Q_e * \left[\frac{(T_{win} - T_{int})}{(T_{ext} - T_{int})} \right]$$

where:

Q_{ext} = the volume of exterior air (acfm)
Q_e = the volume of air chosen from Q_e test data (acfm)
T_{win} = the temperature between the two plastic sheets during the test (°F)
T_{int} = ambient interior air temperature (°F)
T_{ext} = ambient exterior air temperature (°F)

The volume of exterior air (Q_{ext}) was converted to a percentage by dividing through by Q_e.

This method of estimating the volume of exterior air entering the test zone during testing periods has limitations and values thus derived should not be assumed to be accurate. No attempt was made to determine the actual air path of air as it entered the wall cavities while a window was under pressure. Exterior air likely increased its temperature and reached some equilibrium as it passed through walls warmer than the ambient exterior atmospheric temperature, raising questions as to the accuracy of the temperature readings in the test zone. The method was used to determine a rough approximation of the contribution of exterior air to the overall heating load.

Estimates of the amount of exterior air entering a window as a percentage of extraneous air were made for 33 upgraded windows. Thirty-one of these windows retained the original sash with the other two being in-kind replacement sash with vinyl jamb liners. Based on the 33 windows, an averaged percentage of exterior air was calculated. This was multiplied by the average rate of induced extraneous air for each assumed and upgraded window type. This resulting rate of induced exterior air was added to the sash infiltrative

rate measured while using the ASTM E 783-93 modification to provide a total infiltrative thermal loss for a window.

4c. Non-infiltrative Thermal Losses

Non-infiltrative thermal losses were determined from simulations based on the computer model WINDOW 4.1 developed by the LBL Windows and Daylighting Group. User variable window parameters include window size and type, sash material, and type of glass among other parameters. The program calculated window thermal performance in terms of U-values (thermal transmittance), solar heat gain coefficients. shading coefficients, and visible transmittances. Only U-values were used for purposes of this study.

4d. Total Window Thermal Losses

Total window thermal loss was the result of non-infiltrative and infiltrative thermal losses through the window as well as thermal losses due to exterior air infiltrating via the rough opening. Sash infiltrative window losses were based on window air leakage characteristics while infiltrative losses due to exterior air were assumed to be the average of the 33 windows discussed previously. Sash and exterior air infiltrative losses were summed for a whole window infiltrative loss. The whole window infiltrative loss was correlated with natural infiltration rates by use of the LBL correlation model. Non-infiltrative thermal losses were based on WINDOW 4.1 modeling. The two estimates were converted to common units and summed together for an “effective thermal loss”.

The validity of an “effective thermal loss” was not tested in this study and is subject to speculation (Klems, 1984). The aforementioned procedure adds the results of two very different methods of calculating heat losses, one based on infiltrative rates resulting from fan pressurization data (the LBL model) and the other the result of a computer model based on well understood thermodynamic principles (WINDOW 4.1). The concept of “effective thermal loss” was chosen for this study in order to provide an all encompassing parameter describing total thermal loss through a window, which enabled a simplification in the subsequent calculation of total heating costs for a window.

4e. Thermography

In February 1996, thermographs were taken of windows at two sites in Hanover, New Hampshire. Images of three windows were taken at Robinson Hall of Dartmouth College. Two of these windows were large, double-hung, pulley-type windows with conventional triple track aluminum storm windows attached. The third window was a Bi-Glass Systems retrofit with vinyl jamb liners, double-pane insulating glass, and silicone bulb weatherstripping at the meeting rail, head, and sill junctions.

The second Hanover site was 4 Occom Ridge, where double-hung, pulley-type windows were fitted with conventional triple track aluminum storm windows, as well as being caulked with rope caulking. One set of windows in the den was also fitted with an interior plexiglass

storm window, attached by magnetic stripping.

These sets of thermographs were not used in a quantitative manner but were rather used as a means for visual comparisons between window upgrades.

4f. Energy Savings Due to Window Upgrades

Savings in energy costs for a building were based directly on those savings attributable to energy reduction through window upgrades. This was a direct result of the apparent additive nature of the relationship between thermal losses due to windows and the remainder of whole house thermal losses.

The following steps summarize the process used to calculate annual energy costs and savings due to a window upgrade, as compared to annual costs for typical windows:

1. convert typical sash leakage fan pressurization data (Q_s) as scfm/lfc to effective leakage area (ELA_s/lfc);
2. convert the volume of exterior air (Q_{ext}) as scfm/lfc to ELA_{ext}/lfc, based on a field derived percentage of average extraneous air leakage (Q_e);
3. add ELA_s/lfc to ELA_{ext}/lfc for a window ELA per linear foot crack due to infiltration (ELA_{tot}/lfc);
4. multiply ELA_{tot}/lfc by 19 lfc for a typical 36 x 60 inch double-hung window to determine the whole window ELA (ELA_{tot});
5. use ELA_{tot} in the LBL correlation model to predict the average heating season infiltration rate for the window (Q_{nat} - natural air infiltration rate);
6. multiply the average heating season infiltration rate (Q_{nat}) by the heat capacity of air (C_p) to determine total thermal loss rate through the window due to infiltration (L_{inf}):

$$L_{inf} = Q_{nat} * C_{p_{air}}$$

$$L_{inf} = Q_{nat} * \frac{0.018\,Btu}{ft^3 * {}^oF} * \frac{60\,min}{1\,hr}$$

7. calculate non-infiltrative thermal loss rate (L_{non}) due to transmission (U-value) using WINDOW 4.1;
8. multiply the U-value (L_{non}) by 15 ft^2 for a typical 36 x 60 inch double-hung window to determine the total window non-infiltrative thermal loss rate (L_u);
9. add the infiltrative (L_{inf}) and non-infiltrative (L_u) thermal loss rates to determine the "effective thermal loss" of the typical window (L_{eff});
10. determine the annual window thermal loss (L_{yr}) in millions of Btu's (MMBtu) by multiplying the "effective thermal loss" (L_{eff}) by the average Vermont degree-day units by 24 hours per day:

$$L_{yr} = L_{eff} * 7744\ degree\text{-}days * \frac{24\,hr}{day} * 10^{-6}$$

11. calculate the annual cost per window (C_{win}; example based on number 2 fuel oil):

$$C_{win} = \frac{(fuel\ cost\ per\ gal) * (annual\ heat\ required) * 10^{6}}{(fuel\ heat\ capacity\ per\ gal) * (furnace\ efficiency)}$$

$$C_{win} = \frac{\$0.90/gal * L_{yr} * 10^{6}}{(138{,}600\,Btu/gal) * eff}$$

12. repeat steps 1-11 for a given window upgrade; and
13. determine the annual savings per upgrade type (S_{win}) by subtracting step 12 from step 11.

5. RESULTS

One hundred fifty-one windows at 19 different sites were field tested for this study. Sixty-four windows were tested in their original condition with storms both open and closed when operable. The remaining 87 windows underwent some form of upgrade. Six sites had a total of 29 windows tested both prior to and post renovative work. Two other windows underwent detailed testing in the laboratory.

5a. Appropriateness of Flow Model

The correlation of induced air leakage to natural infiltration rates was dependent on extrapolation of field data from the range of test pressures (0.03 - 0.30 in. H_20) down to 0.016 in. H_2O. Extrapolation was based on the standard mathematical flow model:

$$Q = c * \Delta P^X$$

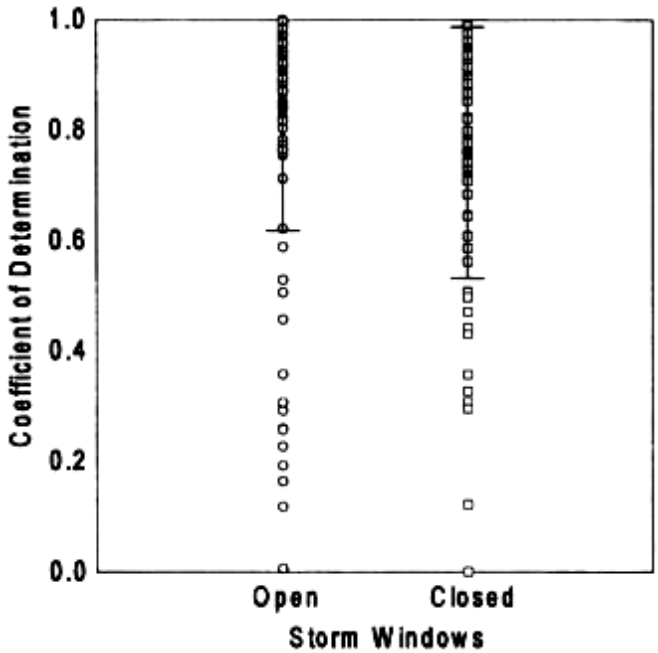
where air leakage is a function of the pressure differential. The degree to which the model accurately described the field data was determined by the value of the coefficient of determination (R^2) for each test, as calculated by linear regression. The coefficient was defined as the proportion of variability in the dependent variable (Q) accounted for by the independent variable (ΔP). Maximum allowable value for R^2 was 1.000, meaning the model was a perfect fit to the field data, resulting in the data falling on a straight line on a log-log graph.

Coefficient of determination values for all windows with storms open and/or closed are shown in Figure 2. The black circles are the mean R^2 values for windows with storms open and closed (R^2 = 0.844 and 0.760, respectively). The lines represent plus or minus one standard deviation from the means and encompass 68% of the data points. The median R^2 value for windows with storms open was 0.921 while the median with storms closed was 0.838. The median represented the middle value of the ranked population, meaning half the population was above the median. In this case, the median values were more robust estimations of the central tendency than the averages, as averages were weighted towards lower R^2 values. It was determined the field data showed a reasonable fit to the flow model, lending confidence to the extrapolated values for air leakage at 0.016 inches of water.

Some variation of R^2 was associated with gusting winds during some testing periods. Depending on direction, these winds had the effect of increasing or decreasing the pressure differential shown in the manometer. Wind induced pressure changes caused unnecessary adjustments of air flow rates to accommodate false pressure readings. Other windows and doors were opened to ameliorate the effects of strong winds.

A larger variation in R^2 values was observed for those windows allowing little induced air

Figure 2: Variability in R^2 values of standard flow model fitted to the field data



leakage. For those windows, the effect of even moderate winds on test accuracy increased as both air flow rates and pressure differentials decreased. Table 3 shows wind speeds equivalent to pressure differentials used in the test, with pressures being expressed in both conventional (Inch-Pound) and metric (SI) formats.

Table 3: Wind speeds equivalent to test pressure differentials

Wind speed (mph)	ΔP (in. H_20)	ΔP (Pa)
25	0.30	75
23	0.25	62.5
20	0.20	50
18	0.15	37.5
14	0.10	25
12	0.07	17.5
10	0.05	
8	0.03	7.5
6	0.016	4

5b. Field Test Results - Original Condition Windows

Sixty-four original condition windows were field tested for air leakage. These data were used to model leakage characteristics of typical, tight, and loose affordable housing windows for comparison with differing window upgrades. The typical double-hung window was assumed to have dimensions of 30 x 60 inches, giving an operable crack perimeter of 19 linear feet and a surface area of 15 square feet.

As previously discussed, a portion of extraneous air leakage made a contribution to the heating load by requiring conditioning. During the latter half of the study, thirty-three windows were monitored for the percentage of exterior air contained in the induced extraneous air leakage during the test period (Appendix E). The average percentage by volume of exterior air entering the test zone within extraneous air was 29% as measured and estimated by temperature differences. This percentage was approximated as 30% for this study. It should be noted again that the validity of the method used to determine the volume of exterior air is open to question. No attempt was made to validate the method in the course of the study.

Field data for each window were converted to sash (Q_s) and extraneous (Q_e) leakage rates, expressed as standard cubic feet per minute per linear foot crack (scfm/lfc). Thirty percent of the extraneous leakage rate was taken to represent exterior air infiltration (Q_{ext}). These results were in turn converted to effective leakage areas per linear foot crack (ELA/lfc) at 0.016 inches of water pressure, the assumed driving force for natural infiltration. After summing the two infiltrative ELA's/lfc, a whole window ELA (ELA_{tot}) was calculated by multiplying the sum by the typical nineteen feet of operable window perimeter.

Table 4 shows assumed air leakage characteristics for typical affordable housing windows based on the field research. Total sash leakage ($ELA_{S\ X\ 19}$) for the typical window was the average of the sash leakage rates of all original condition windows with operable storms in place (35 windows). Both the tight and typical windows were assumed to have storm windows in place, with the tight window having sash leakage characteristics one standard deviation less than the typical window. The loose window was assumed to have no storm in place and was the average of all original condition windows with storms open or missing (47 windows). Based on field measurements of 33 windows, 30% of extraneous air infiltrating a window was assumed to be exterior air and was expressed as a whole window effective leakage area (ELA_{extx19}). Thirty percent of the appropriate averaged extraneous air volume was added to the sash flow ($ELA_{s\ x\ 19}$) of each window to determine a total effective leakage area (ELA_{tot}) for each assumed window.

The column labeled "diameter in Table 4 was included to facilitate visualizing ELA_{tot} It refers to the diameter of the round orifice on which ELA is modeled. As previously stated, ELA is the size of a round orifice passing the same air flow as the cracks associated with a window.

Table 4: Assumed air leakage characteristics for original condition windows

Window Category	$ELA_{s \times 19}$ (in^2)	$ELA_{ext \times 19}$ (in^2)	ELA_{tot} (in^2)	Diameter (in)
Tight Window	0.27	0.59	0.86	1.04
Typical Window	0.89	0.59	1.48	1.37
Loose Window	2.19	0.59	2.78	1.88

The significance of the exterior air contribution to the infiltrative heating load associated with a window may be seen from the above data. Exterior air contributes approximately 20% of the loose window infiltrative load, but rises to 40% and 70% of the total infiltrative heat load for typical and tight windows respectively.

5b i. Air leakage characteristics of windows over time

Air leakage characteristics of three windows at the Central Vermont Community Land Trust (CVCLT) in Montpelier, Vermont, were measured periodically over a time span of eight months, from March until October 1995. The purpose of this long term monitoring was to observe how air leakage responded to environmental factors as the seasons progressed. Wooden windows often become more difficult to operate during the summer season as wood swells in response to an uptake in moisture. The expansion and contraction of the wood affects gap sizes in a window, thereby influencing the rate of infiltration. An understanding of how leakage characteristics changed with long-term weather conditions was desired to determine when field testing was to begin and end, so as to maintain similar test conditions. Potential environmental parameters influencing moisture uptake by wooden windows (and thus potentially affecting air leakage rates) included exterior dry-bulb temperature, relative humidity, dew point temperature, and partial water vapor pressure:

- Exterior dry-bulb temperature - the current ambient air temperature as measured by a thermometer.
- Relative humidity - the ratio of the amount of water vapor in the air to the maximum amount of water vapor the air can hold at the ambient temperature.
- Dew point temperature - the temperature at which the ratio of water vapor pressure to atmospheric pressure is equal to the mole fraction* of water vapor in the air. This is the temperature at which water vapor condenses from the air to form liquid water (dew).
  - Mole fraction - the ratio of the number of moles of a component (water) to the total number of moles of all components in the mixture (air).
- Partial water vapor pressure - that component of the atmospheric pressure exerted solely by the water vapor contained in the air mass.

The relative humidity, dew point temperature, and partial water vapor pressure are all

related as they are dependent on the mole fraction of water vapor in air and the dry-bulb temperature (Appendix D).

Water vapor pressure was the likely driving force in the uptake or release of moisture by wooden windows. The wood in windows of historical buildings was assumed to be air dried to the extent it exhibited a response to changing atmospheric moisture conditions by swelling or shrinking. An increased amount of moisture in the air increased atmospheric water vapor pressure, thereby increasing the water vapor pressure differential between air and wood. It was the pressure differential between atmospheric water vapor and wood moisture content that was assumed to be the driving force for changes in dimensions of wooden windows, which in turn affects rates of air leakage.

The assumption concerning air infiltration rates, wooden windows, and increased atmospheric moisture content during the summer season was that air infiltration would decrease as the summer season progressed, as wood swell would decrease the size of any gaps in the windows, essentially reducing the effective leakage area (ELA). Data from the CVCLT windows monitored over time were unclear as to general leakage trends with seasonal progression.

Total window leakage rates (Q_t) were converted to effective leakage areas for comparison overtime. Windows 1A and 1B exhibited a general decline in ELA while the storm window was in place. This trend was not as apparent when data with storm windows open was observed. Window 1 C showed no general trends, either with the storm window open or closed. No strong correlations were found between air leakage rates and running averages of the four parameters tested when using running averages of one to six weeks. Significant correlations likely required a longer monitoring period and more windows for a larger data base. Such an investigation was beyond the scope of this study. Field testing was halted in May 1995 and resumed in October 1995 and was continued through June 1996 when weather permitted.

5b ii. Leakage characteristics of pin- versus pulley-type windows

Original condition windows were separated into pin- and pulley-type windows to determine if pulley-type windows allowed more air leakage. Leakage through the sash (Q_s) was expected to be equivalent while extraneous leakage (Q_e) was expected to differ, with more extraneous leakage in pulley-type windows than pin-type. A separate variance t-test showed no difference in sash leakage rates (Q_s) between the window types at a 95% confidence level. Pulley-type window extraneous air leakage rates (Q_e) were significantly greater than those for pin-type windows at a 99% confidence level Extraneous air values, expressed as whole window extraneous leakage areas ($ELA_{e\ x\ 19}$) are shown in Table 5.

Separate variance t-tests for windows with storms closed showed similar results as above at confidence levels of 95%. Data for the original condition windows with storms closed were not listed as only interior storm windows decreased the volume of extraneous air entering the test zone. No original condition windows were fitted with interior storms.

Table 5: $ELA_{e\ x\ 19}$ values for original condition pin- versus pulley-type windows with storms open

Window type	n	$ELA_{e\ X\ I9}$ (in^2)	D (in)
Pin	23	1.39	1.33
Pulley	32	2.37	*1.74*

The observed increased air flow around pulley-type windows indicates the importance of window weight cavities to air infiltration and the efficient use of energy during the heating season.

5b iii. Sash leakage reduction due to existing storm windows

The effect of existing storm windows on reducing sash leakage through windows was investigated using data from the original condition windows. Of the 64 original condition windows tested, 24 had data for storm windows in both the open and closed positions. Many windows with attached storm tracks had missing or broken panes. Others were inaccessible due to both sash being painted shut on the interior side

Sash air leakage characteristics for those windows with operable storms were calculated with storm windows in both the open and closed positions. Results were expressed as whole window effective sash leakage area (ELASX 19) and compared using a paired t-test. At a confidence level of 99.9%, windows with existing storms in the open position allowed significantly more sash leakage than did those same windows when storms were in the closed position. Results are found in Table 6, as well as the percentage reduction in sash leakage caused by storm windows in the closed position.

Table 6: comparison of 24 original condition windows with existing storms open and closed

Storm Window Position	$ELA_{s\ x\ 19}$ (in^2)	D (in)	Sash Leakage Reduction
Open	1.86	1.54	---
Closed	1.01	1.13	46%

Reduction in air flow was expected through the sash but was not expected in terms of extraneous air leakage. All existing storm windows encountered were exterior storm windows and thus had no effect on air leaking through the rough opening. To test this assumption, extraneous leakage data were compared using a paired t-test. No significant difference in extraneous air leakage was found between windows with storms in the open and closed positions at a confidence level of 99%.

5b iv. Air leakage characteristics of single- versus double-hung windows

The manner of a window's operation was investigated to determine its bearing on sash leakage characteristics. Thirteen of the original condition windows were single-hung, with the other 51 being double-hung windows. Of the 13 single-hung windows, one (6B) was discounted as it had a wooden storm window caulked into place and could not be removed. That prevented characterizing the window's sash leakage with the storm window off, the condition required to compare single- versus double-hung windows. Sash leakage characteristics with storm windows open were determined for 35 of the 51 original double-hung windows, the remainder having inaccessible storm windows in the closed position.

The upper sash of three single-hung windows (6A, 6C, and 6D) were held in place by wooden stops, but were also caulked to the jamb. These three windows were considered to be true single-hung windows in terms of air leakage, with scfm/lfc based on an operable perimeter of *H + 2xW.* These three windows with caulked upper sash were separated from the other single-hung windows as their leakage characteristics were determined using a different operable perimeter.

Nine of the remaining 12 single-hung window's had the upper sash held in place by a wooden stop or nail. The upper sash fitted loosely in its frame in these instances, allowing air leakage through the sash/jamb junction. Single-hung windows such as these were considered to be double-hung in terms of calculating air leakage as scfm/lfc since air leakage sites in these windows were identical to those for a double-hung window. Operable window perimeter was calculated as *2xH + 3xW* for these windows.

A separate variable t-test was used to compare sash leakage rates of the 35 double-hung windows versus the nine single-hung in terms of whole window effective leakage area (ELAsx19). The 35 double-hung windows allowed significantly less sash leakage than the nine single-hung at a confidence level of 99%. Lower sash leakage for double-hung windows was an unexpected result, considering single-hung windows were characterized not by operable crack perimeter, but by available leakage perimeter and were thus equivalent to double-hung windows. Average leakage characteristics for the original condition windows, expressed as ELASX19, are listed in Table 7

Table 7: Single- versus double-hung window sash leakage characteristics

Window Type	n	$ELA_{s\ x\ 19}$ (in^2)	D (in)
Single-hung	9	3.12	1.99
Double-hung	35	2.00	1 .60

When sash leakage rates of the three "true" single-hung windows were compared to the other nine single-hung, no significant difference in sash leakages rates was found at a

confidence level of 95%. Although not investigated further, a larger sample population of single-hung windows would need to be tested to determine the validity of these results.

5b v. Correlation of descriptive physical parameters with air leakage rates

An early goal of the study was to investigate the possibility of visually inspecting a window and estimating if sash leakage rates were low or high The physical condition of each original condition window field tested was categorized using a check list of 12 subjective parameters describing the general sash, sash/jamb fit, and the glazing (Appendix C).

Descriptive physical parameters were reduced to overall sash condition (glazing and putty for both sash), sash/frame fit (tightness of sash in jamb and squareness), a combined sash/frame and meeting rail fit, and the total gap width on the lower sash side. The meeting rail fit and squareness of the sash in the frame were also investigated as independent parameters. Correlations of all parameters with sash whole window effective leakage area (ELAS 19) and extrapolated sash leakage rates at 0.30 inches of water pressure were investigated for those original condition windows with storms open or missing. Extrapolated values rather than actual sash leakage rates were used as a means of comparison as only ten of 47 windows thus described were able to achieve a test pressure differential of 0.30 inches of water.

There was no significant correlation between overall sash condition, sash/frame fit, sash/jamb squareness, or total gap width with either ELAS 19 or extrapolated sash leakage rates ($R \leq 0.26$ for all four). The $ELA_{s\ x\ 19}$ showed a weak inverse correlation ($R = -0.43$, $p = 0.002$) with the combined parameter sash/frame/meeting rail fit, with ELA_{sx19} increasing as the combined parameter decreased in value. Both $ELA_{s\ x\ 19}$ and extrapolated sash leakage rates had a weak inverse correlation with the meeting rail, with the correlation between $ELA_{s\ x\ 19}$ stronger than the extrapolated sash leakage rate correlation ($R= -0.69$, $p < 0.001$ and $R = -0.41$, $p = 0.004$ respectively). Visual inspection of a window therefore gave little indication as to its leakiness.

5b vi. Original condition window summation

It was found that exterior air can have a significant role in adding to the heat load of any window, whether it be tight or loose. Pulley-type windows were found to be significantly leakier than pin-type windows when including extraneous air leakage, largely due to the presence of a window weight cavity. The window weight cavity provided greater potential for exterior air to infiltrate the window from the rough opening. The window weight cavity provided greater potential for exterior air to infiltrate the window from the rough opening. Single-hung windows were found to have significantly more sash leakage than double-hung regardless of the method used to calculate operable crack perimeter. No significant correlations were found between leakage rates and four environmental parameters nor between leakage rates and visual window appearance

5c. Field Test Results - Window Upgrades

The second round of field testing involved pressurization tests of a variety of window upgrades on eighty-seven windows. Upgrades ranged from retaining the original sash to window inserts utilizing the existing jamb. Table 8 summarizes the number of windows (n) tested for each general upgrade category, with some windows falling into two categories.

Table 8: Number of windows tested by general window upgrade category

General Window Upgrade Category	n
Retain 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

5c 1 Upgrades retaining the original sash

Sixty-two renovated windows retained the original sash with 59 of those windows at nine sites also retaining the original glazing by employing a variety of weatherstripping, vinyl jamb liners, and/or storm window upgrade options. Three other windows retained the original sash by undergoing the Bi-Glass System upgrade which replaced single-glazing with double-pane insulating glass. Thirteen windows retaining the original sash had no improvement other than the addition of replacement storm windows. Those 13 windows are discussed in the section concerning storm window replacement.

Upgrade options tested in the field are summarized in Table 9, along with the number of windows tested for each upgrade type Average sash air leakage characteristics for each upgrade type are also shown, expressed as sash whole window effective leakage areas ($ELA_{s\ x\ 19}$) Data for windows with any storms in place are not included, as the effect of storm windows would mask reductions due to sash upgrades. Also listed along with sash leakage characteristics are 30% of the average extraneous air leakage values for each upgrade type ($ELA_{ext\ x\ I9}$), accounting for exterior air contributions to whole window leakage. These two values are summed for a whole window effective leakage area (ELA_{tot}) for each upgrade type.

The six windows with Caldwell coiled spring balances (site 16) show no data in Table 9 as the average maximum pressure attained during total window testing (Q_t) averaged 0.025 inches of water. These windows were extremely leaky, with nothing having been done to prevent air from passing through the old window weight cavities or the large gaps at the

Table 9: Average leakage characteristics for upgrade types retaining original sash

Site ID	Upgrade Description	n	Q_s Ext. (scfm/lfc)	$ELA_{s\ x19}$ (in^2)	$ELA_{ext\ x\ 19}$ (in^2)	ELA_{tot} (in^2)	D (in)
12	Vinyl jamb liners; no weather stripping	7	1.80	2.49	0.56	3.05	1.97
13	Vinyl jamb liners; silicone bulb weatherstripping at sill and head junctions	8	1.40	2.23	0.56	2.79	1.88
7	Vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail junctions	19	0.78	0.87	0.26	1.13	1.20
2	Bi-Glass System with vinyl jamb liners; silicone bulb weatherstripping at sill, head, and meeting rail junctions; double-pane insulating glass; new latch at meeting rail	3	0.48	0.71	0.33	1.04	1.15
16	Caldwell coiled spring balances with silicone bulb weatherstripping at sill and head junctions; some weatherstripped wooden storm windows	6	***	***	1.32	***	***
17	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	3	0 18	0.48	0.61	1.09	1.18
19	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	2	0.49	0.54	0.17	0.71	0.95
10	Sash weatherstripped with Polyflex T-slot between sash face and parting bead; Polyflex at sill, head, and meeting rail junctions	1	0.10	0.29	0.42	0.71	0.95

meeting rails. This is reflected in the high value for exterior air effective leakage area (1.32 in^2), which is based on only 30% of the extraneous air measured during the field tests.

The lowest sash whole window effective leakage area (ELA_5 x 19) was the window with Polyflex weatherstripping. That value should not be considered typical of the upgrade type as only one example was tested. That specific window required major sash repair prior to weatherstripping, with the entire renovation process requiring twelve man-hours. It was not determined how much sash leakage reduction was a result of sash repair as opposed to weatherstripping.

Both sites 10 and 19 showed equivalent values for whole window effective leakage area

(ELA_{tot} = 0.71 in^2) while having significantly different sash leakage rates (0.29 and 0.54 in^2, respectively). The discrepancy arose from the whole window exterior air leakage area ($ELA_{ext\ x\ l9}$). Site 10 had a significantly larger $ELA_{ext\ x\ l9}$ than site 19 (0.42 and 0.17 in^2, respectively) which was assumed to be more an artifact of building construction rather than window renovation. This further illustrated the significant contribution exterior air can have when determining the heat load of a window.

Both the zinc rib-type and bronze V-strip weatherstripping upgrades show relatively low values for $ELA_{s\ x\ 19}$ (0.48 and 0.54 in^2, respectively). The Bi-Glass System upgrade has an $ELA_{s\ x\ 19}$ substantially greater than either the rib-type or V-strip weatherstripping (approximately 50% and 30%, respectively). It should be kept in mind that the number of samples for these three upgrades is very small and not statistically valid. Comparisons of results should therefore be viewed with caution.

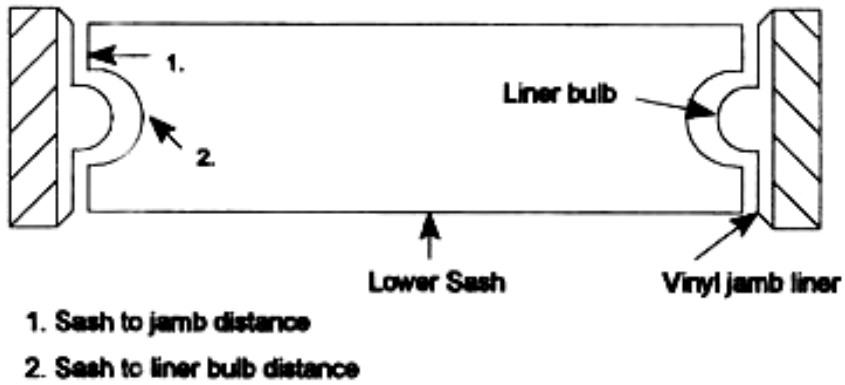
Field sash leakage rates expressed as $ELA_{s\ x\ 19}$ for the three Bi-Glass System upgraded windows are slightly larger than results from the one laboratory window having undergone the Bi-Glass System upgrade (0.71 in^2 versus 0.65 in^2). Due to the nature of the lab set-up, no comparisons could be made for $ELA_{ext\ x\ l9}$ or ELA_{tot} It should be noted that the three field windows were pin-type windows while the lab window was a pulley-type. As noted previously, pulley-type windows had significantly more sash leakage than pin-type but once again, caution should be taken when interpreting these results due to extremely low sample populations.

Windows at sites 7, 12, and 13 used the same brand of vinyl jamb liner, with upgrade differences being found in the location or absence of silicone bulb weatherstripping. Site 12 had no weatherstripping, with the exception of one sill junction. Site 13 had the same size and type windows as site 12, but had weatherstripping inserted into sill and head junctions. No significant difference between the two sites was found for $ELA_{s\ x\ 19}$ at a 95% confidence level.

Site 7 had two window sizes, both larger than the windows at either site 12 or 13. These windows had silicone bulb weatherstripping inserted into the sill, head, and meeting rail junctions. There was a significant difference in $ELA_{s\ x\ 19}$ between site 7 and site 13 at a 99.9% confidence level, with the only difference between the two being weatherstripping at the meeting rail junction. The meeting rail gap had a weak correlation with sash leakage as discussed previously, so addition of weatherstripping at the meeting rail junction likely accounted for a portion of the sash leakage reduction. To further investigate the difference, the jamb liner bulb/sash distance and jamb/sash distance were measured to see if a correlation existed between sash liner fit and sash leakage. Areas of measurement are shown in Figure 3. No significant correlations (R c 0.28, p = 0.05) were found between sash/jamb liner measurements and $ELA_{s\ x\ 19}$ for any of the three sites.

Separate variance t-tests showed site 12 windows to have significantly larger jamb liner/sash gaps than either site 13 or 7 at a 97% confidence level while having statistically the same $ELA_{s\ x\ 19}$ as site 13. Routing of the sash to accommodate vinyl jamb liners was

Figure 3: Schematic of lower sash and vinyl jamb liner junction



done by the same work crew at sites 12 and 13. A different work crew performed the work at site 7. No significant difference in jamb liner/sash gaps was found between sites 7 and 13 at a 98% confidence level while there was a significant difference in $ELA_{s \times 19}$ between the sites. Based on the limited data, it is inconclusive as to whether differing work crews had a significant effect on installation quality. In an earlier study, few significant differences in leakage rates were observed when differing contractors installed the same type windows in new residential housing in Minnesota (Weidt, 1992). It remained unresolved as to why site 7 window upgrades had better sash leakage characteristics than sites 12 and 13.

New windows are characterized by sash leakage rates per linear foot crack and must meet the industry standard of 0.37 scfm/lfc at 0.30 inches of water pressure in order to be certified. Table 9 also lists average extrapolated sash leakage rates (Q_s) at 0.30 inches of water for each upgrade type. Actual sash leakage averages could not be used for comparative purposes as only 21 of 52 windows were of sufficient tightness to attain 0.30 inches of water pressure.

Averaged sash leakage rates of the tightest original sash fitted with vinyl jamb liners and weatherstripping (0.78 scfm/lfc at 0.30 in. H_2O, site 7) showed significantly more sash leakage than the certifiable industry standard window (0.37 scfm/lfc at 0.30 in. H_2O) at a 99.9% confidence level. While other original sash upgrade options such as the Bi-glass System and weatherstripping options appear to have large sash flow reductions, caution must be taken in drawing conclusions concerning those upgrades as no upgrade option had more than three windows tested, sample populations with little statistical significance.

5c ii. Replacement sash upgrades

Two makes of replacement sash utilizing vinyl jamb liners were encountered during field testing, accounting for eleven windows. Both makes were in-kind replacement units with single-glazing and utilized the existing jamb. Table 10 presents leakage characteristics of these windows based on extrapolated values. Three of the eleven windows did not allow attainment of the maximum pressure (0.30 in. H_2O), although two (12B, 12D) allowed pressurization at 0.25 inches of water pressure. The third window (131) was installed in an

Table 10: Leakage characteristics for 11 replacement sash

Q_s Reg. Avg (scfm/lfc)	$ELA_{s\ x\ 19}$ (in^2)	$ELA_{ext\ x\ 19}$ (in^2)	ELA_{tot} (in^2)	D (in)
0.29	0.45	0.30	0.75	0.98

out-of-square frame, with 5 mm gaps at opposing upper and lower corners, attaining a maximum pressure of 0.07 inches of water.

The average extrapolated leakage rate for the in-kind replacement sash (0.29 scfm/lfc) is significantly less than the 0.37 scfm/lfc certifiable standard set by the window industry (confidence level of 99.9%). The in-kind replacement sash met the certifiable standard for air leakage in new windows and were considered tight windows.

Two other sets of replacement sash (18A, 18B) were placed in visually out-of-square frames resulting in reported high levels of discomfort during the winter. These two windows underwent extensive sealing to reduce sash and extraneous air leakage after one heating season. It is apparent from leakage characteristics of windows 13l, 18A, and I8B that squareness of frame was an important issue when using replacement sash.

5c iii. Window insert upgrades

Fourteen replacement window inserts at four sites, representing two manufacturers, were field tested during the study. All but one of these windows (16G) attained the maximum pressure. The extraneous air leakage test (Q_e) for window I 6G revealed a large volume of air leaking through the rough opening (maximum Q_e pressure - 0.07 in. H_2O), an atypical result for other window inserts tested. Table 11 summarizes window insert sash leakage data, both including and excluding window 16G.

Table 11: Sash leakage characteristics for replacement window inserts

	Q_s Actual Avq (scfm/lfc)	Q_s Ext. Avg (scfm/lfc)	$ELA_{s\ x\ 19}$ (in^2)	$ELA_{ext\ x\ 19}$ (in^2)	ELA_{tot} (in^2)	D (in)
16G excluded	0.14	0.13	0.12	0.09	0.21	0.52
16G included	---	0.17	0.13	0.16	0.29	0.61

Window 16G illustrated the importance of sealing the rough opening to reduce exterior air infiltration. When data from window 16G was included, the average $ELA_{ext\ x\ 19}$ increased by approximately 75%. Window 16G also showed window inserts may not necessarily reduce exterior air infiltration significantly.

Replacement window inserts were expected to reduce extraneous air flow as they

consisted of both sash and an integral frame. Table 12 compares the average volume of exterior air for window inserts to other upgrade categories and also shows extrapolated sash leakage rates at 0.30 inches of water pressure (Q_5). Replacement window insert 16G was excluded from the data as it was considered to be atypical in terms of extraneous air leakage.

Table 12: comparison of exterior air volumes by upgrade type

Upgrade category	Site Number(s)	n	Q_s Ext. (scfm/lfc)	$ELA_{ext\ x\ 19}$ (in^2)	D (in)
Window insert	6,7,11	13	0.13	0.09	0.34
Replacement sash	3, 12, 13, 18	11	0.29	0.30	0.62
Bi-Glass System	2	3	0.48	0.33	0.65
Original sash with vinyl jamb liners	7,12,13	34	1.14	0.39	0.70

A significant reduction in ELAex19 was achieved by the use of window inserts at a 99.9% confidence level. This was likely a result of the insert's integral frame sealing the existing jamb.

5c iv. Storm window upgrades

Four different configurations of storm window upgrades were field tested, encompassing both new storm windows and upgrades of existing storm windows. General configurations of storm windows were aluminum triple track, aluminum fixed sash with removable lower pane, fixed wooden sash, fixed interior pane,and two aluminum triple track storms installed as interior storm windows. The number and type of each storm window are listed in Table 13 as well as the percentage reduction in sash air leakage when the storm window was closed.

An overall improvement could not be determined for site 16 windows due to their extremely leaky nature.

Sash leakage reduction varied between the types of storm windows with interior storms providing the largest percentage reduction. This was clearly illustrated at site 14 where six windows were tested, four with aluminum triple track storm windows mounted on the exterior and two with identical storm windows mounted on the interior. The four exterior storm windows reduced sash leakage by 75% while the two interior storms reduced sash leakage by 96%.

A wide range of variability was observed in sash leakage reduction for windows fitted with new aluminum triple track windows. The variability was dependent on site and was likely a result of installment procedures. Aluminum frames at site 14 were caulked to the exterior

Table 13: Storm window upgrades by type

	Upgrade Description	Site ID	n	Q_s Open (scfm/lfc)	Q_s Closed (scfm/lfc)	% Q_s Red.
New	Aluminum triple track, replacement	10	1	1.80	0.93	50%
		14	4	1.16	0.27	75%
		17	3	0.18	0.11	35%
	Aluminum fixed sash, removable lower sash	10	1	1.10	0.48	55%
	Wooden sash, replacement	7	1	2.00	1.32	35%
	Interior mount, aluminum triple track, replacement	14	2	1.11	0.04	96%
	Interior storm window, spring loaded metal frame	10	1	1.10	0.05	95%
	Interior storm window, plexiglass with magnetic stripping	15	4	0.90	0.01	98%
Original	Aluminum triple track, existing frame caulked	19	2	0.49	0.35	30%
	Wooden sash, felt weatherstripping	16	4	***	***	***

*** No data available

trim and were affixed to leaky prime windows (average extrapolated Q_s = 1.14 scfm/lfc). This was reduced to an average extrapolated sash leakage rate of 0.19 scfm/lfc for all six windows when the storms were closed. Site 17 frames had also been caulked in place but were three years old. Compared to site 14, the prime windows at site 17 were much tighter (average extrapolated Q_s = 0.18 scfm/lfc, reduced to 0.11 scfm/lfc with storms closed), an effect that decreases the importance of a reduction due to an effective storm window. Sample populations for all storm window types were too small to allow for valid statistical studies, but can be seen to reduce sash leakage rates.

As well as reducing sash leakage (Q_s) interior storm windows provided the additional benefit of reducing extraneous air leakage (Q_e) by their installation within the interior window jamb, thus blocking air leakage from the rough opening. A drawback to interior storm windows as reported in the literature was the potential to cause moisture related problems from accumulated condensation. Two sites (10 and 15) had fixed panel interior storm windows, while a third location (site 14) had two aluminum triple track storm windows installed on the interior window. Interior installation in this building was done to maintain the historic appearance of its front facade. Table 14 summarizes the reduction in extraneous leakage achieved by each interior storm window configuration. While reductions in extraneous air leakage are large, the small sample numbers should be noted.

Table 14: Percent reduction in extraneous leakage by interior storm window configuration

Interior Storm Window	Site ID	n	Q_s Open (scfm/lfc)	Q_s Closed (scfm/lfc)	Percent Q_e Reduction
Glass with metal frame	10	1	0.77	0.33	60%
Plexiglass with magnetic stripping	15	4	4.22	0.34	90%
Aluminum triple track	14	2	1.13	0.46	60%

5c v. Double- versus single-glazing upgrades

Nineteen of the 87 window upgrades were fitted with double-pane insulating glass. Sixteen double-glazing upgrades were either replacement sash or window inserts, with the remaining three windows being original sash using the Bi-Glass System upgrade. Infiltrative differences were not expected between double- and single-glazed sash as glazing did not affect leakage in upgraded windows. Thermal transmission differences due to a second glazing layer were expected however, and were modeled using WINDOW 4.1. Table 15 lists non-infiltrative loss rates as calculated by WINDOW 4.1 based on a double-hung window with dimensions of 36 x 60 inches. Also included are non-infiltrative thermal loss rates for assumed tight, typical, and loose windows.

The U-values for double-glazed windows and single-glazed windows with storms are relatively similar (0.49 versus 0.51, respectively). Although not encountered during field testing, low-e glazing options were modeled using WINDOW 4.1 and are included in Table 15. It can also be seen that low-e glazing significantly reduces thermal non-infiltrative loss rates regardless of glazing layers.

Any possible effects of wind-driven infiltration moving into the storm window/sash space were not taken into account, that interaction being beyond the scope of the study. Such effects could change non-infiltrative thermal heat loss rates through a window.

Table 15: Non-infiltrative thermal loss rates for assumed windows and glazing replacements

Site ID	Window Description	n	U-value (Btu/hr-ft^2-°F)	R-value (hr-ft^2-°F/Btu)
---	Typical and tight: single-glazed, storm windows	---	0.51	1.96
---	Loose: single glazed, no storm window	---	0.92	1.09
2, 7, 11, 16, 18	Double-glazed insulating wood sash, 1 over 1	13	0.49	2.04
6	Double-glazed insulating vinyl sash! frame, 1 over 1	6	0.47	2.13
***	Single-glazed prime sash with low-e storm window	---	0.43	2.33
***	Low-e, single-glazed sash with standard storm window	---	0.37	2.70
***	Low-e, double-glazed insulating sash	---	0.35	2.86

***Not encountered in the field – results from modeling

5c vi. Window upgrades summation

The importance of exterior air contributing to the overall heat load of a window was seen throughout all upgrades. Exterior air percentages were often as great or greater than sash leakage percentages. Window inserts generally reduced exterior air leakage significantly by virtue of an integral frame. Replacement sash were shown to be effective in reducing sash leakage when placed in a square frame.

Second glazing layers reduced non-infiltrative losses significantly, whether the second layer was a storm window or double-pane insulating glass. Low-e glass was shown to reduce non-infiltrative loss rates even further. Replacement storm windows provided the benefit of a second glazing layer while reducing sash leakage. Interior storm windows reduced sash leakage even further while also reducing exterior air leakage.

Original sash utilizing vinyl jamb liners stilt allowed significant sash leakage, although no correlation was found between sash fit and leakage rates. It was inconclusive as to the effect installation practices had on these leakage rates.

5d. Laboratory Test Window Data

Two double-hung, pulley-type windows were purchased from a salvage warehouse to be used for laboratory testing. The purposes of testing windows in a laboratory were as follows:

1. to test the repeatability of the test procedure and equipment under controlled conditions;
2. to investigate the location of air leakage sites in detail;
3. to test improvements due to routine maintenance and various upgrades; and
4. to compare laboratory results of an upgrade to its field results.

These two windows appeared to be in better condition than many of the original condition windows encountered during field testing. Both lab windows had meeting rails that fit well with operable sash locks. Both windows also had a good sash to jamb fit, sitting squarely in their frames.

Walls were constructed of 2 x 6 lumber with quarter inch plywood facing to support the test windows. No effort was made to mimic older building styles as the intent was to prevent extraneous air leakage via the rough opening from entering the test zone, eliminating a variable (ie exterior air) that is difficult to quantify. Rough openings were sealed against air leakage from other wall areas with plastic and duct tape prior to installation of the windows to ensure measured air came solely through the window (ie, sash leakage, Q_s), removing the need for the exterior plastic sheet as required by ASTM E783-93. The effectiveness of the plastic was tested after window installation by running the fan pressurization test as performed under field conditions. At 0.30 inches of water (the maximum test pressure), a sash air leakage rate below 1.2 cfm was observed for the entire window. This observed leakage rate was lower than the limits of resolution of the pressurization unit flow meter, meaning any leakage was below the measurement capabilities of the test unit. It was therefore assumed the rough opening had been effectively sealed.

5d i. Identification of leakage locations in lab window A

Lab window A was not immediately upgraded, being first tested in its original condition with missing putty, loose glass, and little paint. This was to provide a comparison to routine maintenance. Routine maintenance was considered to be applying new putty, repointing if necessary, and painting of the woodwork. The edge of the exterior trim was also caulked, a step that would reduce extraneous air leakage in the field. These steps provided some idea of the efficacy of simple maintenance in reducing air infiltration as well as a baseline for comparison to more costly rehabilitation options.

Lab tests for window A were comprised of isolating and testing window leakage areas for respective leakage rates to gain a sense of where the majority of leakage occurred. Leakage sites were chosen on the assumption they would likely be addressed during

window renovations. The exception is site F, the inside edges of the exterior trim. This site, along with air from the outside edges of the exterior trim, was chosen to investigate the amount of air entering the test zone by way of the window weight Cavity. Each leakage area was tested six times for statistical validation and was also used to check the reproducibility of the portable air test unit. Individual leakage sites of the window were identified as follows:

A - the window as a whole unit;
B - the meeting rail;
C - the upper sash with the meeting rail sealed;
D - the lower sash with the meeting rail sealed;
E - the junction between the sill and the lower sash;
F - the inside edges of the exterior trim; and
G - the outside edges of the exterior trim.

Reproducibility in terms of the test unit and day-to-day testing (reproducibility over time) were questions specifically addressed during testing of the window as a whole unit (leakage site A). Three sets of three tests were run over the course of nine days to determine the reliability of test results. The air test unit was found to be reliable in terms of reproducibility, with the nine sets of data points falling on top of each other (Figure 4).

These same sets of data also demonstrate the reproducibility of the test over a period of nine days, resulting in a high degree of confidence in the test procedure and the fan

Figure 4: Reproducibility of lab pressurization test results and test device over time

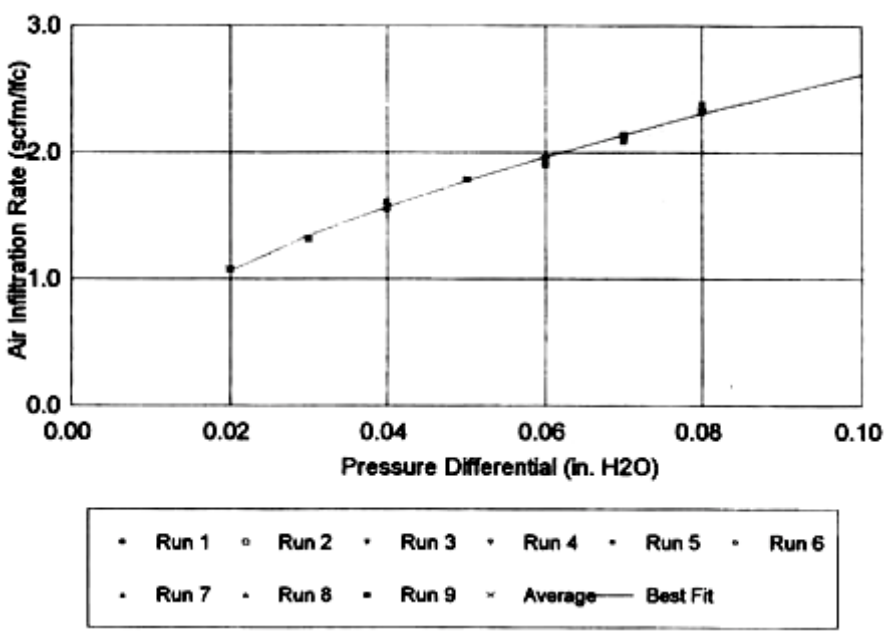
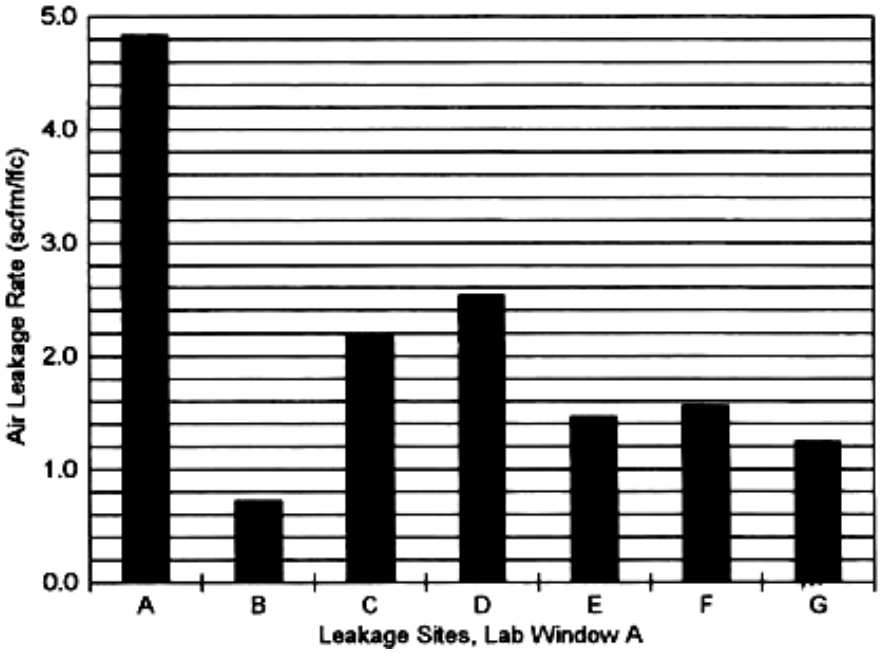


Figure 5: Lab window A leakage rates by site at 0.30 in. H_2O for original condition window



A - Leakage rate through the total window (extrapolated value)
B - Leakage rate through the meeting rail
C - Leakage rate through the upper sash with the meeting rail sealed
D - Leakage rate through the lower sash with the meeting rail sealed (extrapolated value)
E - Leakage rate through the sill junction
F - Leakage rate through the inside edges of the exterior trim
G - Leakage rate through the outside edges of the exterior trim

pressurization unit.

Each individual leakage site investigated using lab window A exceeded the certifiable industry sash leakage standard for whole windows of 0.37 scfm/lfc at 0.30 inches of water pressure for new window units. Figure 5 shows sash leakage rates of the various sites tested on lab window A. Both the window (A) and lower sash (D) failed to attain the specified test pressure of 0.30 inches of water and values shown are extrapolations, based on regression coefficients. Lab window A was considered to be an extremely leaky window as 0.30 inches of water pressure could not be attained for some individual sections.

Examination of Figure 5 shows air leakage rates did not appear additive, as the total window leakage rate should have been equivalent to the summed leakage rates of other leakage sites at equivalent pressures, excluding the sill junction (E). The sill junction was excluded from the summation as it was incorporated in the lower sash reading. Total window leakage rate was just under 5 scfm/lfc while the sum of the individual sites,

physically identical to total window leakage sites, was well over 8 scfm/lfc. While the underlying cause of the discrepancy in summing leakage rates was not investigated, it is possible that different masking combinations for differing leakage sites affected the mobility of window components. Changing mobility would allow a component to remain stationary under one masking combination while moving freely under another, affecting the air leakage rates.

It can be seen that for this one window, both the upper and lower sash each accounted for approximately half the total window leakage when tested individually, constituting major leakage sites. The above data are based on one window and should therefore not be considered representative of typical windows.

5d ii. Improvements due to routine maintenance

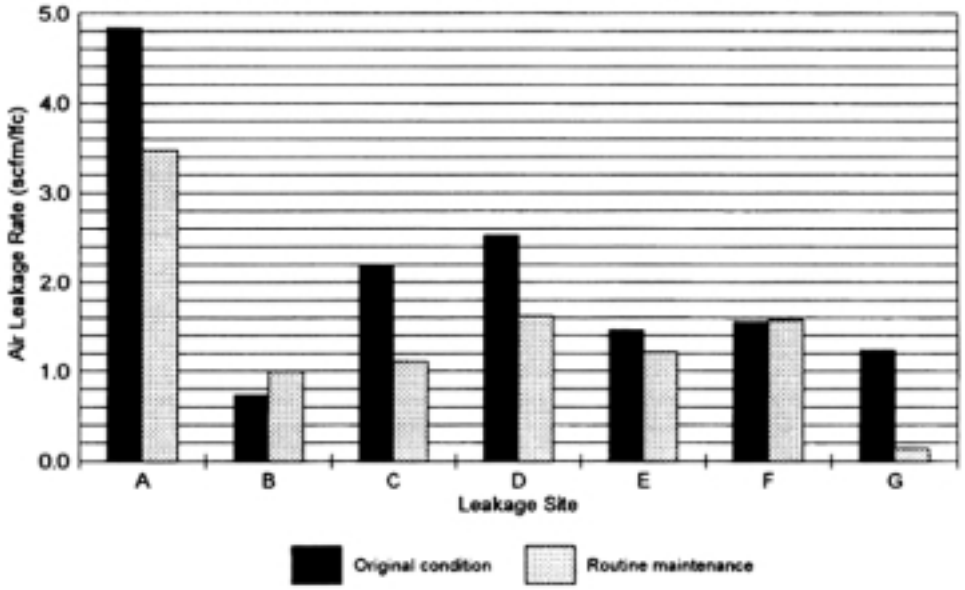
The same leakage sites were retested after lab window A underwent what had been deemed routine maintenance. Routine maintenance included new putty around the glazing of both sash and caulking of the exterior trim/wall junction. New putty was expected to decrease sash leakage (Q_s **)** while caulking was expected to decrease what would be extraneous air leakage (Q_e) in the field.

Expected reductions in air leakage were observed, as illustrated in Figure 6. Also included are the data from Figure 5 for comparative purposes. Reductions in sash leakage rates at 0.30 inches of water pressure were significant at a confidence level of 98%, but the lab window would still be classified as a loose window in the field due to a whole window leakage rate over 3.4 scfm/lfc.

Six of the seven individual leakage sites investigated were still above the certifiable industry standard for whole window sash leakage. The one exception was site G, which allowed air leakage between the wall and outside edges of the exterior trim. This site was the area receiving caulk, a procedure that would reduce exterior air infiltrating around a window in a building. Sash leakage rates (sites C, D) were reduced an average of 65% after routine maintenance, while leakage around the exterior trim/wall junction was reduced by 90%. An overall leakage reduction of 35% was observed for the window as a whole. Simple window maintenance can significantly reduce air leakage for loose windows, but still allow significant leakage. Leakage reduction would not be as significant for tight windows.

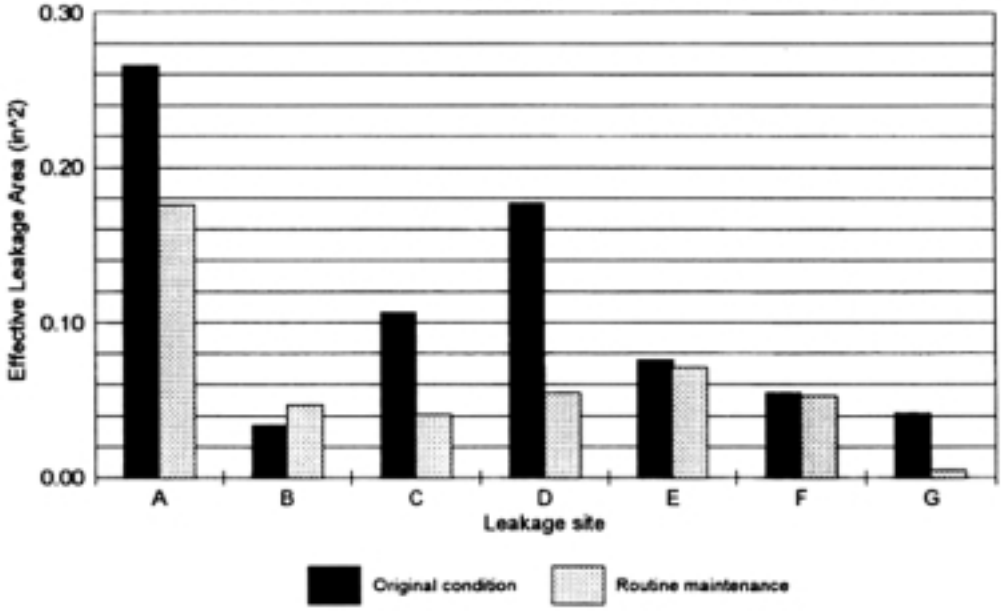
Leakage rates did not appear additive once again, as noted in the previous section. Effective leakage areas (ELA's) were calculated for leakage sites in both the original condition window and after routine maintenance. Leakage site ELA's are shown in Figure 7. Effective leakage areas appear more additive than leakage rates, overestimating the whole window value by an average of 30%, as opposed to a 65% overestimation when using leakage rates. An anomaly serving to increase overestimation based on ELA's was noted at the meeting rail (site B). Air leakage increased by 25% after routine maintenance, but was expected to remain relatively constant, as leakage rates did at sites E and F. That

Figure 6: Lab window A sash leakage rates, original condition versus routine maintenance



increase was not investigated further as the purpose was to check the approximate additive nature of ELA's.

Figure 7: Leakage site ELA's for lab window A, original condition versus routine maintenance



5d iii. Laboratory tests of Bi-Glass System upgrade

Three windows at 40 Nash Place (all single-hung, pin-type windows) and one lab test window (a double-hung, pulley-type window) received the Bi-Glass System window upgrade. Lab window B differed from the Nash Place windows by not being fitted with the double-pane insulating glass insert. The double-pane insert was excluded from the lab window as non-infiltrative losses were investigated by computer simulation rather than lab testing.

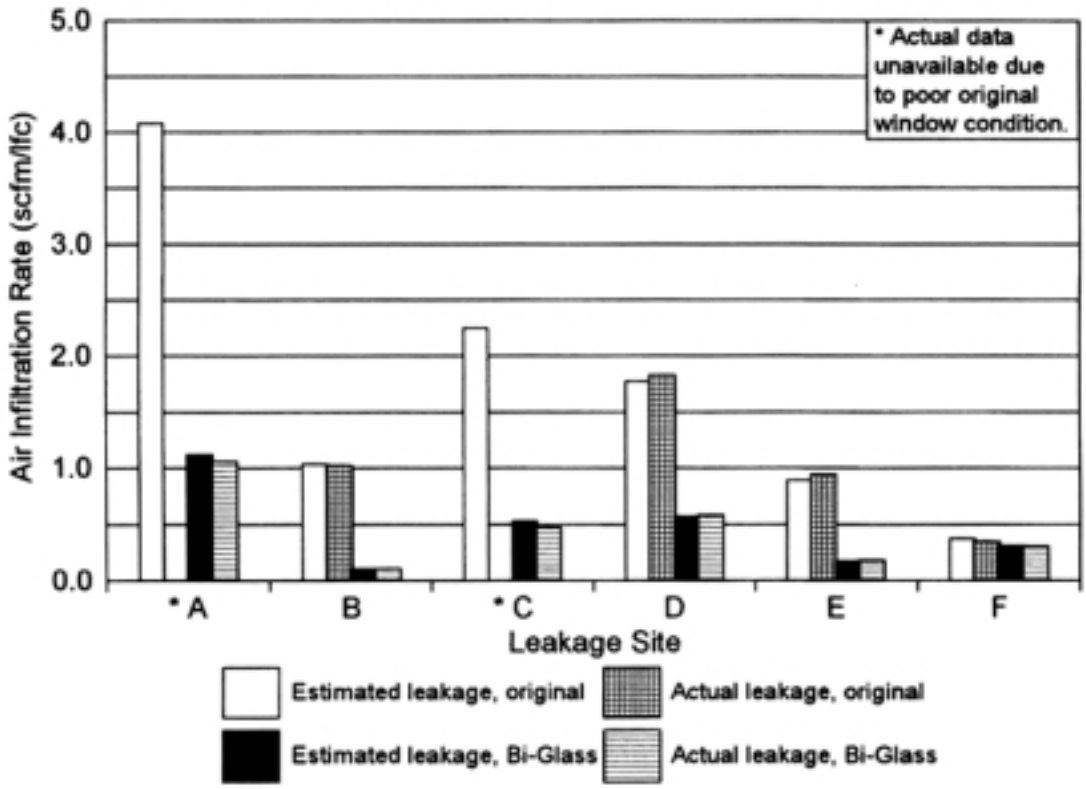
The lab window was a pulley-type window with attached window weights. The Bi-Glass System upgrade involved cutting window weight ropes while leaving the weights in the window weight cavity. Pulleys were removed with fiberglass insulation stuffed into the window weight cavity through the pulley opening. The pulley opening and window weight access panel were sealed with duct tape prior to installation of the jamb liners. Vinyl jamb liners were cut to fit the existing jamb and had an adhesive foam backing to reduce air movement between the jamb and jamb liner. The foam backing was compressed by the sash as well as three support screws on each jamb liner. The existing sash were routed to accept vinyl jamb liners and double-pane insulating glass inserts. Although not present in the lab window, muntins present in a divided light would be trimmed to fit over the replacement glass, mimicking the look of a true divided light. The top rail of the upper sash and bottom rail of the lower sash were routed to accept a silicone weatherstripping bead, improving the seal at the head and sill junctions. A third silicone weatherstripping bead was inserted into the lower rail of the top sash to tighten the meeting rail junction, along with a new vinyl latch type lock attached near the meeting rail center.

Air leakage rates in terms of sash leakage (Qs as scfm/lfc) for various leakage sites of lab window B and its Bi-Glass System upgrade were compared. Figure 8 shows the relative improvements made using the Bi-Glass System. It should be noted that 0.30 inches of water pressure could not be attained for some sections of the lab window in its original condition. Also shown in Figure 8 are extrapolated versus actual values where attainable, illustrating the proximity of extrapolated values to actual values.

The Bi-Glass upgrade made significant improvements to the efficiency of the lab window at all locations except through the outside edge of the exterior trim (F in Figure 8). This site represented extraneous air coming through the rough opening (Q_e), passing into the test zone through the window weight cavities. As mentioned previously, the Bi-Glass System window renovation stuffed fiberglass insulation into the window weight cavities to decrease air leakage. The small decrease in air leakage through the rough opening supports the findings of an earlier Canadian study on the effectiveness of rough opening sealing methods (Proskiw, 1979). That study showed fiberglass insulatiion stuffed into rough openings was a poor sealing method.

Extrapolated leakage rates for lab window B were over 4.0 scfm/lfc, based on regression coefficients for sash leakage at 0.30 inches of water pressure. The Bi-Glass System

Figure 8: Lab window B, relative air leakage reductions at 0.30 in. H_2O due to Bi-Glass Systems upgrade



A - Leakage rate through the total window
B - Leakage rate through the meeting rail
C - Leakage rate through the upper sash with the meeting rail sealed
D - Leakage rate through the lower sash with the meeting rail sealed
E - Leakage rate through the sill junction
F - Leakage rate through the outside edges of the exterior trim

upgrade decreased the sash leakage rate to 1.1 scfm/lfc, a 360% reduction. While the improvement was significant, the air leakage rate was well above the industry standard for new windows (0.37 scfm/lfc at 0.30 inches of water pressure).

A chemical smoke generator was employed to observe air currents to further identify leakage sites in the Bi-Glass System upgrade. Air was observed easily infiltrating the jamb/jamb liner junction, as well as the head/upper sash junction. Leakage through the jamb/jamb liner junction implied the failure of the jamb liner foam backing to perform as intended. The same was true for the silicone weatherstripping bulb in the head/upper sash junction.

5d iv. Lab Testing Summation

Testing of the two lab windows revealed the perimeters of both sash to be major air leakage sites. Routine maintenance was shown to significantly reduce air leakage if the original condition window was in poor condition, but the result was still a loose window allowing substantial air leakage. The Bi-Glass System upgrade significantly reduced air flow for the whole window but did little to reduce air flow through the window weight cavity. Both the weatherstripping at the head junction and the foam backing on the jamb liners allowed air flow when viewed with a chemical smoke generator, implying a poor fit.

5e. Correlation of Induced Air Leakage to Natural Infiltration Rates

Window air leakage rates, as measured by fan pressurization in the field, do not directly correspond to natural infiltration rates through those windows during the heating season. Natural infiltration rates vary over time as a result of a combination pressure differential, induced by wind speed and direction along with interior/exterior temperature differences.

The sash and extraneous air leakage rates for each window were used to extrapolate induced leakage rates at 0.016 inches of water pressure, the assumed heating season driving pressure for natural infiltration. Based on field measurements, 30% of the averaged extraneous air was assumed to be exterior air and was added to the sash leakage rate. This whole window infiltrative leakage rate was converted to a whole window effective leakage area (ELAtot) at 0.016 inches of water pressure. The value was used in the LBL correlation model to convert the ELAtot to a natural infiltration rate (Q_{nat}) for each type of window and upgrade. Parameters typical of the Vermont climate and affordable housing were used in the model. Table 16 lists the assumed parameters used in the LBL model.

Table 16: Parameters assumed typical of Vermont, used in the LBL correlation model

Housing Parameters			Weather and Terrain Parameters		
Volume		30,000 ft^3	Terrain Parameters	y	0.23
Roof Height		19 ft		a	0.73
Leakage area	ceiling	33%	Shielding Coefficient		0.24
	floor	33%			
	walls	34%			
Interior Temperature		68°F			

The Vermont heating season was assumed to extend from the month of October through April. Mean monthly temperatures and wind speeds throughout the heating season for Burlington, Vermont were used to determine the overall heating season natural infiltration rate. The LBL model was placed in a spreadsheet and run using a personal computer. An example of the computer print-out is found in Appendix G. Table 17 summarizes the predicted natural infiltration rates (Q_{nat}) based on results of the LBL correlation for each assumed window and window upgrade. Infiltration rates are based on whole window infiltration which includes the exterior air component.

It should be restated that LBL values shown for Q_{nat} were based on whole window effective leakage area (ELA_{tot}) which was defined to include a calculated volume of exterior air for the purposes of this study. The LBL correlation model was also used in a manner for which it was not intended. Therefore, all values based on the LBL model should not be viewed as absolutes, but rather as relative values to one another. It should also be noted that

Table 17: Estimated natural infiltration flow rates (Q_{nat}) for the period October through April

Window		Site ID	n	Storm open		Storm closed	
				ELA_{tot} (in^2)	Q_{nat} (scfm)	ELA_{tot} (in^2)	Q_{nat} (scfm)
Typical with storm window		---	---	---	---	1.48	2.07
Tight with storm window		---	---	---	---	0.85	1.19
Loose with no storm window		---	---	2.77	3.87	---	---
Original sash, vinyl jamb liners; no weatherstripping		12	7	3.05	4.26	1.48	2.07
Original sash; vinyl jamb liners; weatherstripping at sill, head junctions		13	8	2.79	3.90	1.74	2.43
Original sash; vinyl jamb liners; weatherstripping at sill, head, meeting rail junctions		7	19	1.13	1.58	0.83*	1.16*
Bi-Glass System		2	3	1.04	1.45	0.71	0.99
Coiled spring balances; weatherstripping at sill, head junctions, wooden storm windows weatherstripping		16	2	---	---	3.43	4.80
Rib-type weatherstripping; V-strip at meeting rail, pulley seals, top sash painted in place; new triple track storm window frames caulked in place		17	3	1.09	1.52	0.91	1.27
V-strip weatherstripping around lower sash, top sash painted in place, existing triple track storm window frames caulked in place		19	2	0.71	0.99	0.60	0.84
Polyflex T-slot weatherstripping around upper and lower sash		10	1	0.71	0.99	0.81	1.13
Interior storm window with spring loaded metal frame		10	1	4.25	5.94	0.39	0.55
Fixed aluminum storm window, removable pane		10	1	4.55	6.36	0.64	0.90
Aluminum triple track storm window		10	1	4.25	5.94	0.86	1.21
Reglazed and painted with new aluminum triple track storm windows		14	6	2.16	3.02	0.45	0.63
Interior plexiglass storm windows held by magnetic strips		15	4	2.25	3.15	0.27	0.38
Top sash painted in place; bronze V-strip weatherstripping; old aluminum triple track storm frame caulked in place		19	2	0.71	0.99	0.60	0.84
Replacement sash	Includes 18	3, 12, 13, 18	11	0.75	1.05	---	---
	Excludes 18	3, 12, 13	9	0.87	1.22	0.78	1.09
Replacement window inserts	Includes 16	6, 7, 11, 16	14	0.29	0.41	---	---
	Excludes 16	6, 7, 11	13	0.21	0.29	---	---

*Data based on one window with exterior wooden storm sash. See text for explanation.

most window upgrades have very low sample populations (n) and should not necessarily be regarded as typical of the upgrade type nor viewed as statistically significant.

Values for both ELA_{tot} and Q_{nat} for site 7, storm closed, should be viewed with a large degree of caution. The site had only one wood sash storm window (7B 2) in place with a poor fit to the exterior trim. The averaged site value for leakage with storm windows in place was based on the ratio of extrapolated sash leakage values for the one window tested with and without a storm at 0.30 inches of water pressure. This ratio (0.66:1) was multiplied by the average ELAtot for storm windows open (off) to estimate the effect of storms covering all site windows. The LBL correlation was run using these manipulated values and is subject to speculation.

An anomaly was noted for the site 10 window weatherstripped with Polyflex. Air leakage increased when the fixed wooden storm was in place, a situation that should not have occurred. A cause for this anomaly was not determined.

Replacement sash included two double-pane insulating glass windows not fitted with storms at site 18. The two data values in Table 17 reflect both the inclusion and exclusion of those windows from the group average. It can be seen that these two windows played a major role in reducing average ELA_{tot} and Q_{nat} values with storm windows open. A large portion of the difference was in the volume of extraneous air measured during the pressurization test. Windows at site 18 had an excessive amount of work done to reduce extraneous air leakage and were not considered typical renovations.

The opposite situation applies for replacement window inserts where all but one window showed very low extraneous air leakage values. The one window at Site 16 was considered atypical of the general upgrade category. Again, two LBL correlation values are shown in Table 17 for replacement window inserts, one including window 16G, and the other excluding it.

5f. Thermography

Thermographs were taken of two upgrade options in February 1996. Interior plexiglass storm windows at 4 Occom Ridge, Hanover, NH (site 15) were compared to an adjacent window with the plexiglass storm panel removed. This window also had rope caulking around the operable perimeter and pulleys to prevent drafts as well as an aluminum triple track storm window in place. The caulking was partially removed to demonstrate its ability to reduce air infiltration. The resulting thermograph (Figure 9, page 53) showed the rope caulking reduced air infiltration, keeping the sill a minimum of 8°F warmer than the lower sash. The black corner at the sash/frame junction revealed cold air infiltration through the window. It can be seen that the caulking effectively prevents infiltration around the operable perimeter. Upon pressurization testing, these windows were discovered to be very leaky when the interior storm window and rope caulking were removed.

The second thermograph (Figure 10, page 54) shows the aforementioned window with an adjacent plexiglass interior storm window in place. The surface temperature of the window without an interior storm ranged from below 50°F to 62°F. The surface temperature of the interior plexiglass storm ranged from 58°F to 66°F, with the vast majority of its surface area being in the 60°F to 66°F range. The coldest section was at the storm window/sill junction where the effects of conduction would be seen.

Images of three other windows were taken in Robinson Hall of Dartmouth College. One of these was a Bi-Glass System upgrade while the other two windows were in their original condition. Both of the original condition windows had triple track aluminum storm windows, but one window was missing the lower panel. Where the lower panel should have been was a sheet of plexiglass resting against the window. Figure 11 (page 55) shows this window, with the warmest surface area (65°F) corresponding to the location of the plexiglass panel. The center of glass surface temperature for this window with effectively no storm window, was between 55°F and 60°F.

Figure 12 (page 56) shows the window with the operable triple track storm panels in place. Its average surface area was approximately 65°F, warmer than the window with no effective storm window.

Figure 13 (page 57) shows the Bi-Glass System replacement with its double-pane insulating glass. The surface temperature of the glass ranged from 70°F near the sill to 85°F in the center of glass.

Any conclusions based on the Robinson Hall thermographs must consider the effect of unequal space heating. As in most old buildings, hot water radiators were situated beneath the windows. The temperature regimes of the radiators varied considerably from window to window with the coolest radiator being below the coolest window and the hottest radiator being directly beneath the Bi-Glass System upgrade. The radiators likely had a significant effect on the glass surface temperatures, but it is unlikely either of the other two windows would have achieved as high a center of glass temperature as the Bi-Glass window.

Figure 9: Thermograph of sash infiltration reduction due to rope caulking

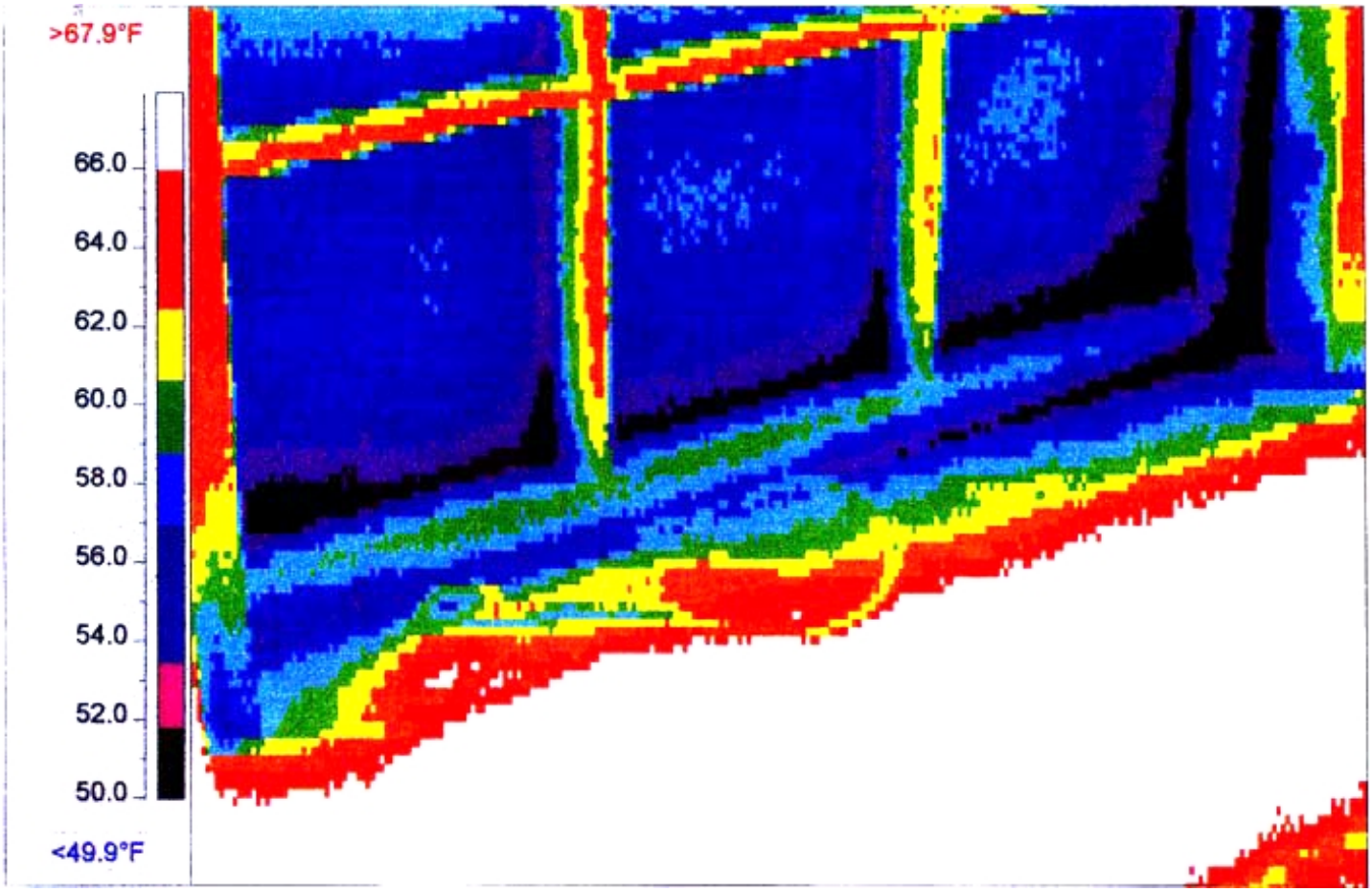


Figure 10: Thermograph of plexiglass interior storm window adjacent to window with interior storm removed

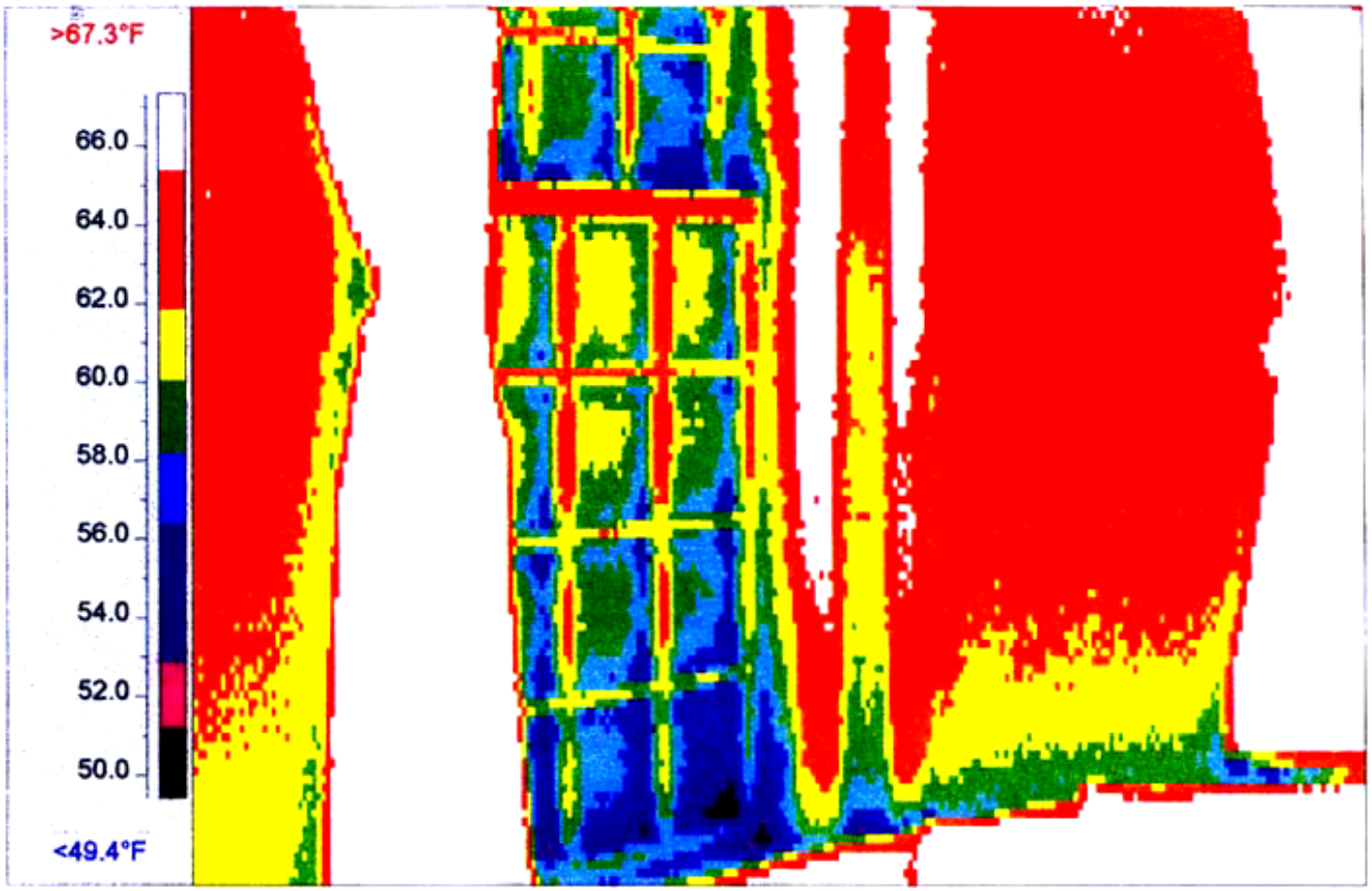


Figure 11: Thermograph of Robinson Hall window with no effective storm attached

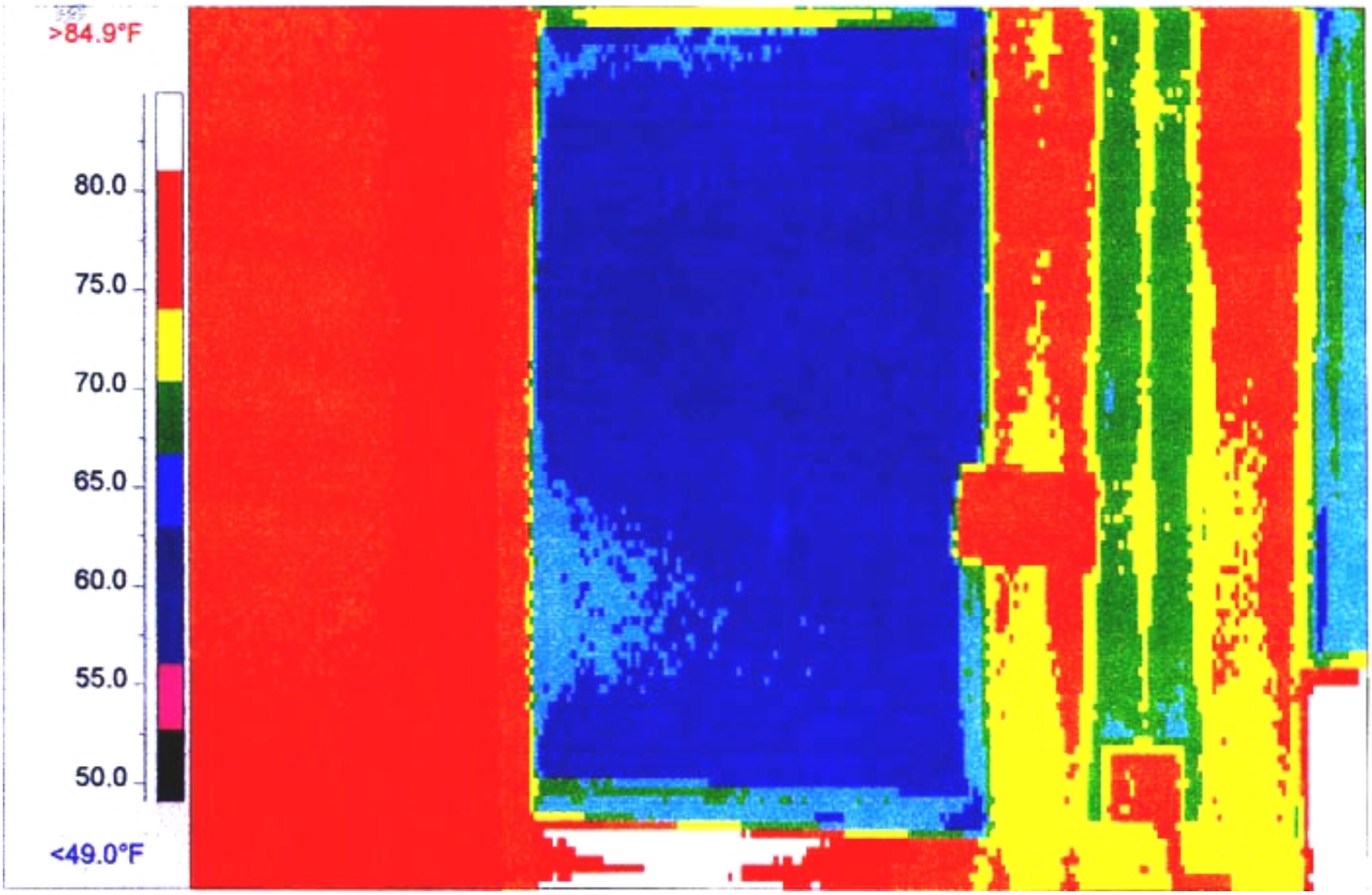


Figure 12: Thermograph of Robinson Hall window with aluminum triple track storm windows in place

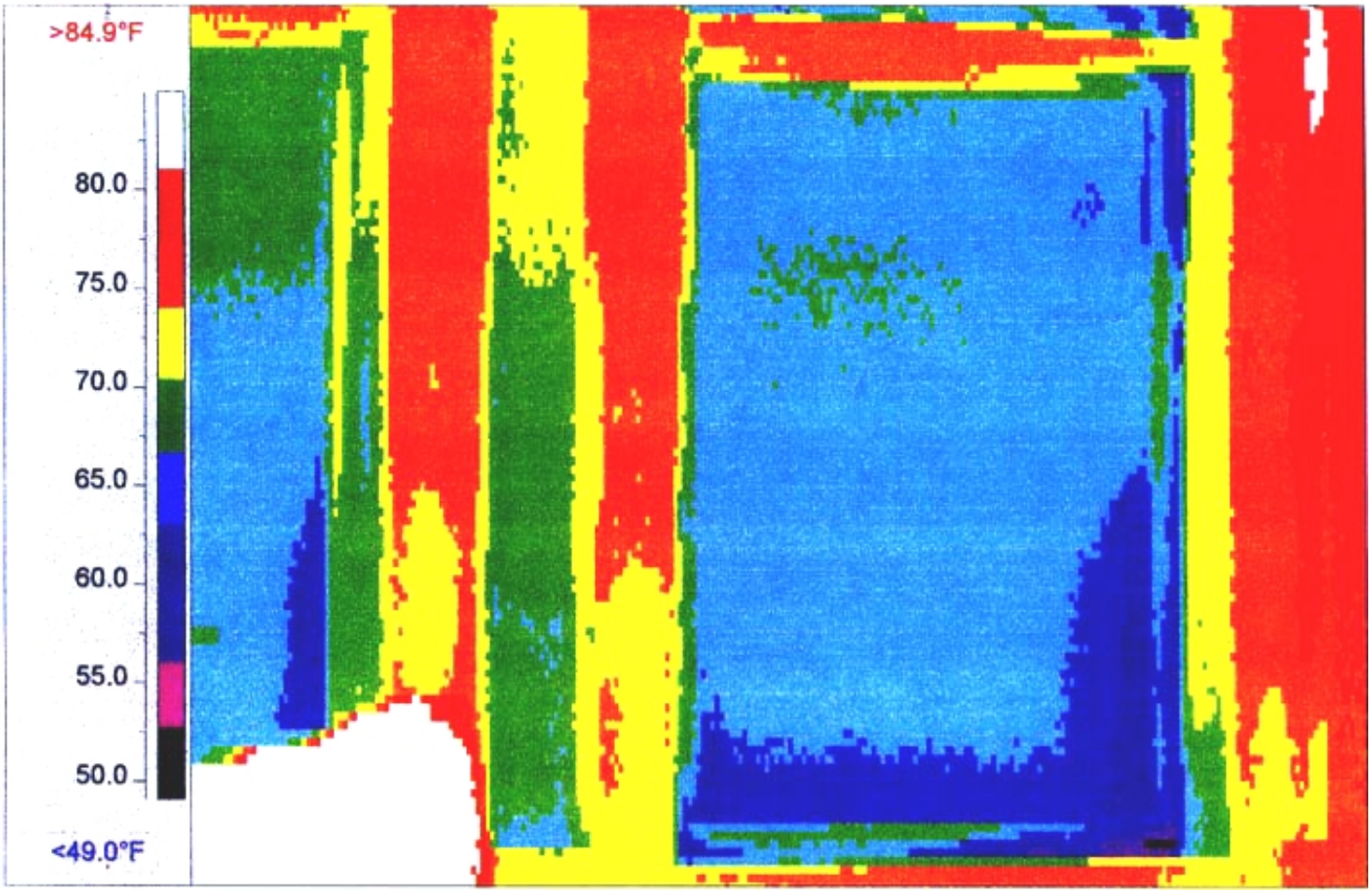
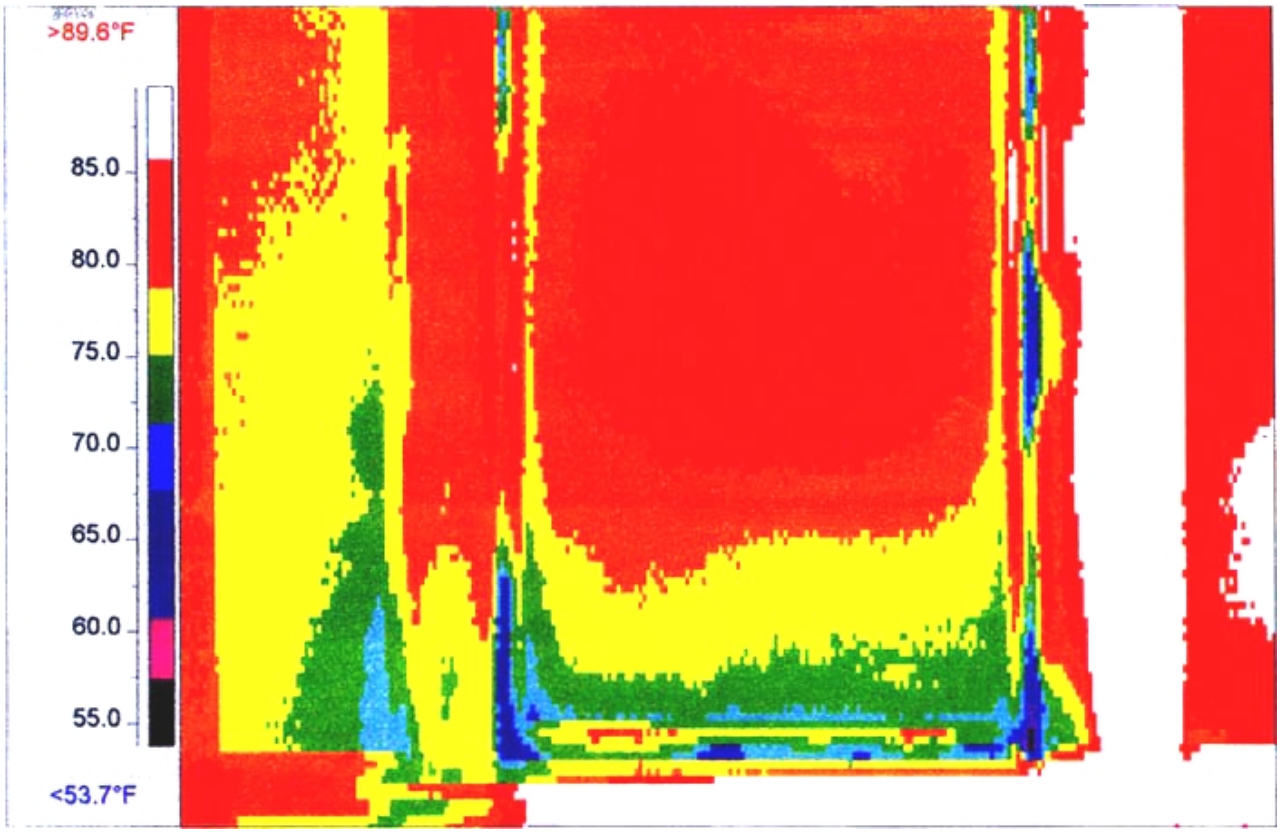


Figure 13: Thermograph of Robinson Hall window with Bi-Glass System upgrade



5g. Energy Savings Attributable to Upgrades

Average seasonal heating infiltrative rates (Q_{nat}) were converted to infiltrative thermal loss rates per window (L_{inf}) by multiplying Q_{nat} by the heat capacity of air:

$$L_{inf} = Q_{nat} * Cp_{air}$$

$$L_{inf} = Q_{nat} * \frac{0.018\,Btu}{ft^3 * {}^oF} * \frac{60\,\text{min}}{1\,hr}$$

Non-infiltrative loss rates (U-values) were converted to non-infiltrative thermal loss rates per window (L_u) by multiplying the U-value by the area of an assumed typical window (15 ft^2). Whole window infiltrative and non-infiltrative loss rates were summed to determine the "effective thermal loss" of a window (L_{eff}):

$$L_{eff} = L_{inf} + L_u$$

Annual heat loss per window (L_{yr}) in millions of Btu's (MMBtu) was calculated by multiplying the "effective thermal loss" (Li,) by the average number of degree-day units in Burlington, Vermont:

$$L_{yr} = L_{eff} * 7744\ degree\text{-}days * \frac{24\,hr}{day} * 10^{-6}$$

The annual heating cost per window in 1996 dollars was calculated by using the fuel cost, fuel heat capacity, burner efficiency, and annual heat Lyr in the following formula:

$$C_{win} = \frac{(fuel\ cost\ per\ unit) * (annual\ heat\ required) * 10^6}{(fuel\ heat\ capacity\ per\ unit) * (heating\ system\ efficiency)}$$

$$C_{win} = \frac{\$0.90/gal * L_{yr} * 10^6}{(138{,}600\,Btu/gal) * 0.75}$$

First year annual heating costs per window were based on number 2 fuel oil as an energy source at $0.90/gallon with a 75% furnace efficiency. Table 18 shows estimated first year annual heating costs in 1996 dollars attributable to the assumed existing window types. Estimated first year costs for each upgrade were compared to those costs estimated for the assumed typical, tight, and loose windows. First year annual costs and savings for each upgrade in 1996 dollars are also shown in Table 18.

It is critical to note once again that in this study, the LBL correlation model was used for

Table 18: Estimated first year annual savings in 1996 dollars due to window upgrades

Window Upgrade Description	Heating Cost per Window Upgrade	Annual first year savings per upgrade as compared to a:		
		Tight Window	Typical Window	Loose Window
Tight window with storm	$14.38	---	---	---
Typical window with storm	$15.91	---	---	---
Loose with no storm	$28.93	---	---	---
Original sash, vinyl jamb liners; no weatherstripping	$15.91	***	**0.00**	$13.00
Original sash; vinyl jamb liners; weatherstripping at sill, head junctions	$16.53	***	***	$12.40
Original sash; vinyl jamb liners; weatherstripping at sill, head, meeting rail junctions	$14.33	$0.05	**$1.60**	$14.60
Bi-Glass System	$13.55	$0.80	**$2.40**	$15.40
Rib-type weatherstripping; V-strip at meeting rail, pulley seals, top sash painted in place; new triple track storm windows, caulked	$14.52	***	**$1.40**	$14.40
V-strip weatherstripping around lower sash, top sash painted in place, existing triple track storm windows caulked in place	$13.77	$0.60	**$2.10**	$15.20
Polyflex T-slot WS around upper and lower sash	$14.27	$0.10	**$1.60**	$14.70
Reglazed and painted with new aluminum triple track storm, caulked to trim	$13.40	$1.00	**$2.50**	$15.50
Interior plexiglass storm window held by magnetic strips	$13.00	$1.40	**$2.90**	$16.00
Interior storm window with spring loaded metal frame	$13.30	$1.10	**$2.60**	$15.70
Replacement sash with storm window	$14.20	$0.20	**$1.70**	$14.70
Low-e replacement sash with storm window*	$10.83*	$3.55*	**$5.10***	$18.10
Replacement sash with low-e storm window*	$12.27*	$2.10*	**$3.60***	$16.70*
Replacement sash with double-glazed insulating glass	$13.65	$0.70	**$2.30**	$15.30
Replacement sash with double-glazed low-e insulating glass*	$10.27*	$4.10*	**$5.60**	$18.70*
Replacement window inserts with double-glazed insulating glass, excluding 16G	$12.33	$2.10	**$3.60**	$16.60
Replacement window inserts with low-e double glazed insulating glass*	$8.95*	$5.40*	**$7.00***	$20.00*

***Denotes negative values for savings
*Denotes window upgrades not encountered during field testing

a purpose for which it was not intended. The estimated first year savings shown in Table 18 and discussed below are relative to each other only in the context of this study and are not absolute values. The values in Table 18 given an indication of the relative energy cost savings attributable to each window upgrade as compared to energy costs associated with assumed windows. These values should not be interpreted as actual energy savings

realized. They may be used to rank upgrades or to interpret which are comparable in terms of energy savings.

Estimated first year annual energy savings realized from a field tested upgrade ranged from zero to a maximum of $3.60 per year per window as compared to annual energy costs for a typical existing window. The maximum value was attained by using a replacement window insert. Although not field tested, using a low-e, double-pane insulating window insert showed an estimated first year annual energy savings of $7.00 per window per year. First year savings compared to an assumed loose window ranged from $12.00 to $16.00 for tested field tested upgrades and up to $20.00 for low-e insulated glass replacement window inserts. Again, all values are relative to one another and not absolute values. Blocks with asterisks represent negative values in terms of savings. Negative values may partially be the result of varying extraneous leakage rates at each site.

There is a large range of variation in estimated first year annual savings by upgrade, but a grouping of upgrades by glazing type reveals field tested double-glazed upgrades show significantly larger savings than single-glazed at a 95% confidence level. It should be noted that the double-glazed windows included 14 replacement window inserts which significantly reduced exterior air infiltration. Therefore, differences in savings as discussed below are not solely attributable to double-glazing.

All field tested double-glazed upgrades were averaged together yielding an estimated first year annual savings average of $2.90 per year per window versus a $1.40 average per year per single-glazed window as compared to the assumed typical window. When compared to the assumed loose window, averaged savings were $16.00 per year per double-glazed window versus $14.00 per year per single-glazed window. Greater first year estimated annual savings would be realized by the addition of low-e glass.

5h. Estimated Costs for Upgrade Purchases and Installation

Along with estimated savings in first year energy costs, initial materials purchase and installation costs in 1996 dollars were considered for the upgrade options. Table 19 shows estimated costs associated with upgrade options as of August 1996 including labor, priced at $20 per hour. The estimated cost of a window upgrade and its installation may be compared to the relative size of estimated savings in first year energy costs as found in Table 18. It should be noted again that the estimated first year savings in Table 18 are not absolutes, but should be used only as a means of comparing one upgrade to another. Therefore, values in Table 18 may not be used to calculate payback periods for a window upgrade when combined with estimated costs from Table 19. No provisions have been made in this study to investigate the life span of any window upgrade, nor have provisions been made to estimate how energy savings change over time.

A further issue in window renovations was that of lead paint. In order to retain an original sash, federal and state regulations mandate lead abatement if lead paint was used on the sash. Lead abatement added an additional $125 to $150 cost per window, sums that are not reflected in Table 19. The inclusion of this additional cost for original sash lead abatement would make the first four options approximately equivalent in price.

Table 19: Estimated window upgrade costs as of August 1996, including materials and installation but excluding lead abatement costs

Upgrade option			Materials	No. Reqd	Unit Cost	Total	Labor Hours	Labor Cost @ $20/hr	Total Cost
V-strip + cam locks, fix upper sash in place, rehab storm			Bronze V-strip	1 set	$5.00	$5.00	0.50		
			Caulk			1.00	0 10		
			Cam Locks	2	1 00	2 00	0.25		
			Pulley seals	2	0 75	1 50	0.10		
			Rope for pulleys	8 ft	0 10	0 80	0.25		
			Window putty	0.25	3 00	0.75	0.50		
			Paint prep			0.50	0.50		
			Storm window rehab			10.00	0.50		
					Total	$21.55	2.70	$54	$76
Vinyl jamb liners, rehab storm			Caldwell DH100 jamb liners	1	$12.00	$12.00	1 50		
			Silicone bulb WS	6	0.90	5 40	0.50		
			Sash lock	1	1 00	1.00	0.25		
			Foam for cavity	0.5	12.00	6.00	0.50		
			Int trim adjustment	5	1.00	5.00	0.50		
			Int. trim paint			2.00	0.50		
			Window plow	0.2	12.00	2 40	1.00		
			Window putty	0.25	3 00	0.75	0.50		
			Paint prep			0 50	0.50		
			Storm window rehab			10.00	0.75		
					Total	$45.05	6.50	$130	$175
Brosco double-hung single-glazed	6/6	$110	Sash lock	1	1 00	1.00	0.25		$210
	2/2	$114	Foam for cavity	0 5	12 00	6.00	0.50		$214
	1/1	$79	Int. trim adjustment	5	1 00	5.00	0.25		$179
	6/6	$174	Int trim paint			2.00	0.50		$274
with low-e glass	2/2	$178	Storm window rehab			10.00	0.50		$278
	1/1	$143			Total		5.00	$100	$243
Marvin E-Z Tilt double-hung, double-glazed	6/6	$520							$615
	2/2	$319							$414
	1/1	$168	Foam for cavity	0 5	12.00	6.00	0.50		$263
	6/6	$594	Int. trim adjustment	5	1 00	5.00	0.25		$689
with low-e glass	2/2	$372	Int. trim paint			2.00	0.50		$467
	1/1	$211	New screen or rehab storm			10.00	0.50		$306
Marvin Tilt-Pac with low-e glass	6/6	$499			Total		4.75	$95	$594
	2/2	$396							$491
	1/1	$222							$317
Harvey Tru-Channel triple track storm window			Standard glass $70						$100
			Low-e glass $87		Total		1.5	$30	$117
Fixed upper, removable lower panel storm window			Standard glass $200						$220
			Low-e glass $240		Total		1.0	$20	$260
Wood exterior storm window			Standard glass $110						$125
			Low-e glass $140		Total		0.75	$15	$155
Allied Window magnetic interior storm window			Standard glass $110						$125
			Low-e glass $150		Total		0.75	$15	$65
Alternative Window interior spring loaded storm window			Standard glass $115						$125
			Low-e glass $150		Total		0.5	$10	$160
Bi-Glass System upgrade						$200-$250 depending on size			$225
Weather Shield "Custom Shield" wood replacement window insert						$500			$500
Vinyl replacement window insert						$200-$300 depending on quality			250

Ancillary notes to Table 19

Window Rehab Option Costs
NOTES

1 Labor and materials do not include paint cost, as that is assumed to be the same for all treatments
2 For existing sash that are retained, 1 hour total assumed for putty and paint prep, and $10 + 1/2 hour for storm rehab
3 Costs are as of August, 1996
4 Costs do not include the following, which may be required in some cases.

sales tax on materials	5%	Vermont sales tax rate
lead paint abatement	$135	typical cost
total reglaze of sash	$25	assumes re-using glass
painting	Range from $25 to $50	
Storm window glass or other repair	Varies	
Contractor markup, OH & P	Range from 10% to 20%	
Total interior trim replacement	$25	
If no pulley cavity for all options except #1.	($22)	deduct if no window weight cavity
Additional adjustment of opening or trim	Varies	

[1] For added ~$50, available with "Poly-Paint" 10-yr warranty, but can not trim window to fit. Price is for 5'-2" height-for custom size of 5'-0" add $50.
[2] Note: price includes prepainted sash&frame, 10-yr warranty paint, 1/1
[3] Mark-up is applied to materials and to labor costs

Replacement Sash Costs		Sash Onl	with Channels	
Brosco single glass				
2-8*5-2 sash opening	6/6	$95.09	110.39	
	2/2	$99.00	114.3	(special order)
	1/1	$79.38	94.68	
	Side channels	$15.30		per pair
Brosco insulated glass	1/1	$106.43	121.73	
true divided lites	2/2, 6/66 not available			
Brosco energy panels				
low-e glass		$63.20		
Marvin Tilt-Pack, low-e	8/8			
insulated glass	6/6	$499.23		
2-8 x 5-2 sash opening	2/2	$395.53		
true divided lites	1/1	$221.33		
includes channels				

Interior spring-loaded storm			
Alternative Window Co.	$115.00	wholesale price	(retail $150)
low-e glass, add	$35.00	wholesale price	
1/3 hour estimated labor	$6.67		
TOTAL	$156.67		

Allied Window Co	197	contractor's price
Top fixed, bottom removeable	based on 10 or more windows, standard color	
Exterior storm, Model HOL	Low-E adds $40	

Harvey Tru-Channel Storms	69.5	wholesale price
low-e glass, add	17	wholesale price

Weathershield (price from Huttig)		single	double	low-e
3-0 x 5-0	6/6			
wood, primed	2/2			
with tilt-turn channels	1/1			

Magnetic interior storm window		
form Allied window	110	
U-channel at head	Low-E adds $40	
Vee-strip weatherstrip at sill		

6. ANALYSIS AND DISCUSSION

Estimated savings for first year energy costs show little variability between upgrade options when compared to the estimated energy costs of a typical window. The cost variability of upgrade options decreases significantly when lead abatement of original sash is included. Estimated first year savings are also of very small magnitude when compared with typical windows. It is therefore not worthwhile to base upgrade decisons solely or even primarily on energy considerations. Other non-energy considerations should play a greater role in deciding whether to upgrade or replace existing windows. Energy performance should be included as part of the decision making process, however. Life cycle costs of window upgrades should also be considered, including maintenance costs over time.

Visual examination of windows gave no clear indication of their leakage classification as tight, typical, or loose windows. However, the lack of an easy method of deducing air leakage rates for a window without resorting to fan pressurization was unimportant given the leaky nature of the majority of original condition windows field tested.

Fan pressurization data showed pulley-type windows allowed significantly larger rates of exterior air leakage than pin-type, illustrating the importance of reducing air infiltration through the rough opening. The significance of the exterior air contribution to a window's total heating load was revealed throughout the study, with exterior air accounting for a large percentage of the infiltrative thermal losses. Reducing exterior air infiltration should be a part of any window renovation, whether the renovation is an original sash upgrade or a replacement sash.

The inclusion of an exterior air component in window infiltrative thermal losses increased the estimated annual window energy costs for all upgrades, approximating actual thermal losses through a window and its surround more closely than thermal losses through the window sash alone. The contributing role of exterior air to the heat load of a tight window is more significant than to the heat load of a loose window as it represents a larger percentage of the overall infiltrative losses for a tight window. Any renovation will serve to reduce sash air leakage, thereby increasing the relative significance of exterior air infiltration unless steps are taken to simultaneously reduce exterior air infiltration.

6a.Infiltration Reduction in Windows Tested Pre- and Post-upgrade

A total of 26 windows at six sites were field tested prior to and after window renovations. Four of these original condition windows were of sufficient leakage to prevent maximum pressurization and were not considered. Of the remaining 22 windows, 17 retained the original storm after renovation or had no storm window when tested. The other five windows were fitted with interior storm windows. Average sash and extraneous leakage characteristics for the 17 windows with either the original storm window or no storm are listed by site in Table 20, with storm windows off or open. The same characteristics for the five interior storm windows are also listed, but with storms removed and in place.

Table 20: Averaged leakage characteristics of windows prior to and post renovation

Site ID	Window Upgrade	n	Pre-upgrade			Post-upgrade			ELA_{tot} % Dec
			$ELA_{s \times 19}$ (in^2)	$ELA_{ext \times 19}$ (in^2)	ELA_{tot} (in^2)	$ELA_{s \times 19}$ (in^2)	$ELA_{ext \times 19}$ (in^2)	ELA_{tot} (in^2)	
2	Bi-Glass System	3	2.75	0.57	3.32	0.71	0.33	1.04	70%
3	Replacement sash	2	1.07	0.70	1.77	0.32	0.24	0.56	70%
6*	Vinyl inserts replacement	3	3.42*	0.63*	4.05*	0.04	0.10	0.14	95%
7	Original Sash with vinyl jamb liners	9	2.18	0.55	2.63	0.81	0.32	1.13	60%
			Interior storm window removed			Interior storm window in place			
10	Spring loaded	1	4.05	0.20	4.25	0.25	0.19	0.44	90%
15	Magnetic stripping	4	1.42	1.67	3.09	0.01	0.23	0.24	90%

* Original windows at Site 6 were single-hung, partially accounting for this relatively large value. As a double-hung window, $ELA_{s \times 19}$ would have been 1.96 in^2, $ELA_{ext \times 19}$ would have equaled 0.36 in2, for an ELA_{tot} of 2.32 in^2.

All pre- and post-test windows retained the original sash with the exception of site 6. Upgrades at this site were vinyl replacement window inserts and were expected to perform significantly better than the original condition windows.

Interior storm windows show the greatest reduction in ELA_{tot} as discussed previously. Three of the four interior storm windows at site 15 allowed zero sash flow within the limits of resolution for the pressurization device flow meter, largely accounting for the significant reduction in $ELA_{s \times 19}$

There is a significant reduction in ELA_{tot} between windows in their original condition and any upgrade, at a confidence level of 99.9%. All relative percentages should be viewed with caution, due to the low number of samples in each population. The only site approaching a significant population number is site 7 with nine windows. The average reduction in ELA_{tot} for that site was 60%.

Extrapolated values for sash leakage rates were also compared, with upgrades again showing significant reductions at a 99.9% confidence level. Extrapolated values were used due to the leaky nature of the original windows.

3b. Improvements Due to Storm Window Upgrades

The use of exterior storm windows provided two energy benefits, significantly reducing sash

leakage when the storm frame was caulked to the exterior trim and providing a second layer of glazing. The storm window as a second glazing layer had a significant effect on reduction of non-infiltrative thermal loss rates during modeling with WINDOW 4.1.

A significant improvement was seen with the use of new aluminum triple track storm windows when frames were caulked to the exterior trim. Four prime windows showed a reduction of 75% in sash leakage when the new storms were closed, while another site with three year old storm windows showed a 35% reduction. It can be assumed the average value for sash leakage reduction is between those bounds. A comparison of 24 original condition windows with aluminum triple track storms in open and closed positions, showed a 46% reduction in sash leakage. It is likely that the use of new aluminum triple track storm windows with frames caulked would exceed original window condition sash leakage reduction, being closer to the 75% reduction seen with the use of new storm windows. Differences between new and old storm windows are largely in the quality of the weatherstripping surrounding the storm sash and the sash/frame fit, if frames for both are caulked to the exterior trim.

6c. Infiltrative versus Non-infiltrative Thermal Losses

Another factor to consider was the relative importance of infiltrative losses versus non-infiltrative losses. Whole window infiltrative thermal loss rates (L_{inf}) were compared to whole window non-infiltrative loss rates (L_u) for window upgrades to gain an understanding of their relative importance. Infiltrative loss rates averaged 16% of non-infiltrative loss rates with only two sites showing an infiltrative/non-infiltrative loss ratio greater than 18%, results supported by the literature (Klems, 1983).

The savings due to a reduction of non-infiltrative thermal loss rates realized by the use of double- versus single-glazed sash was investigated. Three original sash windows of varying leakage characteristics were chosen and annual costs modeled with both single- and double-glazing with a storm window in place. The loose window was based on the site 12 average heating season infiltration rate, the average window was based on the site 7 average, and the tight window was based on the site 19 average. Results were compared to those costs for assumed typical, tight, and loose windows and are shown in Table 21.

An additional benefit of double-glazed sash versus a single-glazing and storm window combination, arises from occupant behavior. During field testing, buildings were seen with a portion of storm windows open during the heating season, an obvious result of occupant behavior. Storm sash in the open position were effectively windows without storms, having greater thermal loss rates. The use of double-glazed sash would negate occupant behavior as no storm window is generally installed if the window is a replacement.

If a double-glazed sash were combined with a storm window (ie, triple-glazing), a larger portion of savings would arise from reduced non-infiltrative loss rates (U-values) due to the third glazing layer. Benefits of triple-glazing are somewhat reduced from what might be expected however, due to the gap distance between the prime and storm windows

Table 21: comparison of first year energy savings per window from double- versus single-glazed sash

Windows from Site:	Tighter Window		Average Window		Looser Window	
	Single-pane	Double-pane	Single-pane	Double-pane	Single-pane	Double-pane
13	***	***	***	***	$13.00	$13.50
7	$0.05	$0.50	$1.60	$2.10	$14.60	$15.10
19	$0.60	$1.10	$2.10	$2.60	$15.20	$15.60

(average 2.5 inches). A reduction in U-values occurs until the optimal gap distance of 0.75 inches is exceeded, after which point U-values exhibit a slow rise as gap distance increases. Triple-glazing was not investigated in this study but was shown to be effective in very cold climates (Flanders, 1982).

7.CONCLUSIONS

Over the course of the study, it became apparent that replacing an historic window does not necessarily result in greater energy savings than upgrading that same window. The decision to renovate or replace a window should not be based solely on energy considerations, as the differences in estimated first year savings between the upgrade options are small. Other factors to consider include life cycle costs, the historical significance of a window and its role in a building's character, occupant comfort, ease of operation, and life-cycle costing, none of which were subjects of this study.

The study addressed the following issues:

- estimate energy savings attributable to existing window retrofits,
- estimate first year savings in heating costs attributable to field tested window retrofits,
- estimate installation and materials costs for existing window retrofits, and
- compare the estimated costs and savings from existing window retrofits to those incurred by replacement windows.

Table 22 summarizes the results of the study by showing estimated purchase and installation costs for the various upgrades field tested as well as comparative savings to the assumed tight, typical, and loose windows. It should be noted again that savings are relative only to each other and do not reflect actual savings. This is due to the modified use of the LBL correlation model used in the study. The field tested window upgrades may be categorized into eight broad groups as follows:

1. retain the original sash using bronze (or plastic) V-strip weatherstripping;
2. retain the original sash utilizing vinyl jamb liners and silicone bulb weatherstripping;
3. retain the original sash by use of the Bi-Glass System upgrade;
5. retain the original sash utilizing new aluminum triple track storm windows;
5. retain the original sash utilizing interior storm windows;
6. single-glazed replacement sash utilizing vinyl jamb liners and silicone bulb weatherstripping;
7. double-glazed replacement sash utilizing vinyl jamb liners and silicone bulb weatherstripping; and
8. double-glazed replacement window insert.

Estimated installation and purchase costs are shown with and without costs associated with lead abatement. Lead abatement was assumed to cost $125. The purchase cost shown for single-glazed replacement sash with vinyl jamb liners is for in-kind replacement (two over two true divided lites). The other replacement sash are one over ones as encountered in the field.

It can be seen that bronze V-strip weatherstripping (category 1) compares favorably to the

Table 22: Estimated costs and first year energy savings of categorized upgrades

		Cost of window with lead abatement**:		First year energy savings per window as compared to assumed:		
	Upgrade category	excluded	included**	Tight window	Typical window	Loose window
Retain original sash	1	$76	$201	$0.60	$2.10	$15.20
	2	$175	$300	$0.05	$1.60	$14.60
	3	$225	$350	$0.80	$2.40	$15.40
	4	$70	$195	$1.00	$2.50	$15.50
	5	$115	$240	$1.30	$2.80	$15.90
Replacement sash	6	$214	---	$0.20	$1.70	$14.70
	7	$320	---	$0.70	$2.30	$15.30
	8	$500	---	$2.10	$3.60	$16.60

**Lead abatement cost assumed to be $125

other upgrade options while also being the least expensive option. However, due to the low sample population (two windows), no statistical significance may be associated with this observation. Bronze V-strip is visually unobtrusive as was noted several times during field research.

In-kind wood sash used as replacement sash can help retain the appearance of the building. Most windows tested during the study were two over twos, with in-kind replacements closely approximating the look of the original sash. One illustrative instance occurred when one face of a building containing six windows was being examined from the exterior. No difference was noted between any windows until inside, when two windows were discovered to be in-kind replacements.

Replacement window inserts may also retain the original appearance of a building while providing the additional benefit of reducing extraneous leakage, making the immediate window environment more comfortable for occupants. Actual window size is decreased when using window inserts due to the integral frame, modifying the building appearance somewhat.

The following points came to light during the course of the study.

- Exterior air infiltrating through the jamb from the rough opening had a significant contribution to the heat load of a window.
- Existing aluminum triple track or fixed panel aluminum storm windows reduced sash leakage by 45% on average.

- New aluminum triple track storm windows tested decreased sash leakage by 75% on average when the frame is caulked to the exterior trim.
- Interior storm windows significantly reduced both sash leakage and exterior air leakage, averaging reductions of approximately 95% and 80% respectively.
- A second glazing layer either from using a closed storm window or double-pane glass significantly reduced non-infiltrative losses.
- Pulley-type windows allowed significantly more exterior air leakage than pin-type windows.
- Original sash filled with vinyl jamb liners and silicone bulb weatherstripping show significantly reduced sash leakage rates over the original condition windows.
- In-kind replacement sash with vinyl jamb liners were effective when placed in a square jamb. Existing jambs utilizing this option should be checked for squareness.
- Replacement window inserts did not always reduce exterior air infiltration as expected, causing the window to perform poorly.
- Thermal performance of all options are subject to variation due to the quality of installation.

The study showed that window replacement will not necessarily reduce energy costs more than an upgrade utilizing the existing sash. The importance of the window frame/rough opening junction was noted throughout the study. An effective method of sealing this junction can greatly reduce the infiltrative thermal losses associated with any window renovation. Storm windows, either existing or replacements, were found to be effective in reducing both infiltrative and non-infiltrative losses. Many sash-retaining upgrades generally retain existing exterior storm windows, which may be left open by occupants. Consequently, options including double-glazed sash are likely to achieve more consistent energy savings than storm window options. Quantifying those differences was beyond the scope of this study.

Further research that would help quantify some of these issues include:

- validate and/or modify the method used to estimate the fraction of extraneous air leakage coming from the outside of the building;
- improve the sample size of the windows tested to achieve more statistically significant results;
- perform economic analyses of window upgrade options, including life cycle costing of installation, financing, maintenance and energy costs; and
- investigate triple-glazing and other upgrade strategies.

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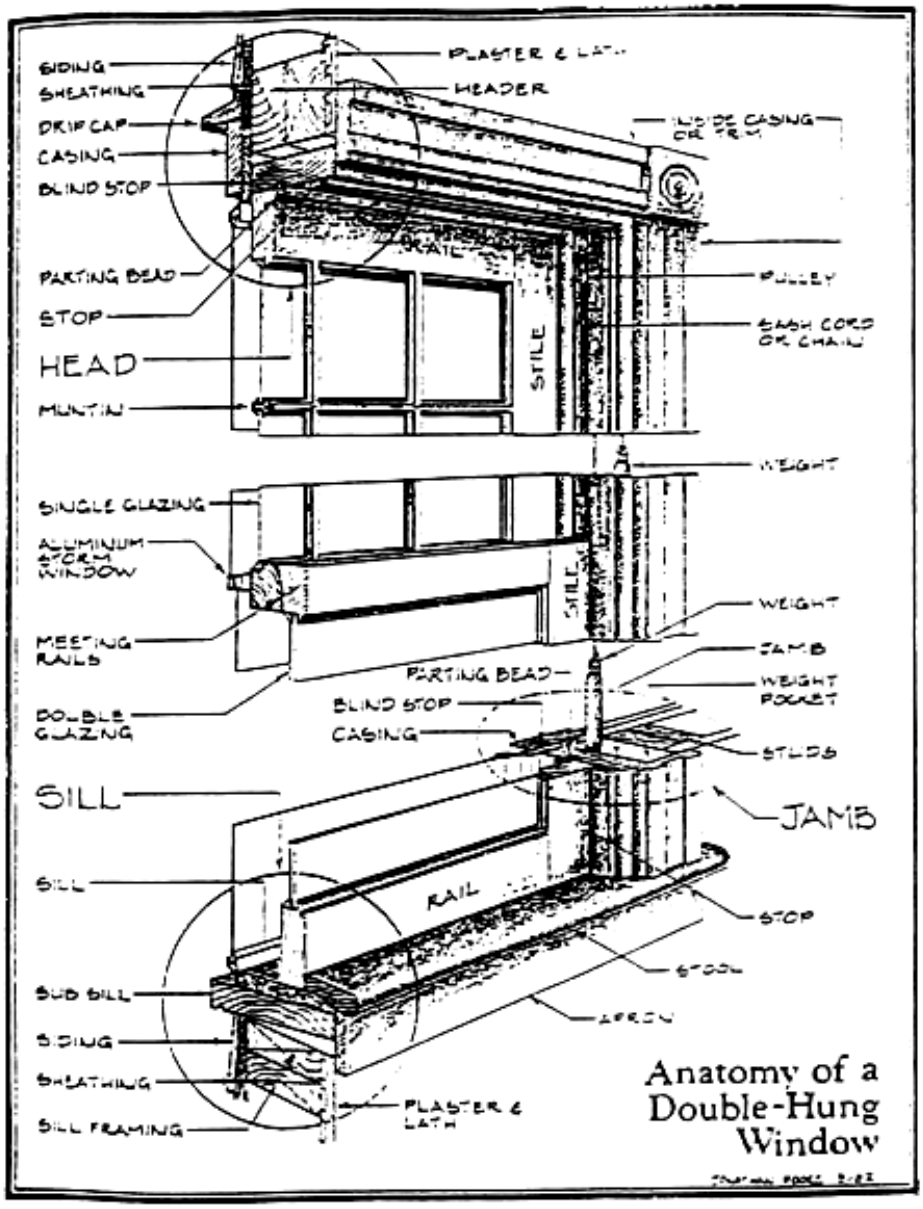
8. APPENDIX

8a.Anatomy of a Double-Hung Window



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8b. Flow and Regression Data for Field Tested Windows

8b i. Sash air leakage (Q_s)

	Storm Window Up or Off							Storm Window Down or On						
Window ID	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef
1 A		1.19	0.307	0.087	0.7109	0.9564	0.4607		0.92	0.196	0.056	0.5384	0.9404	0.5287
1B		2.91	0.519	0.147	1.7313	0.9842	0.5992		1.81	0.428	0.121	1.1723	0.9854	0.4961
1C		1.85	0.498	0.142	1.1103	0.9840	0.4394		1.17	0.286	0.081	0.7739	0.9585	0.5216
2A		3.51	0.496	0.141	2.0599	1.0000	0.6674		1.68	0.273	0.077	1.2654	0.9869	0.6201
2B		4.91	0.486	0.138	2.5401	0.9998	0.7887		1.09	0.184	0.053	0.8183	0.9162	0.6072
2C		3.41	0.551	0.156	1.9762	0.9997	0.6222		2.01	0.059	0.017	2.1494	0.9913	1.2039
2A2	0.38	0.39	0.089	0.026	-0.3466	0.8692	0.5002	0.18	0.27	0.044	0.013	-0.5850	0.7267	0.6136
2B2	0.25	0.25	0.056	0.016	-0.7631	0.7543	0.5118	0.06	0.09	0.051	0.014	-2.2793	0.1218	0.1694
2C2		0.80	0.244	0.070	0.2610	0.8794	0.4039	0.37	0.32	0.118	0.033	-0.7396	0.5091	0.3374
3A		2.13	0.350	0.099	1.4992	0.9939	0.6164							
3B		2.00	0.461	0.131	1.2938	0.9852	0.5003							
3C		1.22	0.246	0.070	0.8510	0.9708	0.5444		0.61	0.097	0.028	0.2630	0.8991	0.6276
3D		1.18	0.326	0.093	0.6966	0.8743	0.4397							
3E		0.98	0.138	0.039	0.7843	0.9856	0.6686							
3F		1.01	0.151	0.043	0.7893	0.9771	0.6493		0.60	0.091	0.026	0.2646	0.7466	0.6424
3G														
3H		3.22	0.477	0.136	1.9531	0.9267	0.6516		1.41	0.222	0.063	1.0991	0.9093	0.6298
3I		2.73	0.316	0.090	1.8895	0.9703	0.7353		1.65	0.367	0.104	1.1106	0.9710	0.5110
3A2														
3B2	0.45	0.43	0.127	0.037	-0.3479	0.8518	0.4144	0.40	0.40	0.157	0.044	-0.5546	0.7117	0.3140
3C2	0.12	0.09	0.077	0.022	-2.3620	0.0059	0.0483	0.23	0.16	0.049	0.014	-1.3150	0.3269	0.4082
3D2	0.11	0.10	0.034	0.010	-1.9017	0.5069	0.3576	0.11	0.10	0.034	0.010	-1.9017	0.5069	0.3576
3E2														
4A		2.36	0.151	0.043	1.9696	0.9898	0.9387		2.14	0.059	0.017	2.2310	0.9139	1.2222
4B														
4C		1.78	0.337	0.096	1.2569	0.9712	0.5673		1.33	0.084	0.024	1.4202	0.6843	0.9426
4D		0.95	0.201	0.057	0.5848	0.9167	0.5290		1.10	0.176	0.051	0.8384	0.8952	0.6226
4E									7.62	0.207	0.059	3.5123	1.0000	1.2306
5A								1.64	1.62	0.463	0.131	0.9979	0.9865	0.4279
5B	1.33	1.36	0.328	0.094	0.8879	0.9971	0.4840							
5C	0.56	0.67	0.164	0.046	0.1642	0.8873	0.4776	0.40	0.39	0.132	0.038	-0.5061	0.8806	0.3663
5D								0.06	0.05	0.019	0.005	-2.4498	0.6068	0.3548
5E														
5F								0.55	0.59	0.110	0.031	0.1643	0.9330	0.5751
5G		0.91	0.186	0.053	0.5586	0.9763	0.5419	0.00	0.80	0.133	0.038	0.5037	0.9856	0.6081
5H	0.49	0.47	0.111	0.031	-0.1554	0.9452	0.4954	0.45	0.37	0.122	0.034	-0.5431	0.7324	0.3775
6A **		5.94	1.35	0.38	2.3921	0.9994	0.5066							
6B **								0.62	0.51	0.25	0.07	-0.3890	0.4423	0.2437
6C **	1.76	1.76	0.40	0.11	1.1771	0.9456	0.5073							
6D **	1.14	1.29	0.17	0.05	1.0634	0.9032	0.6905							
6A2	0.05	0.05	0.004	0.001	-1.8141	0.9122	0.8550							
6B2	0.06	0.06	0.003	0.001	-1.5161	0.9170	0.9839							
6C2	0.16	0.23	0.003	0.001	0.2827	0.8786	1.4671							
6D2	0.15	0.15	0.016	0.004	-1.0032	0.9627	0.7601							
6E 2	0.36	0.26	0.034	0.010	-0.5375	0.9071	0.6867							
6F2	0.16	0.06	0.005	0.001	-1.7061	0.6208	0.8486							

Sash air leakage (Q_s) continued

Window ID	Storm Window Up or Off							Storm Window Down or On						
	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef
11 A	0.17	0.16	0.014	0.004	-0.7924	0.9208	0.8365							
11 B	0.02	0.04	0.011	0.003	-2.7665	0.3574	0.4252							
11 C	0.14	0.16	0.055	0.015	-1.3799	0.7569	0.3701							
11 D	0.13	0.11	0.085	0.024	-2.0996	0.1170	0.0896							
11 E	0.36	0.36	0.024	0.006	0.0931	0.9757	0.9332							
11 F	0.06	0.06	0.040	0.011	-2.5502	0.2263	0.1646							
12 A		1.98	0.769	0.218	1.0717	0.8445	0.3227		1.02	0.178	0.051	0.7444	0.9631	0.5982
12 B		0.30	0.082	0.023	-0.6426	0.4569	0.4519		0.28	0.065	0.018	-0.6826	0.6079	0.5014
12 C	0.37	0.33	0.100	0.029	-0.6003	0.9206	0.4106	0.37	0.31	0.094	0.027	-0.8676	0.9206	0.4106
12 D		0.15	0.037	0.011	-1.3264	0.8231	0.4781		0.13	0.044	0.013	-1.6486	0.2957	0.3579
12 E		0.76	0.297	0.085	0.1156	0.7724	0.3213		0.74	0.082	0.024	0.6035	0.9356	0.7523
12 F	0.34	0.44	0.017	0.005	0.4992	0.9082	1.1012	0.34	0.44	0.011	0.003	0.7483	0.8590	1.2813
12 G		3.00	0.390	0.111	1.9383	0.9955	0.6966		2.21	0.329	0.094	1.5730	0.9874	0.6490
12 H		2.10	0.585	0.167	1.2834	0.9895	0.4352		0.69	0.095	0.027	0.4481	0.8661	0.6784
12 I		2.53	0.703	0.200	1.4541	0.9996	0.4368		0.86	0.312	0.088	0.2745	0.8229	0.3482
12 J														
13 A		1.54	0.400	0.114	0.9878	0.9425	0.4606		0.58	0.176	0.051	-0.0669	0.7900	0.4027
13 B		1.22	0.490	0.138	0.5722	0.9390	0.3135		0.73	0.161	0.046	0.2988	0.7637	0.5131
13 C		1.83	0.557	0.158	1.0962	1.0000	0.4065		1.66	0.088	0.025	1.7111	1.0000	1.0000
13 D		1.25	0.480	0.137	0.6162	0.8372	0.3264		0.89	0.371	0.105	0.2424	0.5627	0.2981
13 E		1.82	0.563	0.160	1.0792	0.9757	0.4000		1.31	0.394	0.112	0.7619	0.9751	0.4095
13 F		0.67	0.291	0.083	-0.0646	0.3062	0.2830		0.45	0.112	0.031	-0.2312	0.9133	0.4744
13 G		1.08	0.317	0.090	0.5707	0.7640	0.4155		0.74	0.275	0.079	0.1120	0.5868	0.3385
13 H		1.78	0.211	0.060	1.4457	0.9932	0.7263		1.02	0.165	0.047	0.7654	0.9139	0.6206
13 I		1.08	0.354	0.101	0.5312	0.9130	0.3795		0.65	0.265	0.075	-0.0765	0.7344	0.3032
13 J	0.28	0.26	0.067	0.019	-0.7803	0.8136	0.4674	0.23	0.17	0.027	0.008	-0.9569	0.7436	0.6455
14 A	0.79	0.84	0.166	0.047	0.4830	0.8934	0.5512	0.17	0.26	0.002	0.001	0.6116	0.7771	1.6306
14 B		1.74	0.553	0.157	1.0297	0.8668	0.3922	0.28	0.25	0.053	0.015	-0.7808	0.8531	0.5243
14 C		1.37	0.321	0.091	0.9064	0.9885	0.4939	0.33	0.37	0.077	0.022	-0.3488	0.8197	0.5344
14 D	0.56	0.67	0.099	0.028	0.3812	0.8838	0.6507	0.17	0.18	0.018	0.005	-0.7721	0.8936	0.7878
14 E	1.12	1.04	0.542	0.154	0.3167	0.9600	0.2244	0.03	0.06	0.062	0.017	-2.6487	0.0010	0.0304
14 F		1.18	0.492	0.140	0.5286	0.9889	0.2994	0.02	0.02	0.077	0.022	-4.4737	0.6440	-0.4630
15 A 1									2.11	0.113	0.032	1.9513	1.0000	1.0000
15 A 2														
15 B 1		2.16	0.330	0.094	1.5449	0.9956	0.6412		0.36	0.351	0.100	-1.0483		0.0000
15 B 2								0.01	0.01	0.008	0.002	-4.9564	1.0000	-0.0000
15 C 1														
15 C 2														
15 D 1								0.70	0.25	0.070	0.007	1.0733	0.3569	0.0300
15 D 2														
16 A								0.00	0.52	0.213	0.060	-0.3007	1.0000	0.3018
16 B								0.00	0.01	0.597	0.170	-6.1286	1.0000	-1.3569
16 C														
16 D														
16 E														
16 F					0.0733									
16 G		0.55	0.054	0.015	0.3624	1.0000	0.7937							
17 A	0.09	0.09	0.087	0.025	-2.4419		0.0000	0.09	0.09	0.087	0.025	-2.4419		0.0000
17 B	0.17	0.20	0.045	0.013	-0.9981	0.5887	0.5104	0.09	0.12	0.029	0.009	-1.5635	0.7429	0.4752
17 C	0.26	0.24	0.132	0.038	-1.2320	0.2568	0.1920	0.09	0.13	0.049	0.014	-1.6114	0.4717	0.3356
18 A	0.33	0.32	0.026	0.008	-0.1134	0.9835	0.8571							
18 B	0.11	0.09	0.014	0.004	-1.6243	0.9208	0.6412							
19 A	0.39	0.41	0.090	0.026	-0.2587	0.8700	0.5183	0.28	0.30	0.070	0.020	-0.6209	0.7986	0.4923
19 B	0.49	0.57	0.109	0.031	0.1214	0.8937	0.5653	0.33	0.40	0.088	0.025	-0.2964	0.8843	0.5154

Sash air leakage (Q_s) continued

Window ID	Storm Window Up or Off							Storm Window Down or On						
	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef
7A		0.95	0.061	0.017	1.0780	0.9539	0.9377		0.97	0.008	0.002	1.9446	0.6459	0.6464
7B		0.88	0.609	0.173	0.0189	0.2920	0.1247							
7C									4.40	0.112	0.032	2.9678	0.9771	1.2518
7D		0.80	0.204	0.058	0.3307	0.9360	0.4641							
7E		1.92	0.572	0.162	1.1494	0.9748	0.4131							
7F		1.26	0.509	0.144	0.6059	0.9055	0.3101							
7G														
7H		2.14	0.484	0.138	1.3706	0.9895	0.5066							
7I		1.00	0.218	0.062	0.6292	0.9793	0.5205		0.70	0.144	0.041	0.2920	0.7430	0.5390
7J		0.20	0.333	0.095	-1.8151	0.1921	-0.1730							
7K		4.06	0.636	0.181	2.1690	1.0000	0.6339							
7L														
7 A 2		0.48	0.111	0.031	-0.1066	0.9792	0.5057							
7 B 2		2.00	0.315	0.089	1.4499	0.8666	0.6295		1.32	0.226	0.065	1.0029	0.8662	0.6025
7 C 2	0.43	0.47	0.129	0.037	-0.2156	0.8030	0.4437							
7 D 2		1.61	0.386	0.110	1.0683	0.9986	0.4882							
7 E 2	0.24	0.27	0.023	0.006	-0.3014	0.8412	0.8414							
7 F 2		1.25	0.374	0.107	0.7126	0.9904	0.4102							
7 G 2	0.19	0.19	0.054	0.015	-1.1503	0.8176	0.4291							
7 H 2	0.51	0.57	0.076	0.022	0.2645	0.7120	0.6855							
7 I 2	0.77	0.75	0.145	0.042	0.3957	0.9191	0.5614							
7 J 2	1.07	1.09	0.220	0.062	0.7416	0.9282	0.5454							
7 K 2	0.80	0.85	0.127	0.037	0.6176	0.9425	0.6476							
7 L 2	1.07	1.11	0.152	0.043	0.9246	0.9497	0.6790							
7 M 2	0.90	0.93	0.245	0.070	0.4724	0.9274	0.4536							
7 N 2	0.58	0.56	0.101	0.029	0.1255	0.8453	0.5853							
7 O 2		0.62	0.128	0.037	0.1753	0.8720	0.5387							
7 P 2	1.04	1.04	0.221	0.062	0.6765	0.9758	0.5289							
7 Q 2		0.22	0.109	0.031	-1.2552	0.2597	0.2339							
7 R 2	0.42	0.38	0.061	0.023	-0.3540	0.8162	0.5219							
7 S 2		0.36	0.069	0.019	-0.3556	0.9570	0.5608							
7 T 2	0.05	0.05	0.003	0.001	-1.6521	0.5294	1.0120							
8A		1.75	0.492	0.140	1.0800	0.9917	0.4327							
8B		2.12	0.338	0.096	1.5056	0.7825	0.6268							
8C		3.63	0.861	0.244	1.8786	0.9985	0.4906							
8D								0.05	0.06	0.017	0.004	-2.1401	0.4307	0.4720
8E								0.17	0.17	0.024	0.006	-0.9557	0.5629	0.6788
8F								0.05	0.05	0.056	0.016	-2.8883		
9A		2.38	0.521	0.148	1.4921	0.9927	0.5186		1.46	0.222	0.063	1.1571	0.9889	0.6450
9B		1.98	0.376	0.107	1.3639	0.9905	0.5665		1.59	0.247	0.070	1.2313	0.9818	0.6353
9C		2.80	0.845	0.240	1.5217	1.0000	0.4068							
9D		1.09	0.281	0.080	0.6434	0.9587	0.4630		0.83	0.310	0.088	0.2142	0.9429	0.3350
9E	0.52	0.54	0.097	0.028	0.0764	0.9337	0.5819							
9F		2.46	0.824	0.235	1.3540	1.0000	0.3740		1.47	0.072	0.020	1.6216	0.7065	1.0238
10A1	1.03	1.10	0.751	0.213	0.2514	0.8373	0.1300							
10A2								0.05	0.05	0.046	0.013	-2.7265	0.3078	0.0863
10B1	1.82	1.80	0.833	0.237	0.8994	0.9916	0.2619							
10B2								0.84	0.93	0.111	0.031	0.7920	0.9610	0.7228
10C1	1.03	1.10	0.748	0.213	0.2475	0.8373	0.1300							
10C2								0.46	0.48	0.122	0.034	-0.1442	0.9127	0.4754
10D 1		2.64	0.457	0.130	1.6903	1.0000	0.5978		1.62	0.194	0.055	1.3582	0.9390	0.7253
10D 2	0.10	0.10	0.054	0.015	-2.0768	0.1632	0.2052	0.19	0.18	0.071	0.020	-1.3101	0.4966	0.3232

8b ii. Extraneous air leakage (Qe)

	Storm Window Up or Off							Storm Window Down or On						
	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef
1 A		1.27	0.159	0.046	1.0857	0.9921	0.7060		1.25	0.168	0.048	1.0517	0.9913	0.6882
1B		0.66	0.072	0.020	0.4890	0.9926	0.7609		0.67	0.176	0.021	0.5036	0.9898	0.7621
1C		1.15	0.130	0.076	1.0195	0.9930	0.7412		1.18	0.136	0.039	1.0484	0.9915	0.7424
2A		1.97	0.306	0.087	1.4430	0.9972	0.6360		2.00	0.352	0.100	1.4077	0.9978	0.5928
2B		2.13	0.330	0.094	1.5188	0.9835	0.6353		2.15	0.322	0.091	1.5497	0.9869	0.6486
2C		2.46	0.424	0.121	1.6231	0.9970	0.6003		2.54	0.441	0.126	1.6494	0.9945	0.5966
2A2	1.37	1.33	0.152	0.043	1.1841	0.9966	0.7429	1.37	1.33	0.151	0.043	1.1893	0.9966	0.7457
2B2	1.72	1.74	0.244	0.069	1.3629	0.9963	0.6706	1.72	1.76	0.241	0.069	1.3881	0.9940	0.6797
2C2	1.90	2.03	0.209	0.059	1.6434	0.9818	0.7768	1.90	2.02	0.212	0.060	1.6305	0.9833	0.7690
3A		2.71	0.406	0.115	1.7755	0.9649	0.6477							
3B	1.52	1.71	0.111	0.031	1.6620	0.9808	0.9336							
3C	1.78	1.79	0.289	0.082	1.3251	0.9980	0.6205	1.83	1.85	0.329	0.094	1.3273	0.9982	0.5900
3D		2.81	0.550	0.156	1.7023	0.9976	0.5564							
3E	1.93	1.93	0.355	0.101	1.3516	0.9978	0.5769							
3F	2.15	2.13	0.577	0.164	1.2923	0.9978	0.4455	2.15	2.12	0.526	0.150	1.3270	0.9981	0.4763
3G	1.55	1.59	0.197	0.056	1.3211	0.9937	0.7121							
3H		3.03	0.463	0.131	1.8839	0.9948	0.6420		3.03	0.463	0.131	1.8839	0.9948	0.6420
3I		3.64	0.624	0.178	2.0168	0.9965	0.6018		3.52	0.590	0.168	1.9937	0.9985	0.6098
3A2	1.15	1.19	0.136	0.039	1.0782	0.9975	0.7445	1.15	1.21	0.135	0.038	1.0827	0.9977	0.7476
3B2	1.02	1.10	0.127	0.036	0.9812	0.9957	0.7374	1.02	1.10	0.131	0.038	0.9659	0.9961	0.7247
3C2	1.19	1.31	0.151	0.043	1.1661	0.9892	0.7395	1.19	1.32	0.148	0.042	1.1736	0.9866	0.7447
3D2	1.27	1.31	0.182	0.052	1.0832	0.9969	0.6746	1.27	1.31	0.185	0.053	1.0723	0.9972	0.6679
3E2														
4A	1.88	1.85	0.480	0.137	1.1725	0.9973	0.4612	1.88	1.81	0.493	0.140	1.1237	0.9818	0.4429
4B		3.76	0.767	0.218	1.9734	0.9759	0.5412		4.11	0.723	0.206	2.1286	0.9978	0.5931
4C	2.45	2.40	0.386	0.110	1.6288	0.9966	0.6240	2.52	2.44	0.392	0.111	1.6473	0.9956	0.6251
4D		3.13	0.415	0.118	1.9716	0.9939	0.6892		3.07	0.463	0.131	1.8974	0.9923	0.6450
4E		3.87	0.807	0.229	1.9968	0.9688	0.5347		4.18	0.756	0.215	2.1302	0.9677	0.5827
5A								0.44	0.43	0.061	0.017	-0.0460	0.9922	0.6629
5B	0.52	0.53	0.081	0.023	0.1207	0.9987	0.6378							
5C	0.84	0.84	0.140	0.040	0.5679	0.9878	0.6121	0.96	1.00	0.141	0.040	0.8121	0.9954	0.6701
5D								0.23	0.24	0.036	0.010	-0.6697	0.9986	0.6486
5E								0.09	0.09	0.016	0.004	-1.8554	0.9525	0.5433
5F								1.15	1.16	0.179	0.051	0.9223	0.9937	0.6389
5G	1.89	1.86	0.330	0.094	1.3292	0.9963	0.5890	1.85	1.83	0.334	0.095	1.3010	0.9962	0.5798
5H	1.55	1.56	0.224	0.063	1.2464	0.9975	0.6629	1.50	1.58	0.197	0.056	1.3139	0.9912	0.7110
6A **		3.96	0.60	0.17	2.1473	0.9985	0.6410							
6B **								2.83	3.13	0.27	0.08	2.1537	0.9780	0.8413
6C **	2.50	2.56	0.30	0.09	1.8165	0.9951	0.7292							
6D **	2.39	2.49	0.23	0.07	1.8792	0.9976	0.8049							
6A2	0.84	0.87	0.105	0.030	0.7256	0.9942	0.7194							
6B2	0.29	0.29	0.030	0.009	-0.3188	0.9856	0.7683							
6C2	0.34	0.34	0.054	0.015	-0.3061	0.9943	0.6345							
6D2	0.33	0.33	0.041	0.012	-0.2502	0.9803	0.7103							
6E 2	0.33	0.32	0.046	0.013	-0.3236	0.9927	0.6652							
6F2	0.52	0.51	0.091	0.026	0.0122	0.9560	0.5805							

Extraneous air leakage (Q_e) continued

	Storm Window Up or Off							Storm Window Down or On						
	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef
7A	1.69	1.67	0.265	0.075	1.2717	0.9899	0.6294	1.69	1.67	0.293	0.083	1.2226	0.9945	0.5929
7B		2.21	0.396	0.113	1.4961	0.9925	0.5863							
7C									1.67	0.298	0.085	1.2221	0.9848	0.5885
7D		3.01	0.513	0.146	1.8274	0.9994	0.6033							
7E	1.58	1.61	0.253	0.072	1.2426	0.9976	0.6325							
7F	1.78	1.84	0.244	0.070	1.4403	0.9923	0.6891							
7G		2.12	0.414	0.117	1.4224	0.9965	0.5574							
7H	1.83	1.85	0.298	0.085	1.3690	0.9940	0.6234							
7I		2.18	0.383	0.109	1.4972	0.9943	0.5940		2.29	0.392	0.112	1.5526	0.9900	0.6019
7J		3.48	0.577	0.164	1.9832	0.9901	0.6127							
7K	1.58	1.61	0.238	0.068	1.2683	0.9868	0.6535							
7L	1.38	1.40	0.161	0.046	1.2255	0.9923	0.7375							
7 A 2	1.53	1.59	0.200	0.057	1.3163	0.9920	0.7067							
7 B 2		2.28	0.312	0.089	1.6265	0.9953	0.6746		2.26	0.312	0.089	1.6265	0.9953	0.6746
7 C 2	0.85	0.85	0.057	0.016	0.9516	0.9978	0.9249							
7 D 2	0.46	0.46	0.042	0.012	0.2270	0.9953	0.8216							
7 E 2	1.42	1.46	0.222	0.063	1.1556	0.9919	0.6433							
7 F 2	0.95	0.99	0.108	0.031	0.9065	0.9880	0.7574							
7 G 2	0.90	0.95	0.072	0.020	1.0035	0.9935	0.8797							
7 H 2	1.02	1.04	0.112	0.031	0.9632	0.9869	0.7635							
7 I 2	1.08	1.10	0.135	0.039	0.9511	0.9834	0.7142							
7 J 2	0.97	1.00	0.124	0.036	0.8600	0.9904	0.7136							
7 K 2	1.07	1.10	0.118	0.033	1.0024	0.9965	0.7579							
7 L 2	0.90	0.93	0.121	0.034	0.7547	0.9926	0.6939							
7 M 2	1.05	1.08	0.136	0.039	0.9248	0.9987	0.7077							
7 N 2	1.26	0.00	0.173	0.049	1.1022	0.9930	0.6903							
7 O 2	1.62	1.69	0.212	0.060	1.3774	0.9857	0.7082							
7 P 2	1.04	1.05	0.119	0.033	0.9556	0.9963	0.7457							
7 Q 2	2.09	2.12	0.324	0.093	1.5198	0.9940	0.6403							
7 R 2	1.19	1.28	0.156	0.044	1.1153	0.9900	0.7191							
7 S 2	1.61	1.66	0.250	0.071	1.2798	0.9904	0.6455							
7 T 2	0.75	0.73	0.073	0.020	0.6358	0.9980	0.7871							
8A	1.46	1.51	0.230	0.066	1.1803	0.9975	0.6401							
8B	2.06	2.04	0.336	0.096	1.4600	0.9942	0.6168							
8C	1.35	1.40	0.198	0.056	1.1435	0.9972	0.6688							
8D								1.33	1.40	0.168	0.047	1.2031	0.9939	0.7221
8E								1.61	1.65	0.179	0.051	1.4105	0.9941	0.7577
8F								1.39	1.45	0.199	0.057	1.1859	0.9951	0.6771
9A	0.57	0.56	0.054	0.015	0.3886	0.9978	0.8007	0.62	0.62	0.042	0.012	0.6301	0.9928	0.9176
9B	0.94	1.01	0.087	0.025	1.0106	0.9957	0.8330	1.09	1.14	0.091	0.026	1.1760	0.9916	0.8641
9C		2.23	0.305	0.086	1.6215	0.9981	0.6800							
9D	1.67	1.72	0.236	0.067	1.3639	0.9930	0.6798	1.71	1.76	0.241	0.069	1.3863	0.9890	0.6795
9E	1.30	1.37	0.158	0.045	1.1993	0.9884	0.7354							
9F		2.72	0.473	0.135	1.7215	0.9940	0.5972		2.72	0.473	0.135	1.7215	0.9940	0.5972
10A1	0.81	0.77	0.125	0.036	0.4836	0.9960	0.6194							
10A2								0.36	0.33	0.087	0.025	-0.5333	0.9920	0.4622
10B1	0.19	0.18	0.031	0.009	-0.9695	0.9872	0.6029							
10B2								0.19	0.18	0.031	0.009	-0.9747	0.9743	0.6046
10C1	0.80	0.78	0.125	0.036	0.4797	0.9960	0.6194							
10C2								0.86	0.85	0.133	0.038	0.5954	0.9980	0.6302
10D 1		2.26	0.466	0.132	1.4655	0.9960	0.5388	0.00	2.25	0.396	0.113	1.5237	0.9961	0.5925
10D 2	1.54	1.55	0.260	0.074	1.1731	0.9974	0.6095	1.54	1.55	0.260	0.074	1.1731	0.9974	0.6095

Extraneous air leakage (Q_e) continued

	Storm Window Up or Off							Storm Window Down or On						
	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef	Actual Q_0.30	Reg Q_0.30	Reg Q_0.016	ELA	Constant	R^2	X coef
11 A	0.48	0.52	0.044	0.013	0.3375	0.9872	0.8341							
11 B	0.41	0.41	0.061	0.017	-0.1188	0.9969	0.6472							
11 C	0.28	0.28	0.037	0.011	-0.4389	0.9846	0.6957							
11 D	0.42	0.45	0.043	0.012	0.1822	0.9855	0.8040							
11 E	0.54	0.54	0.075	0.022	0.1809	0.9960	0.6698							
11 F	0.33	0.33	0.038	0.011	-0.2132	0.9967	0.7388							
12 A	2.26	2.27	0.362	0.103	1.5757	0.9913	0.6269	2.26	2.30	0.373	0.107	1.5832	0.9943	0.6213
12 B	2.32	2.32	0.315	0.089	1.6806	0.9981	0.6853	2.32	2.34	0.314	0.089	1.6738	0.9976	0.6846
12 C	1.75	1.82	0.192	0.055	1.5231	0.9965	0.7684	1.75	1.82	0.192	0.055	1.5206	0.9966	0.7671
12 D	2.26	2.39	0.242	0.069	1.8093	0.9924	0.7806	2.26	2.38	0.243	0.069	1.8039	0.9932	0.7777
12 E		2.56	0.282	0.080	1.8482	0.9898	0.7534		2.55	0.284	0.081	1.8394	0.9910	0.7487
12 F	1.27	1.33	0.117	0.033	1.2903	0.9966	0.8298	1.27	1.33	0.117	0.033	1.2903	0.9966	0.8298
12 G	1.27	1.37	0.136	0.039	1.2571	0.9925	0.7877	1.27	1.36	0.137	0.039	1.2521	0.9917	0.7850
12 H	2.20	2.26	0.322	0.091	1.6156	0.9914	0.6651	2.20	2.26	0.322	0.091	1.6156	0.9914	0.6651
12 I		2.49	0.311	0.088	1.7670	0.9978	0.7097		2.49	0.311	0.088	1.7670	0.9978	0.7097
12 J		5.65	0.905	0.257	2.4850	0.9993	0.6251		5.65	0.905	0.257	2.4850	0.9993	0.6251
13 A	1.98	2.00	0.337	0.096	1.4234	0.9914	0.6072	1.98	2.00	0.337	0.096	1.4234	0.9914	0.6072
13 B	1.90	1.97	0.242	0.069	1.5404	0.9890	0.7152	1.90	1.97	0.242	0.069	1.5404	0.9890	0.7152
13 C		3.48	0.659	0.187	1.9308	0.9977	0.5678		3.48	0.659	0.187	1.9308	0.9977	0.5678
13 D		2.18	0.302	0.086	1.5903	0.9918	0.6738		2.18	0.302	0.086	1.5903	0.9918	0.6738
13 E	1.22	1.32	0.121	0.034	1.2637	0.9925	0.8176		1.32	0.121	0.034	1.2637	0.9925	0.8176
13 F		2.46	0.428	0.122	1.6216	0.9936	0.5974		2.46	0.428	0.122	1.6216	0.9936	0.5974
13 G	2.17	2.23	0.328	0.094	1.5899	0.9900	0.6539		2.23	0.328	0.094	1.5899	0.9900	0.6539
13 H		2.44	0.341	0.097	1.7049	0.9989	0.6728		2.44	0.341	0.097	1.7049	0.9989	0.6728
13 I		2.29	0.348	0.099	1.6066	0.9936	0.6442		2.29	0.348	0.099	1.6066	0.9936	0.6442
13 J	1.76	1.89	0.208	0.059	1.5433	0.9790	0.7534		1.89	0.208	0.059	1.5433	0.9790	0.7534
14 A	0.96	0.99	0.102	0.029	0.9216	0.9935	0.7749	0.96	0.99	0.102	0.029	0.9216	0.9935	0.7749
14 B	1.41	1.48	0.202	0.057	1.2116	0.9901	0.6794	1.41	1.48	0.202	0.057	1.2116	0.9901	0.6794
14 C	1.35	1.39	0.140	0.040	1.2706	0.9974	0.7828	1.35	1.39	0.140	0.040	1.2706	0.9974	0.7828
14 D	0.85	0.82	0.099	0.028	0.6612	0.9950	0.7200	0.85	0.82	0.099	0.028	0.6612	0.9950	0.7200
14 E	1.12	1.16	0.126	0.036	1.0674	0.9968	0.7601	0.54	0.51	0.081	0.023	0.0583	0.9831	0.6226
14 F	1.05	1.09	0.089	0.026	1.1159	0.9954	0.8539	0.40	0.41	0.069	0.019	-0.1803	0.9960	0.6018
15 A 1		4.98	1.117	0.317	2.2213	0.9969	0.5104		4.98	1.117	0.317	2.2213	0.9969	0.5104
15 A 2								0.31	0.32	0.135	0.039	-0.7846	0.9833	0.2954
15 B 1		3.84	0.712	0.202	2.0399	0.9931	0.5754		3.84	0.712	0.202	2.0399	0.9931	0.5754
15 B 2								0.34	0.36	0.145	0.041	-0.6823	0.9693	0.3017
15 C 1		5.44	1.228	0.349	2.3056	1.0000	0.5080		4.98	1.117	0.317	2.2213	0.9969	0.5104
15 C 2								0.42	0.41	0.245	0.070	-0.6771	0.9787	0.1756
15 D 1		5.22	1.059	0.301	2.3074	0.9993	0.5440		3.84	0.712	0.202	2.0399	0.9931	0.5754
15 D 2								0.26	0.26	0.085	0.025	-0.8961	0.9916	0.3785
16 A		4.45	0.616	0.175	2.3079	1.0000	0.6753		4.45	0.616	0.175	2.3079	1.0000	0.6753
16 B		4.19	0.804	0.228	2.1103	1.0000	0.5632		4.19	0.804	0.228	2.1103	1.0000	0.5632
16 C		4.15	0.839	0.239	2.0813	1.0000	0.5456		4.15	0.839	0.239	2.0813	1.0000	0.5456
16 D		4.14	0.795	0.226	2.0991	1.0000	0.5632		4.14	0.795	0.226	2.0991	1.0000	0.5632
16 E		6.41	0.918	0.260	2.6574	0.9980	0.6634							
16 F		4.56	0.915	0.260	2.1769	0.9998	0.5479							
16 G		4.53	0.636	0.181	2.3176	0.9951	0.6701							
17 A	2.35	2.37	0.409	0.116	1.5843	0.9930	0.5995	2.35	2.37	0.409	0.116	1.5843	0.9930	0.5995
17 B	1.90	1.98	0.268	0.076	1.5061	0.9969	0.6827	1.90	1.98	0.268	0.076	1.5061	0.9969	0.6827
17 C	2.40	2.44	0.441	0.126	1.5932	0.9920	0.5833	2.40	2.44	0.441	0.126	1.5932	0.9920	0.5833
18 A	0.54	0.53	0.071	0.020	0.1907	0.9963	0.6860							
18 B	0.58	0.55	0.086	0.025	0.1766	0.9914	0.6372							
19 A	1.27	1.31	0.155	0.044	1.1506	0.9911	0.7288	1.27	1.31	0.155	0.044	1.1506	0.9911	0.7288
19 B	0.77	0.73	0.055	0.016	0.7535	0.9936	0.8835	0.77	0.73	0.055	0.016	0.7535	0.9936	0.8835

8b iii. Total air leakage (Q_t)

	Storm Window Up or Off							Storm Window Down or On						
	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef
1 A		2.47	0.455	0.129	1.5837	0.9948	0.5765		2.17	0.359	0.102	1.5100	0.9950	0.6140
1B		3.51	0.569	0.162	1.9677	0.9930	0.6259		2.40	0.473	0.135	1.5370	0.9936	0.5574
1C		2.89	0.714	0.203	1.6442	0.8773	0.4899		2.34	0.406	0.116	1.5732	0.9917	0.6051
2A		4.94	0.935	0.266	2.2805	0.9830	0.5678		3.68	0.624	0.178	2.0328	0.9993	0.6054
2B		6.83	0.822	0.234	2.7923	0.9913	0.7226		3.34	0.499	0.142	1.9856	0.9970	0.6482
2C		5.96	0.968	0.275	2.5319	0.9981	0.6201		4.24	0.475	0.135	2.3438	0.9995	0.7471
2A2	1.73	1.72	0.238	0.068	1.3551	0.9915	0.6752	1.55	1.62	0.193	0.055	1.3581	0.9894	0.7262
2B2	1.97	2.00	0.300	0.085	1.4715	0.9960	0.6468	1.79	1.82	0.281	0.080	1.3618	0.9956	0.6364
2C2		2.83	0.437	0.124	1.8056	0.9969	0.6371	2.27	2.30	0.327	0.093	1.6376	0.9935	0.6662
3A		4.98	0.744	0.211	2.3867	0.9698	0.6488							
3B		3.96	0.522	0.148	2.2082	0.9979	0.6913							
3C		3.00	0.534	0.152	1.8101	0.9933	0.5898		2.50	0.421	0.119	1.6438	0.9969	0.6066
3D		3.80	0.897	0.255	0.2589	0.9884	0.4925							
3E		2.87	0.498	0.142	1.7763	0.9954	0.5979							
3F		3.09	0.727	0.207	1.7228	0.9991	0.4937		2.71	0.622	0.176	1.6040	0.9939	0.5027
3G														
3H		6.39	0.931	0.265	2.6454	0.9836	0.6571		4.45	0.684	0.195	2.2616	0.9909	0.6385
3I		6.17	0.953	0.271	2.5861	0.9983	0.6370		5.12	0.957	0.272	2.3220	0.9999	0.5722
3A2	1.15	1.19	0.137	0.039	1.0696	0.9977	0.7400	1.15	1.19	0.135	0.039	1.0787	0.9971	0.7462
3B2	1.48	1.52	0.245	0.070	1.1675	0.9876	0.6220	1.42	1.48	0.271	0.077	1.0938	0.9869	0.5803
3C2	1.31	1.40	0.212	0.060	1.1119	0.9803	0.6439	1.42	1.47	0.203	0.058	1.2054	0.9873	0.6762
3D2	1.39	1.41	0.213	0.060	1.1192	0.9952	0.6446	1.39	1.41	0.216	0.061	1.1099	0.9952	0.6388
3E2	1.60	1.67	0.251	0.071	1.2935	0.9929	0.6472							
4A		3.80	0.624	0.178	2.0760	0.9914	0.6162		3.25	0.535	0.152	1.9207	0.9592	0.6160
4B														
4C		3.95	0.748	0.213	2.0578	0.9977	0.5678		3.53	0.514	0.146	2.0514	0.9652	0.6566
4D		4.19	0.604	0.172	2.2274	0.9910	0.6605		4.18	0.639	0.182	2.1995	0.9989	0.6400
4E									7.82	1.012	0.287	2.8984	1.0000	0.6982
5A								2.08	2.04	0.520	0.147	1.2777	0.9938	0.4672
5B	1.85	1.88	0.407	0.115	1.2592	0.9989	0.5221							
5C	1.40	1.52	0.301	0.085	1.0802	0.9824	0.5517	1.35	1.39	0.266	0.075	1.0062	0.9949	0.5638
5D								0.30	0.29	0.057	0.016	-0.5878	0.9907	0.5518
5E								0.09	0.09	0.016	0.004	-1.8554	0.9525	0.5433
5F								1.71	1.75	0.289	0.082	1.3050	0.9924	0.6157
5G		2.70	0.527	0.150	1.6625	0.9996	0.5568		2.60	0.471	0.133	1.6605	0.9976	0.5837
5H	2.04	2.03	0.335	0.095	1.4487	0.9982	0.6152	1.95	1.92	0.321	0.091	1.3861	0.9958	0.6106
6A **		10.09	1.91	0.54	2.9948	0.9996	0.5673							
6B **								3.46	3.53	0.48	0.14	2.0770	0.9895	0.6777
6C **	4.26	4.30	0.69	0.20	2.2128	0.9931	0.6250							
6D **	3.53	3.78	0.40	0.12	2.2458	0.9821	0.7619							
6A2	0.89	0.93	0.110	0.031	0.8002	0.9944	0.7268							
6B2	0.36	0.36	0.033	0.010	-0.0663	0.9946	0.8026							
6C2	0.51	0.53	0.055	0.015	0.3022	0.9920	0.7755							
6D2	0.48	0.47	0.057	0.016	0.1319	0.9898	0.7227							
6E 2	0.69	0.58	0.081	0.023	0.2759	0.9759	0.6765							
6F2	0.69	0.58	0.096	0.027	0.1985	0.9550	0.6151							

Total air leakage (Q_t) continued

	Storm Window Up or Off							Storm Window Down or On						
	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef
7A		2.59	0.320	0.090	1.8163	0.9810	0.7154		2.22	0.323	0.091	1.5896	0.9933	0.6582
7B		3.05	0.949	0.270	1.5920	0.9852	0.3976							
7C									4.80	0.411	0.117	2.5778	0.9887	0.8386
7D		3.86	0.710	0.202	2.0473	0.9977	0.5779							
7E		3.54	0.807	0.229	1.8735	0.9900	0.5048							
7F		3.17	0.706	0.201	1.7706	0.9992	0.5122							
7G														
7H		4.19	0.758	0.215	2.1344	0.9991	0.5833							
7I		3.19	0.599	0.170	1.8463	0.9933	0.5703		2.98	0.541	0.154	1.7945	0.9946	0.5822
7J		3.68	0.812	0.231	1.9223	0.9952	0.5151							
7K		5.15	0.893	0.254	2.3594	1.0000	0.5978							
7L														
7 A 2		2.10	0.307	0.087	1.5335	0.9979	0.6568							
7 B 2		4.27	0.627	0.179	2.2395	0.9942	0.6545		3.65	0.533	0.152	2.0835	0.9968	0.6559
7 C 2	1.28	1.32	0.161	0.046	1.1449	0.9897	0.7176							
7 D 2		2.09	0.413	0.117	1.4038	0.9978	0.5533							
7 E 2	1.67	1.72	0.247	0.070	1.3420	0.9854	0.6621							
7 F 2		2.25	0.462	0.131	1.4600	0.9942	0.5402							
7 G 2	1.09	1.15	0.107	0.030	1.1236	0.9938	0.8145							
7 H 2	1.53	1.61	0.199	0.056	1.3368	0.9727	0.7142							
7 I 2	1.85	1.86	0.279	0.080	1.3975	0.9914	0.6466							
7 J 2	2.03	2.09	0.342	0.097	1.4806	0.9873	0.6177							
7 K 2	1.87	1.95	0.245	0.070	1.5169	0.9912	0.7063							
7 L 2	1.97	2.03	0.274	0.077	1.5369	0.9877	0.6847							
7 M 2	1.96	2.00	0.372	0.107	1.3619	0.9863	0.5728							
7 N 2	1.84	1.88	0.275	0.079	1.4178	0.9930	0.6543							
7 O 2		2.32	0.340	0.097	1.6349	0.9991	0.6560							
7 P 2	2.09	2.10	0.335	0.095	1.4919	0.9925	0.6254							
7 Q 2		2.29	0.434	0.124	1.5162	0.9991	0.5688							
7 R 2	1.61	1.66	0.237	0.068	1.3045	0.9912	0.6636							
7 S 2		2.03	0.316	0.090	1.4718	0.9949	0.6345							
7 T 2	0.81	0.81	0.075	0.022	0.7610	0.9924	0.8098							
8A		3.26	0.710	0.202	1.8063	0.9943	0.5194							
8B		4.78	0.601	0.179	2.3976	0.9606	0.6924							
8C		4.94	1.056	0.300	2.2308	0.9994	0.5265							
8D								1.39	1.46	0.186	0.053	1.2262	0.9911	0.7030
8E								1.79	1.85	0.189	0.054	1.5518	0.9907	0.7772
8F								1.45	1.48	0.195	0.056	1.2307	0.9961	0.6929
9A		2.91	0.572	0.162	1.7314	0.9910	0.5538		2.08	0.260	0.074	1.5819	0.9908	0.7081
9B		2.95	0.457	0.130	1.8474	0.9955	0.6360		2.79	0.328	0.094	1.9034	0.9960	0.7301
9C		5.07	1.124	0.320	2.2412	1.0000	0.5136							
9D		2.92	0.495	0.141	1.7980	0.9997	0.6047		2.71	0.513	0.146	1.6825	0.9996	0.5682
9E	1.82	1.90	0.255	0.072	1.4689	0.9869	0.6857							
9F		4.28	1.377	0.392	1.9217	1.0000	0.3873		3.86	0.558	0.159	2.1457	0.9626	0.6597
10A1	1.84	1.85	0.820	0.234	0.9481	0.9935	0.2773							
10A2								0.40	0.40	0.127	0.037	-0.4679	0.9932	0.3852
10B1	2.00	1.96	0.850	0.242	1.0271	0.9915	0.2877							
10B2								1.03	1.11	0.142	0.041	0.9438	0.9782	0.6999
10C1	1.83	1.84	0.817	0.232	0.9442	0.9935	0.2773							
10C2								1.31	1.35	0.253	0.072	0.9786	0.9909	0.5694
10D 1		4.68	0.946	0.269	2.2004	1.0000	0.5456		3.83	0.592	0.168	2.1114	0.9677	0.6376
10D 2	1.64	1.67	0.279	0.080	1.2487	0.9938	0.6106	1.73	1.73	0.328	0.094	1.2291	0.9985	0.5664

Total air leakage (Q_t) continued

	Storm Window Up or Off							Storm Window Down or On						
	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef	Actual Q 0.30	Reg Q 0.30	Reg Q 0.016	ELA	Constant	R^2	X coef
11 A	0.67	0.68	0.059	0.017	0.6196	0.9809	0.6346							
11 B	0.42	0.45	0.071	0.020	-0.0384	0.9915	0.6296							
11 C	0.42	0.44	0.087	0.025	-0.1577	0.9865	0.5505							
11 D	0.56	0.54	0.116	0.033	-0.0039	0.9758	0.5189							
11 E	0.90	0.89	0.097	0.027	0.7947	0.9926	0.7580							
11 F	0.40	0.40	0.070	0.019	-0.2217	0.9876	0.5904							
12 A		4.65	1.051	0.299	2.1488	0.9528	0.5076		3.50	0.533	0.152	2.0234	0.9983	0.6417
12 B		2.67	0.399	0.113	1.7625	0.9820	0.6486		2.63	0.379	0.108	1.7623	0.9890	0.6606
12 C	2.12	2.16	0.267	0.076	1.6293	0.9936	0.7134	2.12	2.14	0.283	0.081	1.5924	0.9961	0.6906
12 D		2.59	0.271	0.077	1.8814	0.9924	0.7710		2.56	0.280	0.080	1.8481	0.9874	0.7548
12 E		3.31	0.550	0.156	1.9362	0.9978	0.6128		3.50	0.352	0.100	2.1940	0.9866	0.7832
12 F	1.61	1.75	0.137	0.039	1.6152	0.9915	0.8723	1.61	1.73	0.130	0.037	1.6154	0.9922	0.8832
12 G		4.32	0.524	0.150	2.3291	0.9944	0.7193		3.67	0.453	0.129	2.1571	0.9978	0.7131
12 H		4.91	0.832	0.237	2.3192	0.9989	0.6053		3.05	0.409	0.116	1.9369	0.9845	0.6847
12 I		5.20	0.972	0.277	2.3376	0.9999	0.5722		3.40	0.593	0.169	1.9402	0.9961	0.5956
12 J														
13 A		3.65	0.718	0.204	1.9619	0.9998	0.5538		2.54	0.519	0.147	1.5831	0.9992	0.5415
13 B		3.37	0.665	0.189	1.8816	0.9984	0.5537		2.79	0.394	0.112	1.8262	0.9792	0.6868
13 C		5.42	1.202	0.342	2.3081	1.0000	0.5136		4.73	0.749	0.213	2.3113	0.9967	0.6289
13 D		3.51	0.742	0.211	1.8930	0.9951	0.5299		3.07	0.650	0.185	1.7562	0.9827	0.5289
13 E		3.02	0.661	0.188	1.7325	0.9844	0.5191		2.66	0.483	0.138	1.6781	0.9924	0.5820
13 F		2.96	0.726	0.207	1.6641	0.9665	0.4797		2.91	0.540	0.154	1.7567	0.9964	0.5737
13 G		3.39	0.627	0.179	1.9115	0.9976	0.5748		3.01	0.586	0.167	1.7767	0.9939	0.5588
13 H		4.32	0.543	0.155	2.3145	0.9983	0.7072		3.46	0.507	0.144	2.0336	0.9881	0.6564
13 I		3.43	0.678	0.193	1.9004	0.9984	0.5537		2.93	0.593	0.169	1.7314	0.9966	0.5450
13 J	2.04	2.13	0.277	0.079	1.5943	0.9928	0.6963	1.99	2.07	0.236	0.067	1.6196	0.9786	0.7411
14 A	1.74	1.71	0.296	0.070	1.3329	0.9803	0.6631	1.13	1.13	0.096	0.027	1.1369	0.9908	0.8423
14 B		3.13	0.670	0.190	1.7755	0.9762	0.5260	1.69	1.61	0.238	0.068	1.2681	0.9947	0.6543
14 C		2.75	0.449	0.127	1.7591	0.9978	0.6194	1.69	1.75	0.215	0.061	1.4260	0.9911	0.7164
14 D	1.41	1.57	0.158	0.045	1.3896	0.9727	0.7813	1.01	0.99	0.117	0.033	0.8734	0.9947	0.7302
14 E	2.23	2.16	0.618	0.175	1.2855	0.9950	0.4275	0.57	0.59	0.114	0.032	0.1482	0.9909	0.5618
14 F		2.16	0.582	0.166	1.3115	0.9785	0.4481	0.42	0.42	0.097	0.028	-0.2857	0.9991	0.4995
15 A 1									6.16	1.250	0.355	2.4708	1.0000	0.5435
15 A 2								0.31	0.32	0.135	0.039	-0.7846	0.9833	0.2954
15 B 1		5.43	1.092	0.311	2.3519	1.0000	0.5474		3.94	1.025	0.292	1.9226	0.9814	0.4588
15 B 2								0.36	0.36	0.144	0.041	-0.6594	0.9742	0.3097
15 C 1														
15 C 2								0.42	0.41	0.245	0.070	-0.6771	0.9787	0.1756
15 D 1									6.08	1.288	0.366	2.4415	1.0000	0.5291
15 D 2								0.26	0.26	0.085	0.025	-0.8961	0.9916	0.3785
16 A									4.75	0.823	0.235	2.2778	1.0000	0.5978
16 B									2.97	1.140	0.324	1.4830	1.0000	0.3270
16 C												0.0733		
16 D												0.0733		
16 E		4.87	1.023	0.291	2.2263	0.9984	0.5329					0.0733		
16 F		5.47	0.965	0.280	2.4033	1.0000	0.5850					0.0733		
16 G		4.30	0.731	0.208	2.1866	0.9995	0.6046					0.0733		
17 A	2.43	2.44	0.477	0.136	1.5617	0.9939	0.5568	2.43	2.49	0.399	0.113	1.6595	0.9946	0.6236
17 B	2.08	2.20	0.311	0.088	1.5905	0.9930	0.6673	1.99	2.09	0.293	0.083	1.5446	0.9948	0.6711
17 C	2.66	2.66	0.566	0.160	1.6109	0.9852	0.5273	2.49	2.58	0.468	0.133	1.6527	0.9870	0.5831
18 A	0.87	0.85	0.096	0.027	0.7280	0.9956	0.7427					0.0733		
18 B	0.70	0.65	0.100	0.028	0.3280	0.9942	0.6364					0.0733		
19 A	1.66	1.72	0.244	0.069	1.3503	0.9903	0.6677	1.54	1.61	0.224	0.063	1.2883	0.9886	0.6738
19 B	1.27	1.31	0.157	0.044	1.1439	0.9907	0.7247	1.10	1.13	0.136	0.039	0.9985	0.9967	0.7247

8c. Numerical Conversions and Transformations

8c i. Data standardization

Air flow measurements (Q_t and Q_e) were recorded in "actual cubic feet per minute" (acfm) under ambient conditions. The sash flow difference (Q_s) was converted to "standard cubic feet per minute" (scfm) by the following formula, based on standard reference conditions listed in ASTM E 783-93:

$$scfm = acfm * \frac{293.8\ K}{273\ K + \frac{(^{o}F - 32) * 5}{9}} * \frac{atm\ P}{760 mm\ Hg}$$

The unit scfm was referenced to standard conditions at 20.8°C (293.8 Kelvin) and one atmosphere of pressure (760 mm Hg), meaning readings in scfm would generally be larger than readings in acfm due to the cooler ambient air temperatures. Converting to scfm allowed for valid comparisons of air leakage between windows of equal sizes tested under differing environmental conditions.

8c ii. Standard cubic feet per minute per linear foot crack

Windows were found in varying dimensions and comparison of leakage rates through different sized windows was therefore not valid. As an example, the larger of two window with identical leakage characteristics excepting size, would always show a larger leakage rate at a given pressure differential than the smaller window due to its larger operable crack length. A method of standardizing window size was employed to remove size bias. This was accomplished by expressing Q_5 as standard cubic feet per minute per linear foot crack (scfm/lfc) which represented the amount of air flowing through a unit length of operable window crack. Operable crack was defined as the meeting rail and junctures between movable sash and jambs. For a double-hung window, the formula for operable linear foot crack (lfc) was:

$$lfc = \frac{(2 * Height + 3 * Width)}{12 in./ft}$$

where *height* and *width* were the window dimensions in inches. The linear foot crack number (lfc) was divided into the appropriate flow rate (generally Q_5) to obtain scfm/lfc, a number descriptive of the leakage characteristics of the window independent of temperature, pressure, and window size. The standardized flow rates per operable linear crack (scfm/lfc) were listed for the pressure differentials attained for each window and were the numbers normally used for comparative purposes.

8c iii. Standard cubic feet per minute per square foot of sash area

A second method of presenting a standardized leakage rate was as standard cubic feet per minute per square foot of sash area (scfm/ft^2). The formula for the sash area of a double-hung window was:

$$Sash\ Area\ (ft^2) = \frac{(Height * Width)}{144\,in.^2/ft^2}$$

where *height* and *width* were the window dimensions in inches. Once again, this number was divided into the appropriate flow rate to attain the standard flow per square foot of sash area (scfm/ft^2).

When more than one type of window is in a house (ie. double-hung and casement windows) and windows are being compared to one another, the flow per sash area (scfm/ft^2) may be both more appropriate and accurate. This is due to the operating characteristics of differing window types. Double- and single-hung windows of identical size showing equivalent leakage rates when expressed as scfm/lfc do not have equivalent flows when viewed as total air leakage through the sash. The flow through a double-hung window is approximately 70% greater than the flow through a single-hung window of equal size as an allowance is given for the increased operable crack length in a double-hung window. (Most manufacturers of new windows list air infiltration data in terms of scfm/lfc, however, regardless of the window type.)

8c iv. Effective leakage area

A third comparative method and also used in the LBL correlation model was the effective leakage area (ELA). The ELA was used to characterize the natural air infiltration of a building at a pressure differential of 0.016 inches of water pressure. Extrapolation to the reference pressure was based field data fitted to the standard flow formula:

$$Q = c * \Delta P^x$$

where

Q = air leakage in scfm or scfm/lfc
ΔP = pressure differential
c = leakage coefficient
x = leakage exponent

Characterization of the leakage was accomplished by equilibrating the measured air leakage to an opening of a specific area that allows an equivalent leakage. Both x and c are regression coefficients determined from linear regression. ELA calculation is detailed

in ASTM E 779-87, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization,* and was used to characterize air leakage rates through windows for the purposes of this project. Use of an ELA value allowed air openings in a window to be expressed as one total area for comparative purposes. Flow rates for all windows were converted to standard cubic feet per minute per linear foot crack (scfm/lfc) prior to ELA calculation to facilitate comparisons between windows of differing dimensions and varying environmental conditions.

ASTM E 779-87 lists a conventional reference pressure of 4 Pascals (Pa), equivalent to 0.016 inches of water pressure. Both metric (SI) and conventional (inch-pound, IP) formulations are given by ASTM for calculating ELA with the metric formulation being the preferred format. Calculated ELA's used in the study were based on the IP formula as most data had been recorded in IP units. Both formulations yield equivalent results when converted to common units. The IP formula is given below:

$$ELA = 0.1855 * c * \Delta P^{(x-0.5)} * (\rho_e/2)^{0.5}$$

where

ELA = equivalent leakage area (square inches)
c = leakage coefficient from linear regression
x = leakage exponent from linear regression
ΔP = 0.016 inches of water pressure
ρ_e = 0.07517 Ibm/ft^3 (the density of air)
0.1855 = conversion factor

8d. Data Sheet Interpretation

An example of the transformed air leakage data for an individual window is found on the page *Reference Data Sheet* Window identification and a brief description are found on line 17. Above that are the relevant parameters necessary for standardization of the air flow. Block B22 through 629 are the pressure differentials in inches of water pressure used during a test run. Block B 30 (0.016 in. H_20) is equivalent to 4 Pa, the standard reference pressure for ELA's. The 0.016 inches of water pressure differential was assumed to be the annual average heating season differential between interior and exterior pressures and was assumed to be the driving force for natural infiltration. This value was used to compute the effective leakage area (ELA). Window manufacturers report test results at 0.30 inches of water pressure for new windows, equivalent to 75 Pascals. This pressure, 0.30 inches of water, is the reference pressure used in this summation so as to allow comparison with replacement windows.

Blocks C22-29 and 022-29 are the total air flows and extraneous air flows respectively with the storm window open, both expressed as actual cubic feet per minute (acfm). Block E22-29 is the sash flow in standard cubic feet per minute (scfm). Block F22 through H29 shows the same flows for the window with the storm window closed.

Window dimensions are found in block 122 to J23 and were used to standardize the sash flows (Qs) to standard cubic foot per minute per linear foot crack (scfm/lfc) or per square foot (scfm/ft^2). Standardized sash flow per linear foot crack data are found in block K22 to N29 for windows with storm windows both open and closed.

The mathematical model used to describe the induced flow of air through the window is a widely used model for air flow:

$$Q_s = c * \Delta P^x$$

where

- ΔP = pressure differential
- c = leakage coefficient
- x = leakage exponent.

The variables x and *c* need to be determined, but the model as written mathematically describes half a parabola. A natural logarithmic transformation linearizes the data, allowing x and *c* to be determined by linear regression. Linear regression compares data to a straight line. This transformation linearizes the data in the following manner:

$$Q_s = c * \Delta P^x$$
$$lnQ_s = 1nc + x * 1n\Delta P$$

which is analogous to the straight line equation:

$$y = b + mx$$

where

ln c = constant, b (the y intercept)
x = x coefficient, m (the slope)

Blocks B34-42, D34-42, and J34-42 are respectively, the natural logarithms of the pressure differentials and scfm/lfc's for windows with storms open and closed. Linear regression was performed on these data to determine *c* (Constant) and x (X Coefficient), found in block E33 to H41. Linear regression also provided an estimate of how well the data fit the model, known as the goodness-of-fit value (R^2). The closer this value is to 1.000, the better the data fit the model.

The *x* and *c* values, along with the pressure differentials, were used to determine "best fit" data based on the mathematical model. It was these data that were usually used for comparative purposes as opposed to the raw data, due to the leaky nature of many windows tested. These data are found in block P22 to Q30, with P30 and Q30 being the values at 0.016 inches of water pressure (4 Pa).

The regression coefficients *x* and *c* were used with the reference pressure 0.016 inches of water to calculate the effective leakage area in square inches (ELA) as previously described. This value is found in block P34 to Q34. To gain a better understanding of the size of the effective leakage area, the ELA was assumed to be a square with the length of one side given in block P37 to 037.

B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
File:	DERBY.WB2														
Date:	08/13/96							Q_s, scfm/lfc							
								DERBY.WB2							
		Address:	Kidder Hotel Block												
			Derby, Vermont												
		Test Date:	04/29/96	and	04/30/96										
	Window Upgrade:		Six original pin-type windows, pins removed. New Harvey storm windows in place - four exterior, two interior.												
	Window Type:		Double hung, single glazed with Harvey triple track storms.												
Date:	04/29/96														
T (F):	50														
P (mm Hg):	758.2														
Window ID:	14 A		Exterior Harvey aluminum triple track storm window caulked in place.												
														Best Fit Data	
Pressure		Storm off			Storm on				Storm off		Storm on			Storm off	Storm on
Dif	Q_t	Q_e	Q_s	Q_t	Q_e	Q_s		Dimensions	Q_s	Q_s	Q_s	Q_s		Q_s	Q_s
(in. H2O)	(acfm)	(acfm)	(scfm)	(acfm)	(acfm)	(scfm)		(inches)	(scfm/lfc)	(scfm/ft^2)	(scfm/lfc)	(scfm/ft^2)		(scfm/lfc)	(scfm/lfc)
0.30	31	17	13.5	20	17	2.9	H =	60	0.73	0.97	0.16	0.21		0.78	0.24
0.25	28	15	12.5	18	15	2.9	W =	33.5	0.68	0.90	0.16	0.21		0.70	0.18
0.20	25	14	10.6	16	14	1.9			0.58	0.76	0.10	0.14		0.62	0.12
0.15	21	9.9	10.7	13	9.9	3.0			0.58	0.77	0.16	0.21		0.53	0.08
0.10	17	7.5	9.1	8.5	7.5	1.0			0.50	0.66	0.05	0.07		0.42	0.04
0.07	13	5.6	7.1	6.4	5.6	0.8			0.39	0.51	0.04	0.06		0.35	0.02
0.05	8.9	4.4	4.3	4.5	4.4	0.1			0.24	0.31	0.005	0.007		0.29	0.01
0.03	6.4													0.22	0.01
0.016														0.154	0.002
				Storm off						Storm on				ELA	ELA
ln P		ln Q_s		Regression Output:				ln Q_s		Regression Output:				(in^2)	(in^2)
-1.20397		-0.31026	Constant			0.409693		-1.85071	Constant			0.538255		0.044	0.001
-1.38629		-0.38437	Std Err of Y Est			0.139705		-1.85071	Std Err of Y Est			0.640686			
-1.60944		-0.55142	R Squared			0.89337		-2.25617	R Squared			0.777068		Side of square (in.)	
-1.89712		-0.54237	No. of Observations			7		-1.81792	No. of Observations			7		0.21	0.02
-2.30259		-0.69803	Degrees of Freedom			5		-2.94932	Degrees of Freedom			5			
-2.65926		-0.94784						-3.17246							
-2.99573		-1.44524	X Coefficient(s)		0.551242			-5.2519	X Coefficient(s)		1.63059				
-3.50656			Std Err of Coef.		0.085169				Std Err of Coef.		0.390585				
-4.13517															

8e. Field Data Sheets

8e i. Window data sheet

Date: _____ Time _____
Project Name: _____ Location: _____

Orientation _____
Temperature (°F) - Interior T_{dry} -_____ T_{wet} - _____ Exterior T_{dry} - _____ T_{wet} - _____
P_{atm} (mm Hg): _____ Wind: speed (mph) - _____ direction - _____

Window type: _____ Single pane: _____
Multipane: _____ x _____
Pane Size (in) - _____ x _____

Dimensions (in.) : Total Height - _____ Sash Width - _____
Upper Sash - _____ Sash Depth - _____
Lower Sash - _____

Window weight cavity: Y N Connected? Y N

Locking mechanism: Y N Operable: Y N NA
Type _____ Location(s) _____

Storm Window Type: Aluminum triple track Aluminum double track Wood sash Other: _____
None _____
_____

Comments: _____
_____
_____
_____
_____

	Storms up or no storms		Storms down	
ΔP (in H20	Q_t (acfm)	Q_e (acfm)	Q_t (acfm)	Q_e (acfm)
0.30				
0.25				
0.20				
0.15				
0.10				
0.07				
0.05				
0.03				

8e ii. Physical condition check sheet

Physical condition

		Excellent									Poor
Upper Sash											
	Putty condition	10	9	8	7	6	5	4	3	2	1
	Glass tight	10	9	8	7	6	5	4	3	2	1
	Fit to frame	10	9	8	7	6	5	4	3	2	1
	Square in frame	10	9	8	7	6	5	4	3	2	1
Lower Sash											
	Putty condition	10	9	8	7	6	5	4	3	2	1
	Glass tight	10	9	8	7	6	5	4	3	2	1
	Fit to frame	10	9	8	7	6	5	4	3	2	1
	Square in frame	10	9	8	7	6	5	4	3	2	1
Frame											
	Stops tight	10	9	8	7	6	5	4	3	2	1
	Tight to trim	10	9	8	7	6	5	4	3	2	1
Meeting Rail											
	Tight fit	10	9	8	7	6	5	4	3	2	1
Exterior caulking		10	9	8	7	6	5	4	3	2	1

8e iii. Physical condition criteria

Upper and Lower Sash

Putty Condition - Generally, it is the bottom glazing of each sash that weathers most quickly and it is this border that is the primary determinant for putty condition.

10 - Relatively new putty with no cracks.
9-7 - Putty is intact but has varying degrees of cracks.
6-4 - Putty is intact but obviously dried out, large cracks, some flaking apparent.
3-2 - Portions of the putty missing, less than one inch total.
1 - Greater than one aggregate linear inch of putty missing or a gap between the glass and sash is evident.

Glass Tightness - This is very much a function of the putty condition and the putty condition number is considered when determining tightness. Overall tightness is determined by tapping around the perimeter(s) of the glass pane(s). Caution is taken to ensure that only the sash being tapped is causing any vibratory noise.

10-7 - Glass shows little to no vibrations.
6-4 - Glass vibrates and sounds loose.
3-1 - Glass visibly moves under slight pressure. A putty condition of 1 by definition has a glass tightness of 1.

Fit to Frame - This is a combination of visual and physical inspections. The sash is visually inspected for gaps between the jambs and sash and the lower sash is viewed from above for gap symmetry on either edge. Each sash is physically moved from side to side and front to back while unlatched to subjectively determine play.

10-8 - No gaps, fairly symmetrical, little play in either direction.
7-5 - No gaps, somewhat asymmetrical, play in either direction is becoming pronounced.
4-3 - Small gaps are apparent, sash may be asymmetrical, significant lateral play.
2-1 - Easily noticeable gaps, sash readily moves laterally.

Square in Frame - Squareness is also incorporated in Fit to Frame but is also important enough to warrant its own category and is visually determined relative to the jambs and parting beads if present.

10-8 -Sash appears square with exposed stiles being symmetrical and rails being horizontal.
7-4 - Sash is skewed up to 1/4 inch with exposed stiles being asymmetrical.
3-1 - Sash is skewed more than 1/4 inch.

Frame

Stops Tight - This is determined both visually and physically by tapping the stops and listening for vibrations. Paint also is a consideration. Stops are not considered individually but as a unit.

10-8 - Stops are flush to jambs with no discernable vibration when tapped. Wood may be painted with little to no cracking of the paint along the stop edge.

7-5 - Stops vibrate when tapped and have visible cracks up to approximately 1/16 inch for 1/4 aggregate stop length.

4-2 - Stops vibrate freely when tapped and have cracks up to approximately 1/8 inch for 1/4 to 1/2 aggregate stop length.

1 - Stops are missing or not held in place and may fall when tapped. Gaps greater than 1/8 inch are present.

Tight to Trim - Determined by visual inspection of the trim to wall juncture.

10-8 - No visible crack to a hairline crack being apparent around any portion of the trim.

7-5 - Narrow crack around 1/4 to 1/2 of trim.

4-3 - Crack extends around entire frame and varies in width.

2-1 - Crack is large (1/8 inch); frame is not flush with the wall.

Meeting Rail

Tight Fit - The meeting rail is examined while sashes are latched (when latches are present and operable) as this is the expected normal winter operating mode. The interface of the sashes is examined for tightness and whether the upper and lower sashes are horizontal and flush in the vertical direction or are skewed

10-8 - Horizontal, flush, and with a tight interface.

7-4 - Horizontal but not flush and/or slightly skewed with an interface that is not tight for the entire length.

3-1- Meeting rail is neither horizontal nor flush with an interface that does not fully meet or exhibits poor juncture.

Exterior Caulking - A visual inspection is done to ensure all exterior portions of the window unit are present as well as the window unit/exterior wall caulking.

10-8 - Caulking appears to be intact and in good condition.

7-5 - Caulking appears dry and weathered with cracks and minor flaking apparent.

4-2 - Caulking is crumbling, flaky, and missing in areas.

1 - Some exterior window segments are missing as well as large amounts of caulking

8f. Equations for Weather Parameters Based on Psychrometric Data

Calculations to determine dew point temperature (td) and partial water vapor pressure (p_w) given field measurements of weather parameters dry-bulb temperature (t), wet-bulb temperature (t*), and atmospheric pressure (p):

Absolute temperature, T_{abs} or T^*_{abs} (in degrees Rankine):

$$T_{abs} = t + 459.67$$

or

$$T^*_{abs} = t^* + 459.67$$

where

t = *dry-bulb temperature* (^oF)

t^* = *wet-bulb temperature* (^oF)

Natural logarithm of the saturation water vapor pressure, p^*_{ws}, at T^*_{abs})

$$ln(p^*_{ws}) = \frac{C_1}{T^*_{abs}} + C_2 + C_3 * T^*_{abs} + C_4 * (T^*_{abs})^2 + C_5 * (T^*_{abs})^3 + C_6 * (ln\ T^*_{abs})$$

where

$C_1 = -1.044039708 * 10^4$

$C_2 = -1.12946496 * 10^1$

$C_3 = -2.7022355 * 10^{-2}$

$C_4 = 1.2890360 * 10^{-5}$

$C_5 = -2.478068 * 10^{-9}$

$C_6 = 6.5459673$

Saturation humidity ratio, W^*_s, at the wet-bulb temperature, t^*:

$$W^*_s = 0.62198 * \frac{p^*_{ws}}{p - p^*_{ws}}$$

where

P^*_{ws} = *saturation water vapor pressure*

p = *atmospheric pressure (psia)*

Humidity ratio, W:

$$W = \frac{(1093 - 0.556t^*)W_s^* - 0.240(t - t^*)}{1093 + 0.444t - t^*}$$

where

W_s^* = *saturation humidity ratio*

t = *dry-bulb temperature* (°F)

t^* = *wet-bulb temperature* (°F)

Partial pressure of water vapor, p_w, for moist air:

$$p_w = \frac{p * W}{0.62198 + W}$$

where

p = *atmospheric pressure* (*psia*)

W = *humidity ratio*

Dew point temperature, t_d:

$$t_d = 100.45 + 33.193 * (\ln p_w) + 2.319 * (\ln p_w)^2 + 0.17074 * (\ln p_w)^3 + 1.2063 * (p_w)^{0.1984}$$

where

P_w = *partial water vapor pressure*

Calculations to determine relative humidity (0) given field measurements of weather parameters dry-bulb temperature (t), wet-bulb temperature (t°), and atmospheric pressure (p):

Natural logarithm of the saturation water vapor pressure, P_{ws}, at Tabs:

$$ln(p_{ws}) = \frac{C_1}{T_{abs}} + C_2 + C_3 * T_{abs} + C_4 * T_{abs}^2 + C_5 * T_{abs}^3 + C_6 * (ln\ T_{abs})$$

where

$$C_1 = -1.044039708 * 10^4$$
$$C_2 = -1.12946496 * 10^1$$
$$C_3 = -2.7022355 * 10^{-2}$$
$$C_4 = 1.2890360 * 10^{-5}$$
$$C_5 = -2.478068 * 10^{-9}$$
$$C_6 = 6.5459673$$

Saturation humidity ratio, W_s, at the dry-bulb temperature, t:

$$W_s = 0.62198 * \frac{p_{ws}}{p - p_{ws}}$$

where

p_{ws} = *saturation water vapor pressure at the dry-bulb temperature*

p = *atmospheric pressure (psia)*

Degree of saturation, p, at a given temperature and pressure (t, p):

$$\mu = \frac{W}{W_s}$$

where

W = *humidity ratio*

W_s = *saturation humidity ratio*

Relative humidity, Φ:

$$\phi = \frac{\mu}{1-(1-\mu)\frac{p_{ws}}{p}}$$

where -

μ = degree of saturation

P_{ws} = saturation water vapor pressure at thy-bulb temperature

P = atmospheric pressure (psia)

8g. Exterior Air

8g i. Determination of percent exterior air in Qe

Infiltration of exterior air not only occurred through the window sash and sash/frame junction (Q_s) but also through the rough opening as extraneous air (Q_e) adding to the heating load. Quantifying the volume of exterior air is important in understanding the total heat load due to a window The following field method was devised and implemented to approximate the volume of exterior air contained in the induced extraneous air leakage.

An estimate of the volume of exterior air coming through the rough opening may be calculated by knowing the temperature between the two sheets of plastic while testing for extraneous air (Q_e) along with the ambient exterior and interior air temperatures. Knowing these three data points and any measured value of Q_e, a mass balance on temperature and air flow may be performed to estimate the volume of exterior air in Q_e The volume of exterior air in Q_s was determined by the following formula:

$$Q_{ext} = \frac{Q_e * (T_{win} - T_{int})}{(T_{ext} - T_{int})}$$

where:

Q_{ext} = the volume of exterior air (acfm)
Q_e = the volume of air chosen from extraneous air test data (acfm)
T_{win}= the temperature between the two plastic sheets during the test (°F)
T_{int} = ambient interior air temperature (°F)
T_{ext} = ambient exterior air temperature (°F)

The volume of exterior air (Q_{ext}) was converted to a percentage by dividing through by Q_e. If the percentage of interior air (Q_{int}) in Q_e is desired, it may be calculated by subtracting the Q_{ext} percentage from 100%, or directly by the following formula if Q_{ext} is not known:

$$Q_{int} = \frac{Q_e * (T_{win} - T_{ext})}{(T_{int} - T_{ext})}$$

where the variables are the same as those in the previous equation.

The amount of exterior air entering through the rough opening was calculated for 36 windows at five different locales. Data from three windows in Irasburg (windows I 6E, I 6F, and 16G) were not included in an average value as direct sunlight had been heating the wall during the early to mid-morning period prior to testing. Testing of these three windows occurred while the wall was shaded but the calculated exterior air percentages (88%, 88%, and 67%) appeared abnormally large when compared to the other 33 windows. The assumption was made that the wall had not returned to the ambient air temperature prior

to testing, and the data was discounted.

The average percentage of exterior air entering the buildings through the rough openings of 33 windows was 29%, meaning approximately 30% of the measured air in the Qe test must be heated during the heating season and must count towards the heating load of a typical window. The percentage of exterior air in Qe for the 33 windows is summarized in the following table:

Table g.1: Percentage of Q_{ext} in Q_e for 33 windows

Average value of Q_{ext}	28.6%
Maximum value of Q_{ext}	54.5%
Minimum value of Q_{ext}	7.7%

Both pin- and pulley-type windows were included in the 33 windows, with pin type windows averaging 26% exterior air passing through the rough opening versus 31 % for the pulley-type windows.

Of the 33 windows used to estimate a typical value for the percentage of exterior air in Q_e, all but two were the original sash after refurbishing. Windows 12B and 12C were both in-kind replacement sash with vinyl jamb liners. Both replacement windows have low exterior air percentages (12.5% and 13.2%), although some original sash windows (7B2, 702, 12F, 13B, 14B, 14C. and 14D) are of equivalent tightness in terms of Q_{ext}

This method of estimating the volume of exterior air entering the test zone during testing periods has severe limitations and values thus derived should not be assumed to be accurate. Temperatures in the test zone stabilized within a minute, but it is unknown whether steady state conditions had been reached within the building walls. No attempt was made to determine the actual air path through the wall cavities while a window was under pressure. Exterior air likely increased its temperature as it passed through walls warmer than the ambient exterior atmospheric temperature, raising questions as to the accuracy of the temperature readings in the test zone. The method was used to determine a rough approximation of the contribution of extraneous air to the overall heating load.

8g ii. Experimental data used to determine percentage exterior air

Window ID	T_{int} (^oF)	T_{win} (^oF)	T_{ext} (^oF)	Q_e (acfm)	Q_{ext} (acfm)	Percent Ext. Air
7A2	62	58	48	32	9.1	28.6
7B2	61	60	48	42	3.2	7.7
7C2	65	61	53	18	6.0	33.3
7D2	65	59	53	9.7	4.9	50.0
7E2	63	59	52	30	10.9	36.4
7F2	60	57	52	20	7.5	37.5
7G2	60	58	54	19	6.3	33.3
7J2	58	51	38	18	6.3	35.0
7K2	62	56	39	20	5.2	26.1
7L2	62	55	41	17	5.7	33.3
7M2	61	56	44	20	5.9	29.4
7N2	62	57	46	25	7.8	31.3
7O2	60	58	48	31	5.2	16.7
7P2	61	57	51	20	8.0	40.0
7Q2	60	58	51	40	8.9	22.2
12A	70	61	51	40	18.9	47.4
12B	72	69	48	40	5.0	12.5
12C	71	66	33	29	3.8	13.2
12F	71	68	51	22	3.3	15.0
12G	69	60	46	22	8.6	39.1
12H	71	62	46	38	13.7	36.0
12I	72	63	45	37	12.3	33.3
12J	71	66	44	39	7.2	18.5
13A	71	66	54	35	10.3	29.4
13B	70	68	56	34	4.9	14.3
13G	69	64	50	38	10.0	26.3
14B	65	63	50	25	3.3	13.3
14C	64	62	52	24	4.0	16.7
14D	64	62	50	15	2.1	14.3
14E	62	57	49	20	7.7	38.5
14F	62	56	51	19	10.4	54.5
14F2	60	58	51	7.56	1.7	22.2
16B	54	57	62	36	13.5	37.5
16E**	63	68	69	33	27.5	83.3
16F**	65	70	71	31	25.8	83.3
16G**	65	69	71	39	26.0	66.7

**Wall may still be retaining heat from direct sunlight. Data excluded.

8h. Assumptions for using WINDOW 4.1

All windows modeled are double-hung (vertical sliders) measuring 36 x 60 inches. Interior and exterior temperatures were 70°F and 0°F respectively, with a 15 mph wind blowing. Assumed typical and tight window parameters:

1. wood sash;
2. double-glazed with second layer consisting of a storm window 2.5 inches from primary sash (average distance between storm and upper and lower primary sash) Glass is clear with air between glazing layers.

Assumed loose window parameters:

1. wood sash:
2. single-glazed with no storm window. Glass is clear

In-kind, two over two replacement sash parameters:

1. wood sash,
2. double-glazed with second layer consisting of a storm window 2.5 inches from primary sash (average distance between storm and upper and lower primary sash) Glass is clear with air between glazing layers.

Double-pane insulating glass replacement window insert parameters:

1a. wood sash:

2a. double-glazed with second layer 0 500 inches from primary sash. Glass is clear with air between glazing layers

1b. vinyl sash;

2b. double-glazed with second layer 0.500 inches from primary sash. Glass is clear with air between glazing layers.

The following windows were modeled using WINDOW 4.1 but were not encountered in the field:

1. low-e replacement sash with standard storm window;
2. standard replacement sash with low-e storm window;
3. replacement sash with double-glazed low-e insulating glass; and
4. replacement window inserts with low-e double-glazed insulating glass.

8i. LBL Correlation Model Computer Printout

Volume	30,000	22,900	
Pressure		Flow, cfm	
4 Pa		2.069	
4 Pa ELA	1.480	(in²)	0.588
	33	% of leakage area in ceiling	
	33	% of leakage area in floor	
	34	% of leakage area in all 4 walls	
Ao	0.000955	total leakage area (m²)	
Ac	0.000315	leakage area in the ceiling (m²)	
Af	0.000315	leakage area in the floor (m²)	
R	0.6600		
X	0.0000		
	19	height of the roof (ft)	
H	5.7912	height of the roof (m)	
y	0.23	terrain parameter #1 (see table)	
a	0.73	terrain parameter #2 (see table)	
fT	0.757	terrain factor	
C'	0.24	shielding coefficient (see table)	
fW	0.1675	wind parameter	
f'W	0.1269	reduced wind parameter	
fs	0.4433	stack parameter	
Volume	30000	(ft^3)	
Volume	849.6	(m^3)	
Ti	68	Winter Indoor Avg. Temp. (°F)	

Site 12, storm windows closed

ELA_tot = 1.48 in^2

Q_net = 2.069 scfm

Month	ACH	Qtot (m^3/se	Qwind (m^3/sec)	Qstack (m^3/sec)	VT-wind v'	v's	f's	TiF	VT-temp ToF	TiK	ToK
JAN	0.0047	0.0011	0.0005	0.0010	4.25	1.04	0.20	68	17	293.2	264.9
FEB	0.0046	0.0011	0.0005	0.0010	4.11	1.02	0.20	68	19	293.2	266.0
MAR	0.0043	0.0010	0.0005	0.0009	4.20	0.91	0.20	68	29	293.2	271.5
APR	0.0036	0.0009	0.0005	0.0007	4.16	0.73	0.20	68	43	293.2	279.3
MAY	0.0029	0.0007	0.0005	0.0005	3.93	0.52	0.20	68	55	293.2	286.0
JUN	0.0023	0.0005	0.0004	0.0003	3.71	0.32	0.19	70	65	294.3	291.5
JUL	0.0022	0.0005	0.0004	0.0003	3.53	0.32	0.19	75	70	297.1	294.3
AUG	0.0021	0.0005	0.0004	0.0003	3.31	0.32	0.19	72	67	295.4	292.6
SEP	0.0026	0.0006	0.0004	0.0004	3.62	0.44	0.20	68	59	293.2	288.2
OCT	0.0032	0.0008	0.0005	0.0006	3.84	0.63	0.20	68	49	293.2	282.6
NOV	0.0039	0.0009	0.0005	0.0008	4.25	0.81	0.20	68	37	293.2	276.0
DEC	0.0045	0.0011	0.0005	0.0009	4.38	0.98	0.20	68	23	293.2	268.2
Average Annual	0.0034	0.0008	0.0005	0.0006							
Oct-Apr Average	0.0041	0.0010	0.0005	0.0008							

Burlington Avg Tem	Avg DDays		
15	1,494	0.192924	JAN
17	1,299	0.167743	FEB
19	1,113	0.143724	MAR
29	660	0.085227	APR
43	331	0.042743	MAY
		0	JUN
		0	JUL
		0	AUG
59	191	0.024664	SEP
49	502	0.064824	OCT
37	840	0.108471	NOV
23	1314	0.16968	DEC
	7744	0.004207	
DDay weighted avg			

AVERAGE PREDICTED INFILTRATION RATES

TEST DATE: 06/28/94

	Air Changes per Hour	Average cfm
Average Annual	0.0034	1.715
Oct-Apr Average	0.0041	2.069
	Wind-Driven	Stack-Driven
Average Annual	43%	57%
Oct-Apr Average	38%	62%