Reducing Building Energy Loads through Improved Fenestration Design

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May 1999

Senior thesis project completed in partial fulfillment of the requirements for an ScB degree in Environmental Studies

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Acknowledgements

I would like to thank Kurt Teichert for the hours he has spent leading me through building plans and mechanical systems. The clarity, patience and generosity with which he imparts his knowledge and experience have been instrumental to the undertaking and completion of this project. I am particularly grateful to Harold Ward for his continual guidance throughout this last year, as well as the three preceding. Without annoyance or exasperation, he has consistently directed me to the next step, whatever the path I might have chartered for my life at that hour. I am indebted to Chris Ladds and Steven Wilkinson for the information that they generously provided on the Carr House project. And of course, I must thank Andrew Pleasant and Nancy Matthews for their time and work spent on transforming my writing style from something along the lines of this Acknowledgments page, to something *a bit more like a science thesis*.

Abstract

This study analyzes the means by which building energy loads may be reduced through improved window insulation, application of low-e coatings and optimized fenestration design. Buildings consume 36 percent of United States energy for the purpose of keeping occupants "comfortable". Maintaining the ideal temperature within the building through mechanical heating and cooling takes almost half of that energy. A United States Department of Energy statistic, attributing 25 percent of heating and cooling loads to *poorly insulated* windows, suggests the replacement of these units as a first step to reduce unnecessary energy use.

Of course, the replacement window must, in fact, have a greater resistance to heat transfer. Air infiltration through windows is not a significant source of building heat loss, so blindly replacing an old window does not guarantee energy savings. The window specification for Carr House at Brown University was used as a case study to determine the thermal performance of the typical new window installed today. The stipulated windows were found to be "poorly-insulated" as they lacked most of the technologies known to enhance thermal performance. Though the nation's leading glass manufacturer, IPG, incorporates warm edge technology, Brown still specifies aluminum spacers, which cause heat loss and condensation. Argon, a low conductivity gas, improves window insulation by 33 percent over air, with only a 10 percent higher price tag. Nonetheless the Brown window specification calls for air—insulated glass. Additionally, the University sole—sources wood and conventional aluminum windows. Pure—wood frames require significant upkeep that can be avoided with claddings or hybridization of the material with plastic. Mass-market aluminum frames conduct unnecessary quantities of heat due to insufficient thermal breaks. High performance aluminum windows, manufactured by Kalwall and Visionwall, have not been considered for a University project. Nor has the invitation to bid on projects been extended to manufactures of high performance windows that are comprised of alternative materials, like fiberglass.

Another consideration for fenestration design is the regulation of heat gain. Heat gain, primarily in the form of solar energy, increases the cooling load of a building but also reduces the heating load. The visible light component of solar energy reduces the lighting load of the building, as well as the cooling load incurred from electric lighting. Optimizing the transmittance of solar energy to minimize the overall building energy load is critical for the recovery of any portion of the energy loss innate to fenestration. Factors involved in establishing the optimal balance include the relative costs of heating, cooling, lighting, the internal heat gain of the building, and the exposure to sunlight that the building can expect in winter. The urban location of Carr House and its proposed commercial use (thus daytime occupancy with significant internal heat gains from lighting and office equipment) dictate that the focus for passive solar design is on cooling load avoidance rather than heating load reduction. Furthermore, due to the University's particular heating and cooling systems, the cost of an increased cooling load resulting from the greater transmittance of solar gain for passive winter heating would negate savings to the heating bill.

Solar gain and visible light transmittance are regulated with fenestration design – area, orientation, and construction – and the application of low-e coatings on the glass. The optimization of these qualities requires the consideration of so many variables that

computer-modeling software specific to building energy has been developed to facilitate the process. After experimentation with one such energy design tool, PowerDOE, I concluded that comprehensive energy analysis is too cumbersome for an architect to incorporate at building conception for ideal fenestration design, but a great asset for specific component changes later in the design process. In addition, the breadth of analysis empowered by PowerDOE provides engineers with an equally dependable, but far more accurate, means of sizing mechanical systems than that offered by current methods. The incorporation of energy design tools in the design process raises issues of energy efficiency that might otherwise be missed and stimulates greater collaboration between the architect and engineer. Generally, too little attention is paid to the significance of building design on operating costs and energy expenditures.

The mandate for an architect to use an energy design tool throughout the design process may force simplistic designs ideal for the tool's method of energy modeling rather than an architect's creative abilities. However, educating architects on the general rules of thumb of passive solar design would vastly reduce the energy use of a building inherent to its design.

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I: Linking the Building System to the Ecosystem

There is a worldwide effort underway to slow global warming through the reduction of greenhouse gas emissions. The United States is the greatest single contributor to the anthropogenic (human-caused) sources of these emissions. This country alone emits a quarter of the world's carbon dioxide, the principal greenhouse gas. Carbon dioxide, the primary form in which carbon is contained within the atmosphere, is released through the conversion of fossil fuels into energy. At the United Nations-sponsored Earth Summit in 1992, the United States pledged to return carbon emissions to 1990 levels by the year 2000. However, on present course, the country will emit 1,577 million metric tons of carbon next year, missing the goal by 240 million metric tons (15 percent).[1]

To reverse this trend of consumption, energy use practices must be reassessed at the levels of government, business, and the individual. One energy use, common to all, is the acclimatizing of buildings for occupant comfort. At the turn of the last century, buildings were simply structural frames encased within façades. They have since been recognized for being the complex systems that they are. A new regard for the issues of energy efficiency and indoor air quality has upgraded building exteriors from "wrappings" into "sealed envelopes". Yet, the fact that buildings consume 36 percent of the nation's energy invalidates this notion of a sealed or closed system.[2] The energy used within the building system, for heating, cooling and lighting, has direct impacts on our global environment.

As apertures in the building envelope for sunlight and ventilation, windows epitomize this link between the building system and the ecosystem. Through transmitting solar gain and conducting heat, windows allow more energy to move through the building envelope than any other component of the building's exterior. In terms of building energy loads, the solar energy radiated through the glass partially offsets the demand for electric lighting and winter space heating, but also increases the load carried by the air conditioning during the warmer months. Conduction through window units upsets the intended balance of heat within the building, exacerbating the need for mechanical heating and cooling. Windows amount to a puncture in the building envelope not only for light and view, but for the conservation of energy within the building system.

Therefore, improving fenestration design and construction would yield significant energy savings. The United States Department of Energy (DOE) states that 25 percent of United States heating and cooling loads are attributable to *poorly—insulated* windows.[3] Combined with the fact that heating and cooling equipment consume 42 percent of

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[1] United States, United States Energy Information Administration, 26 Feb. 1999 <http://www.eia.doe.gov/emeu/cabs/usa.html>.

[2] EREC Brief: Energy Efficiency and Renewable Energy in Buildings, Energy Efficiency and Renewable Energy Network (EREN), US Department of Energy, 23 July 1998 <http://www.eren.doe.gov/consumerinfo/refbriefs/tpbldgs.html>.

[3] EREC Brief: Energy Efficiency and Renewable Energy in Buildings, Energy Efficiency and Renewable Energy Network (EREN), US Department of Energy, 23 July 1998 <http://www.eren.doe.gov/consumerinfo/refbriefs/tpbldgs.html>.

America's building energy, this statement suggests that the remediation of these windows is an advisable first step. Unfortunately, as a guide for action, the statement is crippled by ambiguity. Without a definition of what "poorly insulated" denotes, the magnitude and, more importantly, the solution of the problem cannot be determined. What distinguishes a *poorly--insulated* window from any other? How many windows in the nation fit this description? What can we do to *fix* them? Very little can be done to improve the insulation of a window once it has been manufactured, thus *upgrading* a window essentially translates into *replacing* a window. If the DOE is encouraging a group replacement of windows why does it omit the role of *radiated* heat transfer on heating and cooling loads? Insulation only affects the transfer of heat through conduction and convection. Solar gain and radiated heat loss are also both large, but *avoidable* contributors to heating and cooling loads. New windows need to be purchased with consideration for all the processes by which energy is lost through fenestration.

My attempts to clarify these concerns directly with the DOE subsidiary organization that posted the statistic were unsuccessful. My first contact there could not answer my questions, but gave me the email address of someone he thought could. Curiously, the note I sent to that address was answered by my first contact again. This time, however, he informed me that, "the trail to [the statistic's] origin has eroded to the point where it is un-hikeable."[4] In other words, the calculations through which the Energy Information Association had compiled the statistic, before posting it on the Energy Efficiency and Renewable Energy Network web site, were lost. Though something of a setback, the uncertainty surrounding the statistic only fueled my interest in the subject. Therefore, as a means to minimize energy consumption by buildings, I have studied the upgrading of fenestration to reduce heating and cooling loads. The following four questions have shaped the path of this study

i. What defines a *poorly*- (and conversely, a *well*-) insulated window?
ii. Are all new windows *well* insulated?
iii. How significant is radiated heat loss and solar gain to heating and cooling loads? Is it sufficient to just look at the insulation of a window unit, or does the overall fenestration system play a role in these loads requiring of attention?
iv. Are energy design tools, the new recommendation of energy consultants, helpful to traditional building designers looking for guidance on improving the fenestration system?

[4] Paul, Hesse, E-mail, "Reference for (non)-EREC statistic," 17 March 1999.

II: The Mechanics of Heat Transfer

When I first read the DOE indictment of poorly—insulated windows, I imagined rotting wood windows with flaking paint and cracked windowpanes. Consequently, I first researched the magnitude and effects of air infiltration through windows. Heat exists in two forms, sensible and latent, both of which are contained in a given volume of air. Sensible heat is the energy associated with temperature: the rate at which molecules in a substance are moving. Latent heat is the energy locked up in the water vapor carried by air. While sensible heat passes through all materials, latent heat travels only with air movements. By this stipulation and the nature of its (water molecule) carrier, latent heat is associated with humidity. Humidity makes air feel hotter than its true temperature because humidity impedes the evaporation of perspiration from our skin, the natural mechanism by which we cool. Thus, as a medium of heat transfer, humid air, unlike all other substances, carries both forms of heat and makes a room feel even hotter than it is. From this point of fact, I first hypothesized that the needless cooling expenditures referenced by the DOE statistic were generated by the infiltration of humid air through cracks in window units. I ascribed the heating loads also attributed to *poor* window insulation by the DOE to the leaking of indoor air out the same cracks. However, my research refuted that intitial theory.

Air leaking through and around the windows of a building has little effect on indoor temperature. Moreover, the leaks serve a vital function for the overall building system. Infinitesimal amounts of air moving through a building envelope help maintain a balance of pressure between the interior and the exterior. In addition, tightly—sealed buildings without mechanical ventilation need some way to recycle stale indoor air. Poorly sealed homes, in which 30 to 40 percent of the heating load might stem from uncontrolled air infiltration, have drafts coming through the floor, ceiling and wall cavities that are far more significant than those coming through the windows.[5] The typical infiltration through a new window falls in the range of 0.1 and 0.6cfm of air (under test conditions) which is virtually undetectable.[6] And owners of old leaky windows rarely hesitate from blocking major cracks with weather stripping or sheets of plastic. Cheap yet effective, weather stripping eliminates any energy loss that *could* be associated with air leakage through windows. As stated by Consumer Reports:

> Weather stripping, which blocks drafts around doors and windows, won't save much energy. Recent studies have shown that such drafts actually contribute little to overall heat loss. Still, weather stripping will do a lot to make the house feel more comfortable. That may save some energy indirectly since you may not need to turn up the thermostat as much if the room isn't drafty.

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[5] John Krigger, Residential Energy, Cost Savings and Comfort for Existing Buildings, Quality Books Inc., Thomson-Shore Inc., 1994, p.55.

[6] Design Issues and Strategies: Energy Overview, Energy Crafted Home, (A project managed by Conservation Services Group and sponsored by utilities in the Northeast), 15 June 1990, chapter 4-11.

John Krigger, Residential Energy, Cost Savings and Comfort for Existing Buildings, Quality Books Inc., Thomson-Shore Inc., 1994, p. 112.

(For more information on weather stripping, see Appendix A)

With my initial theory - that air infiltration was largely responsible for the nation's excess need of heating and cooling - shown to be incorrect, I turned my attention to the transfer of sensible heat through the window unit. Sensible heat moves by three mechanisms: conduction, convection and radiation. Conduction occurs through solids, liquids and gases, while convection flows through only the latter two media. Radiation involves the transfer of heat from one object to another via infrared heat waves and, thereby, does not affect the air temperature between the two. From this information, I concluded that the DOE statistic considers only the contribution of conduction and convection on heating and cooling loads. Because windows are installed to transmit light, any insulation inserted between the panes must be transparent. Infrared heat penetrates transparent materials. Thus, upgrading the insulation of *poorly—insulated* windows will not affect the transfer of radiated heat through the glass of these units. In short: a building's *heating load* is the amount of heat, ideally balanced between sensible and latent, that must be added to the building on the coldest day of the year in order to keep it warm. Conversely, a building's *cooling load* is the rate of heat rejection required on the hottest day of the year to the keep the building cool.[7] Logically, therefore, heat transfer through the building envelope, by all avenues of travel, will affect these loads. That DOE raises the connection of heating and cooling loads to windows, but excludes the contribution of solar energy and heat radiated through the glass is odd, to say the least. In hopes of finding a sensible explanation for this omission, I undertook a more detailed study of the mechanisms by which heat transfer occurs through windows.

The Mechanics of Heat Transfer

Conduction is the chain reaction of movement between adjacent molecules. Through the building envelope, conductive heat transfer is driven by the temperature gradient between the exterior skin and the interior wall. In the Northeast, where the summers are relatively mild, conductive heat *gain* (from the outside in) is negligible. Substantial conductive heat gains are associated only with those circumstances where the sun shines directly on a section of building wall or roof. Conductive heat *loss* occurs through building components that are more conductive than air and bridge the inside face of the wall with the outside. The *conductivity* of a material quantifies how quickly heat flows through it. Aluminum, for instance, has a thermal conductivity of 117Btuh*in/sf/F° , while glass has a conductivity of only 0.65Btuh*in/sf/F° and air, a mere 0.015Btuh*in/sf/F°[8].

The conductivity of a window unit is usually stated in terms of a U-value: the number of Btu that flow through a square foot of the material for each degree Fahrenheit difference from one side to the other, in an hour. This differs from conductivity (k) and conductance (C) because it refers to the entire building component rather than just an inch, or other specified thickness, of the constituent materials. The U-value is a fairly

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[7] John Krigger, Residential Energy, Cost Savings and Comfort for Existing Buildings, Quality Books Inc., Thomson-Shore Inc., 1994, p. 228.

[8] John Krigger, Residential Energy, Cost Savings and Comfort for Existing Buildings, Quality Books Inc., Thomson-Shore Inc., 1994, p. 53.

new unit of measurement within the industry. Introduced to complement the R-value, which denotes *resistance* to heat transfer, a U-value (the reciprocal of an R-value) more intuitively defines the *insulation* of a material. Unfortunately, linear quantitative comparisons can not be calculated between U-values. In order to demonstrate percentage comparisons and summate insulation factors, U-values must be converted into R-values.

The U-values of walls, ceilings and floors range between 0.05 and 0.01Btuh/sf/F°, while those of windows generally fall between 1.7 and 0.25Btuh/sf/F°. The magnitude of difference between these two ranges is more obvious through R-values: 19 to 60hr*sf*F°/Btu for general building components and 0.6 to 4hr*sf*F°/Btu for windows. The five to twenty factors of magnitude between the insulation of building components and that of windows expresses the liability of fenestration to heat loss through the building envelope. However, a second look at the R-value range for the typical window also reveals the disparity in insulation available for windows. If a window with an R-value of 4 is installed instead of one of 0.6, conductive heat loss is reduced by 650 percent. Or, even more amazing, the installation of a premium efficiency window, with an R-value in the ballpark of 8hr*sf*F°/Btu, (U-value: 0.125Btuh/sf/F°) would reduce conductive heat loss by as much as 1300 percent!

Convection involves the bulk movement of heat between areas of unequal density within a fluid or gas. Since density is inversely proportional to temperature, convection is driven by the same temperature differential as conduction. Convection currents form both near and between the glass panes of a window, as well as within wall cavities. In the wintertime, convection currents are begun by the conduction of heat from the inside air to the outside through the window. Air sinks as it loses heat, pushing air below outward into a warmer area. When the displaced air collects heat from its new location, it rises, pushing the air that was above back toward the window. The cycle is perpetuated by the conduction of heat from the newly arrived warm air out through the window. Convection currents thereby feed heat from the middle of the room to the window where conduction transports it outside. The movement of air also creates wind currents, commonly referred to as *drafts*. Often mistaken for outside air infiltration, drafts create a perceived need for more heat resulting in higher heating expenditures.[9] Because convection currents are begun by the conduction of heat through the window unit, insulation reduces heat loss through convection. Therefore, the DOE recommendation to improve window insulation at least addresses two of the three mechanisms by which heat transfer occurs.

Radiation differs from conduction and convection because it does not involve a molecule of air or material for travel. The infrared heat waves of radiation are both their own engine and wheels. Thus, while increasing the insulation of a window inhibits the movement of molecules through which conductive heat transfer occurs, radiation continues to pass through with relatively little resistance. Radiation, at least in the Northeast, is also distinct from conduction and convection, because it brings a significant amount of heat *into* the building, as well as out. At worst case scenario, 75 percent of the residential cooling load is attributable to heat transmitted through windows with

[9] John Krigger, Residential Energy, Cost Savings and Comfort for Existing Buildings, Quality Books Inc., Thomson-Shore Inc., 1994, p. 55.

sunlight.[10] Known as *solar gain*, this passive source of heat exacerbates cooling loads in the summer but reduces heating loads in the winter.

The ratio of solar gain to outdoor sunlight depends upon the incidence at which the sunrays strike the glass. Consequently, the orientation of a window dictates, in large part, the amount and timing (summer versus winter) of solar gain. The sun is high in the summer, so the incidence of the sunrays is closer to horizontal with the windows at sunrise and sunset. Therefore, the most solar gain is transmitted through fenestration on the east and west exposures of a building. At midday, the sun is overhead, so the rays are practically vertical with the window and cannot penetrate. Conversely, in the wintertime, the sun is naturally low thus the incidence of the sunrays is closest to horizontal around midday. The obvious conclusion to be drawn from this information is that windows on the south face of a building offer the potential for passive winter heating while those on the eastern and western elevations simply exacerbate summertime cooling loads. Even though this assumption is fundamentally correct, there is some imprecision because sunrays hit the window face with a range of angles between horizontal and vertical. Furthermore, the need for heating and cooling is not confined to the depths of winter and the heights of summer. Solar gain through the east in autumn beneficially warms a building after a cold night. Solar gain through south-facing fenestration on a hot spring afternoon will burden an already loaded cooling system. As a complement to the control of solar gain by fenestration design (size, layout and orientation), and to inhibit the radiation of heat *out* of building windows, glass manufactures have developed filtration coatings for windows. These coatings are able to differentiate between heat waves and visible light waves by wavelength, permitting only the latter to penetrate. The target cutoff wavelength is determined by the composition of the coating, so the coatings of different manufacturers allow through different percentages of heat for the sunlight transmitted. Therefore, the building designer must determine the level of solar gain desired before purchasing glass and coating.

Optimizing the balance between heating load reduction and cooling load exacerbation is obviously tricky, which may explain why the DOE ignored radiated heat transfer, fenestration orientation and coating application. However, the effect of solar gain on heating and cooling loads is sufficient that such an omission is costly, both for the building owner and the environment. In determining window performance, I believe the entire fenestration system must be analyzed and discussed, not just the insulation of the unit. Consequently, I proceeded to research the thermal performance of windows typically installed today, examining every component of the system.

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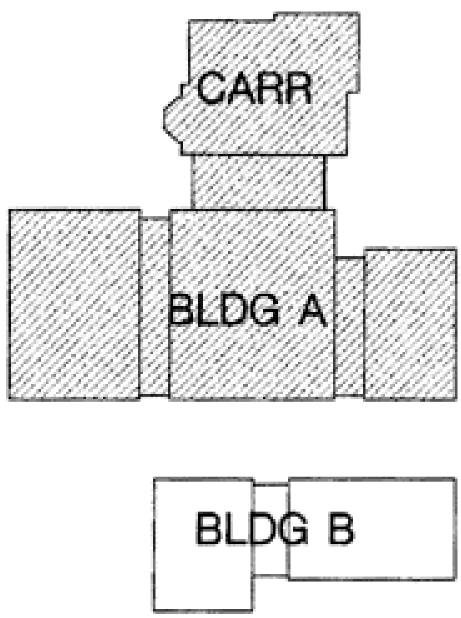
[10] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.13.

III: Case Study

In order to study the orientation, area, and construction of the fenestration – qualities unique to every building – I needed a case study. As I am a student at Brown University, I chose an ongoing University building project.

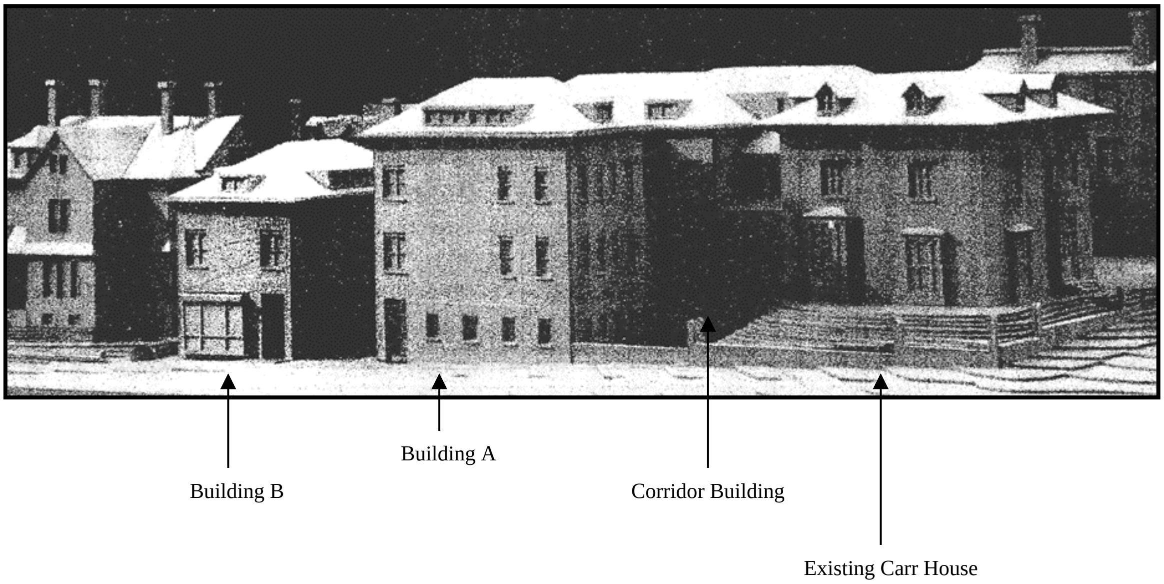
The recently completed, technologically replete W. Duncan MacMillan Hall was my initial proposed case study. Heralded as the University's masterwork in energy--conscience building, MacMillan Hall was tempting to scrutinize. However, as the building had already been completed, there was no opportunity for me to influence design. The next case study I investigated was the proposed Watson Institute for International Studies. A $15 million project designed by a "name" New York architect, the building has – at various evolutionary stages of the design – contained a large glass atrium, elevator towers projecting through the roof, projected glass box windows, and a glass–roofed main hallway. In spite of such extraordinary opportunity for fenestration analysis, I had to forgo the project due to delays resulting from a tug-of-war over aesthetics and costs between the trustees and the University design team.

Finally, I turned to Carr House. A restoration project with an expansion component, Carr House will house the University's creative writing program, English department and *black box* theatre space. As the project incorporates both window replacement and new window installation it provides a broad spectrum of issues for investigation. In addition, the choice of a local project architect and engineer eased acquisition of plans and engineering calculations.



The Carr House complex will in fact contain two buildings, though the project will carry the misnomer of simply *Carr House* through the continuance of this paper. Displayed in the site map at left, the addition includes two three–story rectangular buildings, separated by a thin alleyway. Building A is connected to the existing historic house by a corridor-like structure visually distinguished by a tin sheet veneer and casement windows on the exterior. The principal portions of the addition have a contrasting brick veneer and double hung windows. On the facing elevations of Buildings A and B are two large shop front windows that frame the front entrance–ways. Projected windows are located at the symmetric midpoints of the buildings, along the main axes. The existing Carr House has a range of wood windows.

The complex will amass a total of 40,000sq.ft. and is categorized as commercial office space under US Bureau of the Census guidelines due to its significant allotment of space to administration and faculty offices.[11] The DOE cites commercial buildings as accountable for 15 percent of United States' carbon-dioxide emissions[12] and 40 percent of national building energy consumption.[13] Considering the magnitude of United States energy consumption on a global scale, these percentages are clearly sufficient to warrant a focus on the thermal performance of commercial building fenestration.



[11] Energy Information Association, Description of Building Types, Commercial Buildings Characteristics, 14 Aug. 1997 <http://www.eia.doe.gov/emeu/cbecs/char95/appendc.html >.

[12] Statistic includes emissions from the generation of the electricity consumed by buildings.

[13] EREC Brief: Energy Efficiency and Renewable Energy in Buildings, Energy Efficiency and Renewable Energy Network (EREN), US Department of Energy, 23 July 1998 <http://www.eren.doe.gov/consumerinfo/refbriefs/tpbldgs.html>.

IV: Assessing Window Insulation

Ten years ago, triple glazed wood windows with U-values of 0.4Btuh/sf/°F were considered state of the art.[14] Today, the premium high-tech window has a U-value of 0.09Btuh/sf/°F. While the upper bound of window performance has risen tremendously, windows at the lower end maintain a sizable share of the market. Windows that do not incorporate any of the new technological advances for improved thermal performance have U-values of 0.4Btuh/sf/°F and above. The conduction of heat through these windows allows further heat loss by radiation and convection. The inability of these windows to hold heat generates condensation, which inhibits visibility through the glass and encourages mold growth. *High performance* windows, superior in their insulation and unlikely to incur condensation cost 15 percent more. The 33 percent improvement in energy efficiency achieved by these windows redeems the incremental cost over time, but enhanced comfort is a better argument for their purchase than "cost-effectiveness."[15] As suggested in Chapter One, the puncture of the building envelope with fenestration is rarely cost--effective, so to base window selection solely on that factor is illogical. Windows are installed to enhance occupant comfort by providing light and view. Therefore, when windows reduce occupant comfort, they cease to justify the inherent heat loss of their incorporation. Such is the case for the windows proposed for Carr House.

The boundary U-values stipulated by the architect for the windows of a project sets the tone for the entire specification. The constraining U-values for the windows of the Carr House expansion have been set at 0.63 and 0.55Btuh/sf/°F, as follows:[16]

> Section 08520 ALUMINUM WINDOWS 1.09 Testing and Performance Requirements
>
> Thermal Transmittance Test (Conductive U-Value)
>
> With window sash closed and locked, test unit in accordance with AAMA 1503.1-1988
>
> b. Conductive thermal transmittance (U-Value) shall not be more than .63 BTU/hr/sf/degrees F.

> Section 08520 ALUMINUM WINDOWS 1.09 Testing and Performance Requirements
>
> Thermal Transmittance Test (Conductive U-Value)
>
> With window sash closed and locked, test unit in accordance with AAMA 1503.1-1988
>
> b. Conductive thermal transmittance (U-Value) shall not be more than .55 BTU/hr/sf/degrees F.

These specifications are about 30 percent weaker than those of MacMillan Hall, the University's last major building project. The level of insulation prescribed by these U-values is just that of a single glazed window with a storm window. Any double glazed

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[14] Mark A. Jackson, "Superwindows" Retrofit Show Significant Energy Savings, Home Energy Magazine Online, Sept./Oct. 1994 <http://www.homeenergy.org.eehem/94/940910.html>

[15] What's Working and E Build, Inc., "Windows and Doors," Environmental Building News™ Product Catalog, 1998.

[16] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English Department, March 1999.

window with these values is “poorly-insulated” under any definition of the term. The components that lead to such window performance deficiencies are highlighted through the following critique of the Carr House window specification.

Windows consist of four principal sections: the sash, frame, structural opening, and glass assembly. **Sashes** hold the glass panes and are either sliding, hinged, or fixed. Of the three standard sash designs, casement and awning (vertically and horizontally hinged) seal the tightest and open most effectively for ventilation, while double-hung (sliding sash) hold the market edge for their traditional aesthetic. The fenestration of the Carr House renovation and addition includes both casement and double hung sash designs.

The **frame**, as its name suggests, holds the sash within the window cavity or “rough opening’. The frame's most significant property, from the standpoints of both aesthetics and energy efficiency, is the material of which it is constructed. The cheap and low maintenance choice has traditionally been aluminum. However, since the discovery that aluminum frames are direct conduits for indoor heat to escape outside, epoxy and vinyl sections have been incorporated as “thermal breaks”. If the sections are continuous throughout the entire unit, including the mullions and sash, the U-value for a typical residential-sized aluminum window decreases from 2 to 1. However, even a full partitioning of the exterior portion of the frame from the interior can not raise the thermal performance of aluminum to within 15 percent of either wood or vinyl.[17] Through their own “real world” retail research, Consumer Reports determined aluminum to be a poor choice for Northeast buildings, regardless of the low initial cost and maintenance. As published in the journal: [18]

> In cold weather, heat inside the house travels readily through the [thermally–broken aluminum] frame to the outdoors, making the indoor side of the window feel cold to the touch. In a temperate climate, an aluminum frame may be a practical choice. But it won’t offer the best thermal protection in cold New England winters.

The windows specified for the Carr House addition are nonetheless aluminum.

Commercially produced aluminum windows conduct heat because the “poured-in-place two part polyurethane” thermal barrier, as specified in the Carr House specification, is of insufficient width. High-quality custom aluminum window manufacturers such as Kalwall and Visionwall, however, do construct well-insulated aluminum frames.

As expansive fenestration designs, such as curtain wall, have yet to be constructed from materials other than aluminum, this is the only material choice for the storefront windows of Carr House. To maximize the thermal performance of the storefront windows, language prohibiting thermal bridging by structural components must be included within the specification.[19] As written in the projected window specification: [20]

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[17] Cooperative Extension of University of Massachusetts, Windows, Super Good Cents Program Manual: 1987: ch. 5.7.

[18] Consumers Union of United States, Replacement Windows, Consumer Reports: 58(100): Oct.1993: pp. 664-67.

[19] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English

Section 08520 ALUMINUM WINDOWS 2.04 Fabrication [Hung Windows] A. General

> 2. Mechanical fasteners, welded components and hardware items shall not bridge thermal barriers.

This stipulation prevents the transfer of heat around the thermal break through structural components and metal latches.[21]

The remaining windows of the project are not constrained by their structure to a particular material. However, the frame material for the windows of the existing Carr House is limited by a desire for historical accuracy. Wood carries a lower embodied energy than aluminum and provides better insulation, but is also substantially more expensive and maintenance intensive.

Wood is susceptible to rot and must be preserved, and then stained, painted or covered. Preservative treatments typically include ingredients like the following used by Pella:[22]

Polyphase=ICBO
3 parts ICO (iodine)
2 parts Popynyl
Butyl Carbamate (fungicide)
Dursban (insecticide)
98% mineral spirits

To illustrate the potential harm of these base coatings: it takes only one fifth of an ounce of Dursban to kill an adult human. Paints and stains, the manufacturing of which produces toxins, release VOCs (Volatile Organic Compounds) at application. Applying the first set of finishes at the factory ensures a more durable job and greater containment of pollutants than could be achieved on site, but subsequent applications are not afforded the same opportunity. To offset the environmental and health risks that are related to paints and stains, wood window manufacturers offer a wide range of plastic or metal claddings as exterior covering.

Vinyl cladding is inexpensive and a good insulator, but prone to shrink and expand over small temperature differentials, leading to frame failure. [23] In addition, vinyl is available in only a limited selection of colors, all of which eventually fade or brown. An acrylonitrile butadiene styrene (ABS) called CYCOLAC® was recently introduced onto the market in a greater range of colors, but remains virtually untested for durability. Aluminum cladding, on the other hand, is assuredly durable and long lasting. Now manufactured in an extruded form to resist the denting and bending common to the traditional rolled sheet, the material's major drawback remains its conductivity.[24] In spite of the air pocket incorporated between the frame and the cladding by some manufacturers

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Department, March 1999.

[20] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English Department, March 1999.

[21] Cooperative Extension of University of Massachusetts, Thermal Performance of House, Super Good Cents Program Manual: 1987: ch. 1.4.

[22] terrain@cow-net.com, " GBList Re: windows," Online Posting, 12 January 1999, Green Building List Serve <greenbuilding@crest.org>.

[23] Efficient Windows: Benefits, Efficient Windows Collaborative, 27 Jan. 1999 <http://www.efficientwindows.org/energycosts.html>.

[24] Loewen Promotional Spec Sheet (Loewen Windows, PO225 ENG0896/50)

to improve insulation, aluminum cladding typically increases the U-value of a wood frame a full Btuh/sf/°F.[25]

Cladding protects a window from superficial water damage, but even the moderate absorption of moisture by the frame induces swelling and "pulling away" at the joints. To ensure that frames withstand these stresses, Consumer Reports recommended the purchase of windows with double mortise and tenon joints at the corners, rather than simple screws.[26]

> Section 08550 WOOD WINDOWS <u>2.02 Millwork for Historic Sash and Related Parts</u>
>
> A. All wood shall be straight grained solid of a species listed below… All millwork shall be mortise and tenon and slot and tenon.

The scarcity of the hard wood, from which quality wooden frames are manufactured, is another environmental issue raised with use of the material. As illustrated by the Carr House material specification, only top quality, knot free, hard wood is acceptable for window construction:[27]

> Section 08550 WOOD WINDOWS <u>2.02 Millwork for Historic Sash and Related Parts</u>
>
> A. All wood shall be straight grained solid of a species listed below…
>
> B...
>
> C. Wood Species for sash:
>
> 1. Sash stiles and rails: Clear Sweitenia mahogany
> 2. Interior glass stops: Clear Sweitenia mahogany
> 3. Parting beads: Clear Sweitenia mahogany
> 4. Sash Blocks: Clear Sweitenia mahogany
>
> Section 08550 WOOD WINDOWS <u>2.09 Materials for Sash Repair</u>
>
> C. Wood Materials
>
> 1. Wood for splicing, dutchman or solid wood fill exterior or opaque finished repairs shall be premium grade straight grained mahogany… Wood shall be free from all imperfections which might impair its strength, durability, or appearance.

The upside of a high price and scarcity is that these woods can be profitable *sustainable* crops. *Sustainable farming* or in this case *sustainable timber harvesting* involves the selective growth and falling of trees, in contrast to clear cutting. Though no North American window manufacturer exclusively uses wood harvested from certified well-managed forests, requests for the wood by purchasers encourages more extensive

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[25] <u>Efficient Windows: Benefits,</u> Efficient Windows Collaborative, 27 Jan. 1999 <http://www.efficientwindows.org/energycosts.html>.

Loewen Promotional Spec Sheet (Loewen Windows, PO225 ENG0896/50)

[26] Lerner|Ladds Architects, Inc., <u>Project Manual</u>, Brown University Carr House English Department, March 1999.

[27] Lerner|Ladds Architects, Inc., <u>Project Manual</u>, Brown University Carr House English Department, March 1999.

incorporation of the material.[28] Another means to slow the exhaustion of forests is to substitute laminated-veneer and laminated-strand lumber for hardwood in unseen joints. These e*ngineered wood*s are manufactured of wood scraps and strong glues, which make them more resilient to weather and easier to replenish, than traditional wood.[29]

Vinyl is also an easy and inexpensive material to generate. However, in spite of the fact that vinyl frames provide the same level of insulation as wooden ones and are virtually maintenance free, they incite much criticism:

> To speak of quality vinyl seems a misnomer (or mismonomer)- vinyl is a cheap plastic by design (its wide use is an indicator of some design success), a poor use of its base ingredients, and a misuse of the environment.

Poly-vinyl-chloride (PVC) is banned in Europe because of the toxins involved in producing the chlorine component and the nastiness of the additives required for durability and flexibility.[30] Manufacturing movements to alleviate environmental concerns by using recycled PVC have been exposed as frauds, since the process is economically infeasible.[31] Anderson's scrap PVC/post-industrial recycled wood hybrid material, Fibrex®, is the sole exception to this rule because the materials are taken directly from other manufacturing lines on site. Incorporated into their Renewal™ Line, the sash and frame material is virtually maintenance free like PVC, but stronger and less susceptible to shrinkage and expansion because of the wood additive.[32] PVC is so sensitive to heat that even a sunny day will induce decay, resulting in a slight odor known to irritate hypersensitive individuals. In fires, PVC releases lethal dioxins with combustion.[33]

The most energy-efficient of mass-marketed frames are made out of fiberglass. Recently reintroduced in a new pultruded form[34], foam-insulated *Fibertherm* frames provide better insulation than wood, have a similar look and maintenance schedule to aluminum, and are manufactured by two environmentally responsible companies, Accurate Dorwin and Thermotech Windows Ltd. The coefficient of thermal expansion for fiberglass is identical to that of glass, coordinating the shrinkage and expansion of the frame and glass to that of a single unit. The stress avoided on the glass-to-sash seal helps ensure the resilience of the window to condensation, air infiltration, and leakage of the insulating gas. Fiberglass is also exceptionally strong, which allows the frames to be cut

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[28] Alex Wilson, Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: p.14.

[29] Alex Wilson, Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: p.15.

[30] _____, Should We Phase Out PVC, Environmental Building News, 3(1): Jan/Feb 1994.

[31] Greenpeace, Executive Summary, PVC Plastic: a Looming Waste Crisis, undated <http://www.greenpeace.org/~comms/pvctoys/reports/loomingsummary.html>.

[32] Alex Wilson, Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: p.16.

[33] Andre Fauteux, Letter, Environmental Building News, 5(3): May/June 1996: pp.2-3.
_____, Should We Phase Out PVC, Environmental Building News, 3(1): Jan/Feb 1994.

[34] (*Pultrusion* denotes the process by which the fiberglass strands are *pulled* through the heat die.) Thermotech Windows, 5 March 1999 <http://www.thermotechwindows.com/col2.htm>.

narrow and increase the percentage of glazing within each unit. Or alternatively, the frame can be cut with a more narrow profile to permit a greater angle of light to penetrate.

Of course, strength, quality and comfort come at a price. The major drawback of fiberglass windows is that they cost $250 a piece for projects even as large as the Carr House. To keep production costs to a minimum, Accurate Dorwin and Thermotech offer only a limited range of sash designs and manufacture screens and structural components that lack some of the strength inherent to the frame. These qualifications keep fiberglass from taking a clear lead in the field as the frame material of choice. Nonetheless, the University should offer fiberglass window manufacturers an opportunity to bid on campus projects. The current sole-sourcing of wood and aluminum severely diminishes the University's ability to ensure comfort, energy, and economic efficiency through its choice of windows.

Heat loss through fenestration does not end at the frame perimeter. Convection currents form within **cavities** between the wall and the boundaries of the rough opening. Initially left for the weight and chain pulley-system used to open windows, the introduction of new window systems has virtually eliminated the need for cavities of this kind. Unfortunately, the windows of the existing Carr House do not follow this trend because of their awesome height and uncommon slenderness. Removing the weight and chain pulley system and filling the void can not be undertaken without rendering the windows inoperable. However, since the building will be mechanically ventilated and air-conditioned, such a trade off for the conservation of heat is tolerable. Opening a window in a climate controlled building disrupts the pressure (im)balance carefully constructed between the indoors and outdoors, leading to the suction of mechanically heated or cooled indoor air outside. Therefore, the opening of a window is a seldom and disparaged practice. Provided at least one window is left operational for the purposes of emergency ventilation or exit, sealing the remaining units will have little impact on the comfort of occupants. The cavities may then be pumped with Icyene, wet cellulose or some other means of expandable insulation. (Though technically insulation conducts heat better than air, such losses are minimal as compared to the savings in convection, radiation and air infiltration related heat transfers.)[35]

The final component of the window unit is the **glass assembly.** A single-paned glass assembly simply consists of a pane of glass sealed within the sash. An *insulated* glass assembly involves two or more glass panes, suspended a small distance from one another by a spacer. The extra layer of glazing creates a pocket in which dead air or gas is trapped to insulate against conductive heat transfer. The R-value of a double-paned system is almost twice that of a single pane.[36] However, the insulation provided by the air is severely undermined if the spacer is aluminum. *Warm edge* alternatives are comprised of dense foam plastic, plated, thin-walled and thermally broken steels, vinyl, fiberglass and/or wood.[37] As the effect of a spacer extends 2 ½ inches beyond its edge,

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[35] Cooperative Extension of University of Massachusetts, Thermal Performance of House, Super Good Cents Program Manual: 1987: ch. 1.5.

[36] Cooperative Extension of University of Massachusetts, Windows, Super Good Cents Program Manual: 1987: ch. 5.3.

[37] Efficient Windows: Benefits, Efficient Windows Collaborative, 27 January 1999 <http://www.efficientwindows.org/energycosts.html>.

the U-value of a typical 3' X 4' window is 1.0 Btu/hr-sq. ft-°F higher with an aluminum spacer than a warm edge alternative. The six to eight degrees (°F) afforded by a warm edge spacer, at the bottom of the window also reduces the chances of condensation.

The Carr House window specification cites condensation resistance as a critical standard for a window to meet, but offers no guidance on how a window will meet the specification. The CSI Short Form Guide, from which the Carr House aluminum window specification was derived, references warm edge technology:[38]

> CSI Short Form Guide Specification (ANSI/AAMA 101-88 Format).
>
> Section 08520, ALUMINUM WINDOWS, Part: 2.02 Materials [Single-Hung Windows], E. 1.
>
> > Glass is to be 1" insulated glass units utilizing warm edge technology as manufactured by EFCO Corporation, a licensee under PPG Industries patents covering the Intercept™ IG unit and consist 3/16" at exterior, (5/8") air spacer and (3/16") interior.

But in the transcription, the Carr House spec includes only the glass and pocket dimensions.[39]

> Section 08520, ALUMINUM WINDOWS, Part: 2.02 Materials [Single Hung Windows] E, 1.
>
> > Glass is to be 1" clear float insulated glass units consist (sic) 3/16" at exterior, (5/8") air spacer and (3/16") interior.

This intentional omission of the warm edge reference, in addition to mention of "aluminum anodized spacer bars" in the budget submitted by Ricketson Windows for the restoration of the wood windows, suggests that the spacers of the Carr House windows will be aluminum.[40] Although an ineffective insulator, aluminum spacers have been standard protocol for the University. The spacers of the Macmillan Hall windows are also aluminum: [41]

> Section 08800 GLASS AND GLAZING 2.01 Glass Materials and Products
>
> D. Insulated Glass: Provide factory assembled, hermetically dual sealed units with dehydrated air space and having the following characteristics:
>
> > 3. Spacer: Aluminum with welded, soldered or bent corners…

Convinced of the cost and energy efficiency, the largest glass manufacturer, IPG, uses warm edge spacers in place of aluminum. Brown University should follow their lead.

The insulation provided by the air pocket itself has also been improved through replacing the air with a lower-conductivity gas. The rare gases krypton and xenon edge

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[38] CSI Short Form Guide Specification (ANSI/AAMA 101-88 Format). Section 08520, ALUMINUM WINDOWS, Part: 2.02 Materials [Single Hung Windows], E. 1.

[39] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English Department, March 1999, Section 08520, ALUMINUM WINDOWS, Part: 2.02 Materials [Single Hung Windows] E, 1.

[40] Peter Longo of RICKETSON Sash & Door Company Inc, "Re: Budget Quote, Windows and Doors. English Department Building. Brown University," 6 Nov. 1998.

[41] Koetter, Kim and Associates, Inc., Architects, GMP Package, Brown University Macmillan Hall, 16 Aug. 1996.

out the competition in performance, but argon, an abundant gas both in the atmosphere and on the market, yields a 33 percent improvement over air and costs only 10–15 percent more.[42] As with other missed opportunities, the Carr House windows are currently specified for air insulation.[43]

The optimal pocket width for air insulation is 1/2 to 1 inch. The ideal widths of argon and krypton fills are 1/2 and 1/4 inches, respectively.[44] The formation of convection currents negates the conservation of heat accomplished by increasing the pocket width beyond these ranges for extra insulation against conduction. Though the aluminum windows of Carr House will all have pocket widths within this range, those of the wood windows are inefficiently thin. The thinner pocket width specified for the wood windows is on account of the window's true divided lites.

Windows with true-divided lites are typical of residential buildings where the sash is split up with mullions into smaller square units, each with its own individual pane of glass. Glass panes lose the greatest amount of heat at their edges, so the system is innately inefficient.[45] Furthermore, when true divided lites are designed for insulated glass the mullions must be cut very thick, significantly reducing the size of aperture within each square. Therefore, the greatest energy loss associated with true divided lites results from the common preference for single paned glass, or inefficiently thin air pockets. The Carr House wood windows, which have 6 bays, further partitioned by true divided lites, are specified for the latter tactic. Since the thickness of jamb liner required to support standard 1" glass would severely intrude on the aperture of each bay, the architect has specified 1/2" insulated glass, with an air pocket of just 1/4" width.[46] The compromise, although preferable to using float glass, will not achieve the insulating advantage warranted by a $70,000 window replacement project.[47] A 1/4" fill of Krypton would be a more energy-efficient solution.

Another tactic to reduce heat loss around the circumference of each pane, and through the inadequately insulated glass, is the replacement of true-divided lites with a *faux-divided lite* grille. A single plate of insulated glass is inserted into the sash, and a checkerboard grille is affixed to it. The new aluminum hung windows of Carr House will incorporate such technology:[48]

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[42] Though sources cite small incremental cost, specific price percentage difference based upon Loewen Windows' *Heat Smart with Argon and Low-e* as compared to Loewen Windows' *Clear-Insulated*.

[43] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English Department, March 1999, Section 08400, ALUMINUM STOREFRONT, Part: 2.02 Materials B.

[44] Alex Wilson, Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: p.11.

Consumers Union of United States, Replacement Windows, Consumer Reports: 58(100): Oct.1993: pp. 664-67.

Design Issues and Strategies: Siting/Orientation, Energy Crafted Home. (A project managed by Conservation Services Group and sponsored by utilities in the Northeast), 15 June 1990, chapter 5-3.

[45] Alex Wilson, Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: p.12

[46] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English Department, March 1999, Section 08550, Wood Windows, A.

[47] Peter Longo of RICKETSON Sash & Door Company Inc, "Re: Budget Quote, Windows and Doors. English Department Building. Brown University," 6 Nov. 1998.

[48] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English

Section 08520 ALUMINUM WINDOWS Part 2 Products D.

> 1. Muntins shall be shop attached (non-removable), exterior grid designed to replicate steel, putty glazed sash. True muntins separating the insulated glass shall not be permitted in the vent.

Pella markets a line of wood windows, the Architect Series, which has wood grilles bonded to both pane faces and non-glare polymeric spacers inserted between the simulated-mullions, for a true-dimensional look.[49] In addition to minimizing heat loss, faux divided-lite technology reduces manufacturing costs and the possibility of seal and weather stripping failure.

For renovation projects that require replacement of the sash only, Pella has developed the Precision Fit Series. Custom fit to tolerances of 1/4", these extra narrow frames are easily inserted (*Do-it-yourself*) directly into the existing window frame, sash stops removed.[50] Unfortunately, the Carr House windows that require only a sash replacement have unconventional dimensions, well outside the range of mass-market sizes.

Bi-Glass technology offers a final means of enhancing the thermal performance of divided-lite windows with sashes in good condition. As more fully described in Appendix B, Bi-Glass technicians cut out the divided lites and manufacture a single insulated unit on site. As with Pella's Architecture Series, grids are affixed to both sides of the insulated glass unit. Since the mullion bars are no longer structural, they can be cut thinner to grant more room for the thick jamb liners required by full 1" insulated glass.

Radiated heat loss reductions through a window unit occur independent of the sash and glass pane design. The application of tinted and reflective coatings to a window will block 80-95 percent of the incident solar energy, but will block out portions of the visible light spectrum in order to do so. While this may a suitable solution for industrial or commercial enterprises with an internal heat gain sufficient to warrant draconian measures for the limiting of solar gain, most building occupants desire more visible light than these coatings allow. To address this need, low-emissivity (low-e) coatings were developed in 1979. As briefly introduced in Chapter Two, these transparent silver or tin-oxide coatings block out long-wave infrared radiation without dramatic distortions to incoming, shorter–wave visible light. (Speculation that low-e coatings block the transmittance of nutrients potentially contained in full spectrum light remains unsubstantiated.)[51] Applied either directly to the glass pane(s) or a thin polyester film hung within the air pocket, low-e coatings not only reduce the heat gain associated with sunlight, but also lessen wintertime heat loss by as much as 60 percent.[52]

Department, March 1999.

[49] Alex Wilson, Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: p.12

Pella Corporation (PPP Flyer 1998)

[50] Press Releases, Pella Window Corporation, undated <http://www.pella.com/about/pressREleases/precisionFit.asp?userType=remodeler>.

[51] Andre Fauteux, Letter, Environmental Building News, 5(3): May/June 1996: pp.2-3.

[52] Consumers Union of United States, Replacement Windows, Consumer Reports: 58(100): Oct.1993: pp. 664-67.

There are two classes of low-e coatings, Pyrolytic or hard-coat and soft-coat. Hard-coats are sufficiently rugged to handle exposure to the outdoors, as required by storm window and single glass pane applications. Hard-coats achieve their strength because they are actually incorporated into the surface of the glass during the manufacturing process. They are less expensive than soft coats, but also block a lower percentage of the heat transmitted with solar energy. Hard coats are therefore most suitable for situations in which solar gain is advantageous for passive solar heating.

Soft low-e coats are more plastic in nature because they are not actually fired into the glass. They are more amenable, as a consequence, to the suspended film application that simulates an extra layer of glazing. The quality also makes soft coats more susceptible to damage from the elements and human disturbance, so they must be applied to the inside layers of the glass. Within the soft-coat class, an additional coating, referred to as low-e^2, has recently been introduced onto the market. Both series of low-e coatings transmit between 70 and 75 percent of visible light, but low-e^2 transmits only about 35 percent of incident solar energy, while standard low-e transmits in the area of 55 percent. (Solar energy includes invisible ultraviolet and infrared radiation in addition to visible light.) The quantity of solar heat transmitted by a coating is denoted by the solar heat gain coefficient (SHGC) of the coating. The following comparison between two otherwise identical double-glazed casement, Fibertherm (fiberglass) windows from Thermotech indicates the range of SHGC's available:[53]

	Glass Properties			Window Properties	
Glass Code	Visible trans.	Solar trans.	U-value Btuh/ft^2/°F	SHGC	U-value Btuh/ft^2/°F
211 (Cardinal e^2, #2)	0.72	0.36	0.25	0.28	0.27
211 (LOF, #3)	0.75	0.58	0.29	0.49	0.30
Glass Code: # glass panes, # spacers, # low e coatings and argon gas fills (Low-e manufacturer, surface on which low-e is applied)					

The SHGC disparity is not a function of quality but market niche. Building designers looking to benefit from free passive solar heat require a low-e coating that insulates against heat loss but does not inhibit solar gain. Conversely, buildings with high internal heat gains need a low-e coating with a low SHGC that blocks solar gain.[54] As noted in the table, the specific pane face(s) chosen for application also varies according to intent. For example, to keep solar gain at a minimum, a soft low-e coating might be placed on the inside surface of the outside windowpane. This ensures solar energy is absorbed only through the first plate of glass before it is reflected.[55] Were soft coats less fragile, the coating would obviously be on the outside surface of the windowpane to prohibit any heat absorption.

The Carr House specification includes language for the application of a low-e coating to the glass of, curiously only, the wood windows. The aluminum windows, which are the concentrated fenestration on the eastern, western and southern (and

[53] Stephen's Column Vol. 1 No.2, Thermotech Windows, 5 March 1999 <http://www.thermotechwindows.com/col2.htm>.

[54] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.16

[55] Alex Wilson, Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: pp.1, 11.

therefore sunnier) exposures are overlooked for reasons unexplained. Contributing to the confusion, the low-e specification gives no indication for the intended purpose of the application:[56]

> Section 08550 WOOD WINDOWS 2.03 Glass and Glazing A
>
> 1. Provide glass with low E coatings

As detailed in the paragraph above, low e-coatings are available in a range of transmittance specifications, from which a client must chose the most appropriate. The MacMillan Hall project gave a complete low-e specification, which reads:[57]

> Section 08800 GLASS AND GLAZING 2.01 Glass Materials and Products
>
> B. Low Emissivity Coated Glass: Provide clear, non-reflective transparent metallic coated glass to match the Architect's sample; provide glass having the following characteristics [based on 1" insulating unit with outer layer 1/4" clear glass with low e coated on side 2 and inner layer of 1/4" clear glass]:
>
> 1. Daylight Transmittance: 75%
> 2. Daylight Outdoor Reflectance: 17%
> 3. Shading Coefficient: 0.75
> 4. Winter Nighttime U-value: 0.39 Btu/hr/sf/°F

Although the solar heat gain coefficient is now the accepted value by which heat gain is determined, reference is still made to the outdated *shading coefficient*. The shading coefficient compares the solar transmittance through the subject window with that of a single pane of glass. *Visible transmittance* is a straight percentage of how much light gets through with no internal base line with which to compare. *Transmittance of ultraviolet radiation* is measured in the same terms as visible light and as UV radiation fades furniture colors, it is best kept to a minimum.

In order to compile a complete low-e specification for Carr House, the optimal transmittance of solar energy for passive heat, cooling load avoidance and natural daylight must be established. With the goal of a minimum building energy load, the price of heating, cooling and lighting must be compared, along with the indirect costs of each. The following chapter weighs these factors, in part, for the purpose of writing the optimum low-e specification for Carr House.

Had Carr House not yet been at the 90 percent design level, altering fenestration design would have also been a recommended means of controlling the transmittance of solar gain. Downsizing and reorienting fenestration also, of course, reduces conductive heat loss through the building envelope.

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[56] Lerner|Ladds Architects, Inc., Project Manual, Brown University Carr House English Department, March 1999.

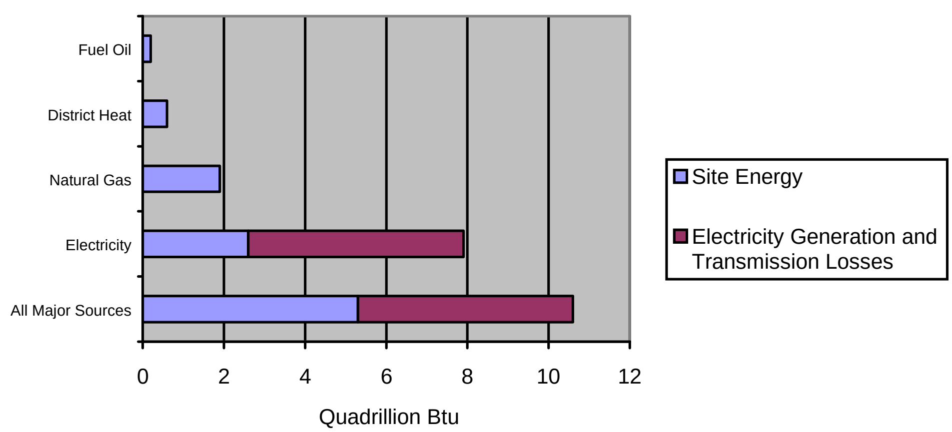
[57] Koetter, Kim and Associates, Inc., Architects, GMP Package, Brown University Macmillan Hall, 16 Aug. 1996.

V: Heating, Cooling and the Role of Solar Gain

There are two ways to determine the ideal transmittance of solar gain for the maximum optimization of heating load reduction and cooling load avoidance. (The word *avoidance* is used in place of, the perhaps more obvious, *reduction* to connote the nature of cool air as lacking heat.) The most precise approach — modeling the building using a computer simulation — will be further discussed in the next chapter. The less technical tactic is to compare the economic savings for each Btu of heating load reduction with the costs incurred by the indirect escalation of cooling load by solar gain. The latter method yields more approximate results, but they are direct and simple so I undertook finding them first.

Space heating consumes the largest portion of on-site building energy of all end uses. Fortunately commercial heating primarily utilizes gas or oil, so the total energy consumed for heating is just that used on site.[58] In contrast, 93 percent of commercial cooling is fueled with electricity, which consumes more energy to be produced than it yields on-site. The following graphic detailing the primary energy consumed for each energy source used by commercial buildings illustrates this distinction:

Primary and Site Energy Consumption by Energy Source, 1995

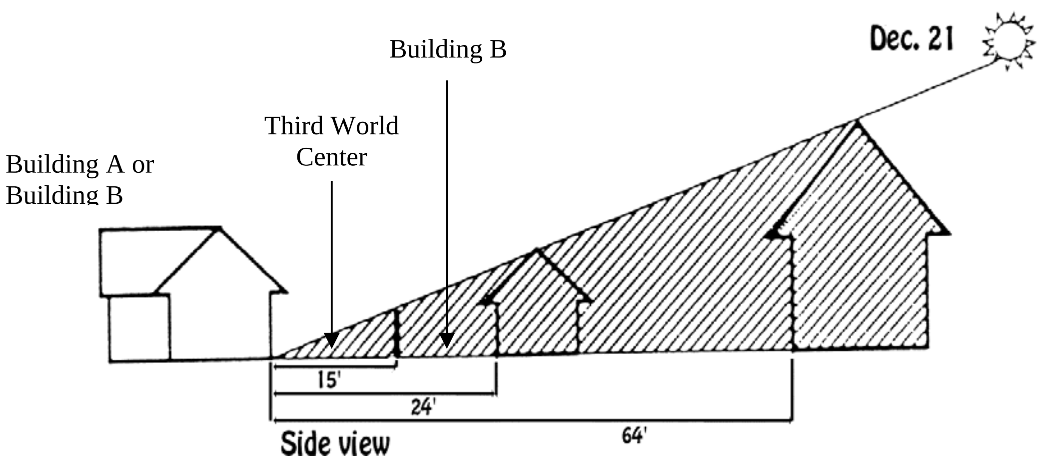


After factoring primary energy into its two main components, space heating remains the predominant use of energy, but the relatively low output of cooling per Btu of energy consumed is illuminated. As indicated by the graph, the energy consumed by electricity over gas and oil necessitates a larger increment of heating load to be offset through solar gain in order to warrant the indirect increase of the cooling load by one Btu. Nonetheless, the incentive for passive winter heating remains. The DOE asserts that the heating bill of a house can be cut in half as a result of simply a one percent increase in construction costs. The rules of passive solar design mandate that the longitudinal axis of the building faces within 5° of true south, 13° west of magnetic south in Providence. Deviations up to 30 percent only reduce heating performance by 5-20

[58] Energy Information Administration, A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures, p.19.

percent, but dramatically increase unfavorable summer solar gain with each degree. Window glazing must have a high transmissivity (making it especially vulnerable to summer solar gain) and a tilt between 60° and 90° from horizontal. The building energy load can be reduced a further 25 percent, without any additional construction costs, by the incorporation of efficient heating, cooling and lighting technologies throughout the house.[59]

However, the constraints of passive solar design extend beyond building design to the site. To receive 80 percent direct solar exposure between the hours of 9 a.m. - 3 p.m., the presence of any structure within 15 feet of the façade must be prohibited. Beyond this distance (or outside an angle of 45° radiating from the outermost window), a modest fence may be erected. Provided the nearest neighbor lives in a single story ranch house, they may situate just outside a periphery of 24 feet. However, no second floor additions may be added unless they relocate another 40 feet beyond that. These requirements disqualify Carr House from attaining any significant gains through passive solar heating. As shown by the diagram below, triple story Building B of the complex is located just 20 feet due south of Building A, and the Third World Center stands only 8 feet behind Building B, along the same axis.[60]



Although passive solar heat gain of any amount reduces the heating load of a building, Brown has little money to save by embracing such potential. The University efficiently generates the hot water for campus-wide heating at a central plant, and pipes out to each site as required. Centralizing the load means that the boilers are rotated at maximum capacity, achieving maximum efficiency. The only piece of machinery necessary on-site is a heat exchanger to facilitate the transfer of heat from the water to the fan coils distributed throughout the building. Consisting of tubes and coils rather than mechanical moving parts, the size of a heat exchanger, unlike cooling equipment, is a greater function of the quantity and flow of the incoming water (from the central plant)

[59] EREC Brief: Energy Efficiency and Renewable Energy in Buildings, Energy Efficiency and Renewable Energy Network (EREN), US Department of Energy, 23 July 1998 <http://www.eren.doe.gov/consumerinfo/refbriefs/tpbldgs.html>.

[60] Design Issues and Strategies: Siting/Orientation, Energy Crafted Home, (A project managed by Conservation Services Group and sponsored by utilities in the Northeast), 15 June 1990, ch. 5-2.

than its own heat generating capacity. Thus, the savings attained by reducing a particular building's heating load do not include the strict dollars per ton in reduced equipment, associated with cooling. The incremental monetary savings of reducing the University's heating load are thereby just from the fuel unused by the central plant for hot water production and distribution. Life Cycle Cost Analysis, performed by Vanderweil Engineers on behalf of the University's Barus and Holly project, factored this rate, accounting for 5 percent distribution losses, to be $0.59/therm.[61]

Conversely, Brown could spend substantial sums of money relieving buildings of the additional solar gain permitted in the summertime, as a result of the passive solar heat permitted in the winter. Brown uses the same central plant and pipe network to supply the campus with chilled water for cooling. However, due to the expense of the additional packaged cooling systems needed on site at each building, and the fuel choice of electricity (the industry-standard) for the central chillers, University cooling is more expensive per Btu than heating.

The flat–rate for electricity is not only higher than that of gas and oil (the fuel choices for heating) but the rate climbs on a sliding scale associated with *peak loading*. The centralized nature of electricity generation requires utility plants to establish their capacity against the compounded energy demand of their customers. Since people naturally gravitate towards the same basic schedule of energy use, power plants are vulnerable to dramatic deviations in energy demand throughout the day and year. Looking to operate the plant's prime (and most profitable) equipment at full capacity, distribution companies manipulate the market with rate scales. Thus, *peak rates* are imposed on large energy users, like Brown, during periods of peak demand. Conversely, lower rates are offered during the slumps to encourage consumption. Peak rates are closely linked to cooling, because the load varies according to weather and can not be predicted by time of day alone. A 1° rise in temperature on a summer afternoon in Los Angeles, as an example, translates into a 300megawatt increase in peak electric load.[62] E Source, an energy and environmental research organization, found the energy used to make buildings comfortable led to 43 percent of the summer peak loads in the United States.[63] As the building mechanical load that peaks in the summertime, cooling stands out as the source for these power crunches. The ramifications of peak loads are stress on distribution and the use of inefficient generation equipment at the plant. If peak capacity is reached too frequently, electricity-generating plants are forced to expand their general generation capacity, incurring enormous capital costs. To offset this new debt, base rates to the customer are not only raised, but greater electricity consumption is encouraged, increasing carbon emissions.

Increasing a cooling load does not only translate into greater operating costs, but significant equipment investments. Cooling equipment costs in the range of $1000-$1500 per ton.[64] Therefore, a 10 percent increase in the anticipated load of Carr House would translate into an additional $10,000 just for the equipment on site. Expanding the

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[61] G.R.G Vanderweil Engineers, Inc, HVAC System Options Life Cycle Cost Analysis for Addition and Renovations to Brown University, 3 March 1999.

[62] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.13.

[63] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.1.

[64] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.13. David Houghton, Building Comfort with Less HVAC, Architectural Record: Dec. 1998: p. 132.

capacity of the central plant would come at a significantly greater cost since equipment is already in place. Along these same lines, *reducing* the cooling load of Carr House would yield substantial initial cost savings.[65]

An article, (sufficiently meticulous in its research for approval by the American Institute of Architects for AIA Continuing Education credits to readers,) was recently published in the Architectural Record on building comfort with less heating and cooling. The author, President of the Resource Engineering Group, which specializes in energy-efficient mechanical systems for commercial buildings, wrote:

> Of [heating and cooling loads], cooling loads are the troublemakers because cooling capacity is more expensive to buy and install; chillers cost more than boilers. Cooling also eats up more building space than heating equipment and costs more to run — pumping 100,000 Btu of heat out of a building with electricity can cost twice as much as adding 100,000 Btu of heat with natural gas, especially during peak load times.[66]

Apparently, until the introduction of commercial gas cooling units (predicted to be 50 percent more efficient than today's best absorption chillers) the incurred costs for additional cooling would negate the savings by passive solar heating.[67]

Not only does this conclusion recommend against the pursuit of passive heating at Brown, but encourages more aggressive cooling load avoidance, even with the potential loss of passive solar heat. The following pie chart details the approximate distribution of cooling loads for a commercial building. An equivalent chart for Brown would dedicate a larger percentage of the load to solar gain, because the University has incorporated energy efficient lighting and machines.

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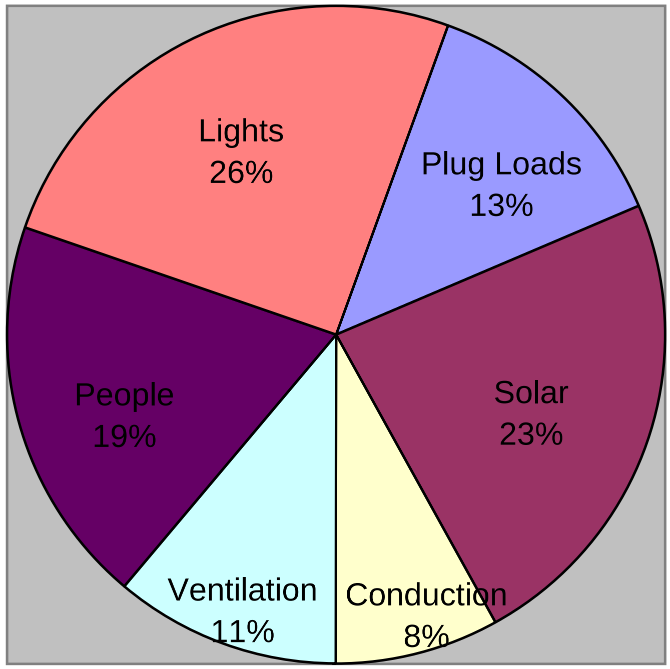
[65] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.13.

[66] David Houghton, Building Comfort with Less HVAC, Architectural Record: Dec. 1998: p. 132.

[67] Energy Information Association, Overview of Commercial Buildings Energy Consumption and Expenditures 1995, 18 Feb. 1999 <http://www.eia.doe.gov/emeu/cbecs/ce95/c&e_rept.html>.

Distribution of Cooling Loads for a typical 40,000sqft Commerical Building



Data from E-Source: Space Heating Technology Atlas [68]

E Source estimates that energy use for cooling can be reduced approximately 50 percent nationwide, through cooling load avoidance strategies.[69] One such strategy is to maximize of the transmittance of daylight. The most efficient source of illumination, daylight carries only one unit of heat for each unit of light. For comparison, incandescent lamps give off 9 units of heat for every unit of light that they provide, and compact flourescents emit 3 units of heat for every unit of light. However, maximizing the transmittance of daylight may also result in greater solar gain. And the most effective strategy for reducing a building's cooling load is to minimize summertime solar gain.

As explained in Chapter 2, eastern and western elevations accrue the largest quantity of solar gain in the summer. The following figures calculated for Springfield MA, whose latitude is within 0.5° that of Providence RI, show that eastern and western exposures gain 56 percent more summer solar radiation than southern. The following chart illustrates the progression over the course of the year[70]:

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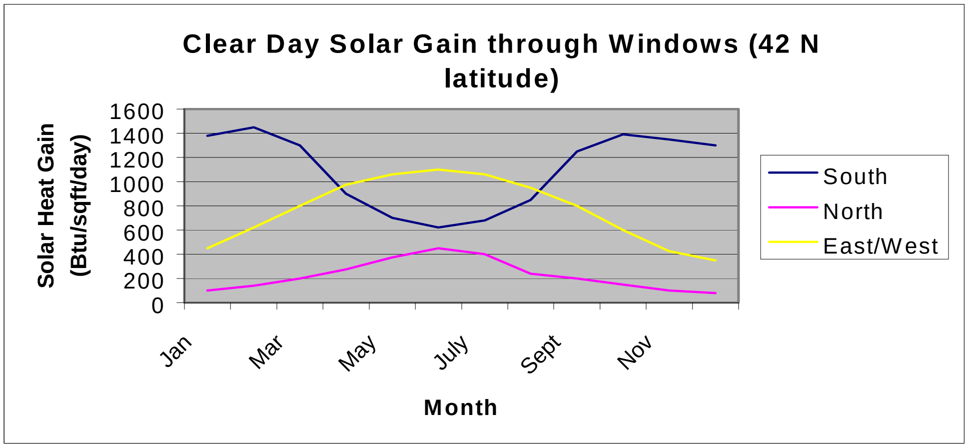
[68] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.15

[69] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.13

[70] Cooperative Extension of University of Massachusetts, Windows, Super Good Cents Program Manual: 1987: ch. 8.4.



Low as southern summer solar gain may be, designers recommend against adding a greater area of fenestration on the southern face of the building than would cover 8 percent of the floor area. Typical furnishings and drywall can absorb adequate heat to maintain a comfortable temperature within the room, provided the percent of fenestration remains under that level. Larger percentage ratios will lead to overheating, glare and fabric bleaching, as well as greater heat loss than gain in the wintertime.[71] The limiting fraction increases to 12 percent of floor area if other measures such as overhangs or thermal storage (slab floor, brick wall facing, etc) are incorporated.[72]

Optimizing an overhang for maximum winter passive solar heating, but minimum summer radiation is a tricky business. Some green building designers recommend nothing more than a modest built-in over hang, for aesthetic reasons as much as any other. In their opinion, design time and money is better spent on minimizing eastern and western fenestration and the application of low-e coatings, than overhangs.[73]

Since heating is relatively inexpensive for the University, and the Carr House site is not amenable to passive heating, the primary intent of the low-e coating should be to reduce the cooling load of the building. However, whether the best approach for the accomplishment of this task is to maximize day lighting or to block the transmittance of solar energy is difficult to determine. Current practices for calculating cooling loads offer no advice or suggestion on the optimization of this balance. Mechanical engineers typically incorporate day lighting and solar gain into cooling load calculations just through the following equations provided by ASHRAE:[74]

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[71] Design Issues and Strategies: Passive Solar, Energy Crafted Home. (A project managed by Conservation Services Group and sponsored by utilities in the Northeast), 15 June 1990, ch. 7-5.

[72] Alex Wilson, Keeping the heat out, Environmental Building News, 3(3): May/June 1994: p.16
Design Issues and Strategies: Passive Solar, Energy Crafted Home. (A project managed by Conservation Services Group and sponsored by utilities in the Northeast), 15 June 1990, ch. 7-6.

[73] swiftjr@NU.com, "GB: solar angles based on location," Online Posting, 2 May 1999, Green Building List Serve <greenbuilding@crest.org>.

[74] American Society of Heating, Refrigerating and Air Conditioning Engineers

$$\sum_{i=1}^{n}\left[CLUOi + CLXUOi + CLGi + CLSi + CLCi + CLCi\right] + \sum_{j=i}^{m} CLUi,\, j + CLMi,\, j$$

i = matrix consideration for each orientation
j = matrix consideration for each wall mass construction type for the given concentration
m = number of wall construction types per orientation
n = wall orientations
CLC = term that correlates cumulative annual cooling loads from internal gains (occupants, lights and equipment)
CLS = term that correlates cumulative annual cooling loads from incident solar gains
CLC = term that correlates cumulative annual cooling with climatic variables for a specific location

The value for solar gain, CLS, is computed simply upon basic ratios and values like the area of aperture to wall, orientation of the façade, and the temperature common to the location.

$$CLSi = FCi\left\{ EAi\begin{bmatrix} CS1i + CS2 \times VSi \times CDD50 + CS3i(VSi \times CDD50)^2 \\ +CS4i \times VSi \times CDD65 + CS5i(VSi \times CDD65)^2 \\ +EAi^2\left[CS6i + CS7(VSi \times CDD65)^2\right] \end{bmatrix}\right\}$$

EAi = effective aperture fraction for zone under consideration
VSi = annual average daily incident solar energy on façade
CDD50 = cooling degree-days base 50°F
CSni = coefficients based upon N,E, W and S

with Design Degree Days, as listed in the tables at the back of the book:

	Elevation (ft)	HDD65	CDD50
Providence	51	5884	2743

These equations do not incorporate the effect of critical, site—specific qualities, like external shades (neighboring buildings and trees) and common cloud cover, on the exposure of the fenestration to sunlight. Moreover, the internal heat gain avoided by offsetting electric lighting with sunlight receives mention only through the following qualification:

8.6.10.3 CONSTRAINT ON DAYLIGHTING CREDIT:

For a given orientation, daylight credit may be used in Eq. 8B-1 [General Cooling Equation transcribed above] and 8B-5 [parallel General Heating Equation] only for that portion of the fenestration area that is less than or equal to 65% of the gross wall area of orientation.[75]

[75] Design Issues and Strategies: Siting/Orientation, Energy Crafted Home. (A project managed by Conservation Services Group and sponsored by utilities in the Northeast), 15 June 1990, chapter 5-11.

(*Daylighting* is the industry term for the purposeful transmittance of daylight to offset the need for electric lighting.)

Obviously, these equations can not factor the trade-off between reduced electric light and greater solar heat gain. The only means through which a precise optimization may be obtained, incorporating all the tradeoffs and variables, is that provided by a computer modeling program. Such energy design tools factor in energy costs, system efficiencies, site and shade, and the effect of different low-e coatings on heating and cooling loads.

VI: Energy Design Tools

There are already over 100 different energy design tools from which to choose. They vary in breadth of analysis, simplicity of input interface and display of output. Some are particular to a single building component, such as the path of a shadow across an overhang, while others study the entire building, from the make-up of the foundational walls to the color of the roof. Picking the appropriate analysis tool for a project requires a degree of optimization unto itself; as the greater and more specific is the output, the more time and input intensive is the program. After exploring the range of tools available, (the list of which has been included in Appendix 3) I decided only a comprehensive whole-building analysis tool would suit my needs. For one, I wished to compare the heat emitted by electric lighting with the solar gain associated to daylighting. In order to balance the relationship, I required a design tool that varies lighting output to the daylight modeled within the room. Although programs that focus just on windows and lighting accomplish this task, they are incapable of translating the energy use and heat generated into heating and cooling loads, from which the overall building energy load can be calculated. Simplified (rather than *comprehensive*) energy design tools that incorporate the entire building system were unsuitable because they do not model the building's exposure to the sun, with respect to external shades. An area of uncertainty with regard to daylighting at Carr House is the level of natural light the building could even garner, considering the proximity of neighboring structures. Had I to repeat this process, I would give greater consideration to using a simplified whole-building design tool for general calculations, and incorporate the results from specialized analysis tools for components of special interest. Although using a single design tool to study every component of the building system in the desired detail eliminates the possibility for input redundancy, it also assures detailed input will be required for components less central to the user's study.

The pinnacle program of whole building energy analysis is DOE-2.1. However, the software is so complicated that "users" are trained "DOE professionals", who charge in the order of 10,000 dollars to model a building. Looking for a tool that architects could use, but engineers would trust, I turned to DOE-2.1—derivative programs with graphic front ends. These programs use the same accepted system, approximations and assumptions of DOE-2.1, but facilitate input with plain English user dialogue boxes, graphic renderings of the model, and simplified results. A sample of these programs includes EZDOE, Compare-IT and EnergyPro. EZDOE is appealing for every thing suggested in its name, Compare IT has an interface designed for novice energy analysts, and EnergyPRO will export forms to AutoCAD for direct inclusion into blue prints. Unfortunately, as all these programs have already been released, they carry price tags too steep for a student looking only to experiment with energy analysis. A researcher at the Lawrence Berkeley Lab, with whom I was in touch about modeling tools, recommended that I become a beta-tester for one of the new programs just coming out. Beta-testers are granted use of a program, free of charge, with the understanding that they can not make a commercial profit from the tool, and that they will provide the programmer with information on any difficulties or bugs experienced. As a student writing her thesis my situation was ideal for John Hirsh, the designer of PowerDOE, to grant me such license.

(Unfortunately, an unreleased program lacks the 750-page manual that typically accompanies other comprehensive energy design tools. Consequently, I spent the first month of my PowerDOE ownership compiling the hypertext-like help menu into a linear manual of steps to model a building.)

The foundational component of a PowerDOE model is a *space*. A space is virtualized as three-dimensional and does not require that a *surface* (wall, floor, etc) be constructed upon each face. Therefore, if only the heat transfer through the exterior wall is of interest to the user, then PowerDOE will not require the remaining surfaces be "built". However, the nature of comprehensive energy analysis requires that the space be connected to a full mechanical system, mode of use and occupancy schedule. In order for light and heat to translate into building energy loads, some *use* must be associated with the energy. After specifying a particular heating, cooling, and ventilation (HVAC) system, users must input details about the overall building so that PowerDOE can establish the size of the equipment. This stipulation inhibits architects from using PowerDOE before they have a building design from which to work. Ideally, PowerDOE would influence fenestration design from the onset of the design process. However, the specificity of input required makes the tool more amenable to individual component changes rather than total building design.

More specifically, the default examples provided by PowerDOE consist of only five or six different spaces while Carr House, a building with a fairly boxy design, has over 35. The simplicity of the PowerDOE examples was enabled by extensive use of multipliers based upon a repetitive building design. However, the goal of passive solar design is not to constrain creativity, but rather to push architects outside of traditional conventions. Therefore, to mandate that an architect use an energy design tool throughout the design process may force simplistic designs ideal for the tool's method of energy modeling rather than an architect's creative abilities. Such an outcome is neither preferable nor productive. A better approach toward accomplishing energy-efficient design is to educate architects on the general rules of thumb of passive solar design and mandate the use of energy modeling with the arrival of the engineer in the process.

As further support for PowerDOE's utilization by engineers versus architects, the technical knowledge required for modeling a HVAC system is found in an engineer's area of expertise rather than that of an architect primarily concentrating upon aesthetic design principles. In my case, it took two months just to acquire the specialized technical knowledge necessary to ensure correct input. Considering the deadlines and workload inherent to the architectural profession, it is unlikely that the traditional architect would make the time to master the technicalities and then enter them into PowerDOE. The following chart demonstrates the complexity and quantity of technical input each component of the system required:

Input Justification for Condenser Loop Pumps

Location: Miscellaneous (Click on "More")

Pump	CD Pumps
Head	92 feet
	Mechanical Equipment Schedule
Flow	

	Professional help from PowerDOE recommended that I input either Head or Flow and allow PowerDOE to size the other accordingly. Inputting both would confuse the program.
Head Ratio	N/a
Flow Ratio	1 (default)
	If allowed to size the pump itself, PowerDOE will oversize the design flow rate of the pump using this ratio. As we wish PowerDOE to come up with the same pump as already specified by the Carr House project mechanical engineer, who has already incorporated safety over-sizing factors, we will maintain the default value.
Head Setpoint	Only applies to situations in which the pumps have been attached directly to the equipment and not the loop itself. Therefore by keeping this square open, we instruct PowerDOE to default to the head setpoint of the primary loop.
Head Setpoint Ratio	Only applies to situations in which the pumps have been attached directly to the equipment and not the loop itself. Therefore by keeping this square open, we instruct PowerDOE to default to the head setpoint of the primary loop.
Pump Head F(Flow)	Pump-Head-Fflow **NOT YET CONFIRMED**
Pump Power F(Flow)	Pump-Power-Fflow **NOT YET CONFIRMED**
Electric Meter	EM1 **NOT YET INPUT**
Number	2
Pump Energy	Can input the design power consumption of the pump only if you have specified the corresponding flow rate. As we are letting PowerDOE dictate the flow rate, we leave this square open.
Motor Efficiency	As the Carr House project Mechanical Engineer has not specified the efficiency of the pump motor, by leaving this space open I alert PowerDOE to make its own estimation of the efficiency through the Pump Power and Motor Class.
Mech Efficiency	0.77 **NOT YET CONFIRMED**
	The mechanical efficiency of the pump impeller.
Min Speed	N/a
Motor Class	Premium
	Section 15500, p. 36/43
Capacity Ctrl	One-Speed Pump
	In lieu of any mention of variable speed motors by the Mechanical Engineer, the assumption is that all motors are one-speed.
Max Pump Ratio	1.3
	When two or more pumps are used in parallel, as in the case of the Carr House Project, a pump can typically move more fluid than the design rate as the fluid head is lower than the design value. PowerDOE defaults this ratio at 1.3 and strongly recommends against increasing it unless quite sure of accuracy. As I have no information to recommend any ratio number, I defer to the default.
Pump Power Exponent	3.05
	As an ideal pump would have an exponent of three to depict the variance of horsepower with speed, PowerDOE strongly recommends an exponent of 3.05 for all real world pumps.

(I have included much of my input justification within Appendix D)

The stipulations of a space for mode of use and occupancy schedule are tedious for any user to input, but are nonetheless worthwhile for the engineer's accurate assessment of a building's heating and cooling needs. Engineers currently evaluate these loads upon single numeric values representing occupancy, building configuration, and sunlight exposure. In order to meet the worst case scenarios within this framework, multiple safety factors are incorporated. Since the costs of later corrections lie with the engineer, while initial equipment costs and operating costs are borne by the client, engineers have a greater incentive to over-size the mechanical system than to optimize efficiency. Consequently, engineers add a blanket 25-30 percent to an anticipated load already calculated with safety margins of 20-100 percent for each component of the equation. These compounded safety factors can result in systems over-designed by 100 percent or more. Not only does this translate into a larger investment for the building owner, but also mechanical systems running at a highly inefficient 20-50 percent of capacity. [76]

The same calculations as developed for Carr House demonstrate the influence PowerDOE can have in mediating these issues. The calculations determining the Carr House heating and cooling loads currently incorporate a U-value of 1.1 Btuh/sf/°F for the wood windows and 0.62 Btuh/sf/°F for the aluminum windows. These values reflect the amount of heat transmitted through a single-paned window and a poorly insulated double-paned window, dramatically higher than the true expectations for the Carr House windows. That over–estimate of heat loss ensures that the engineer is covered in his calculations even if the windows do not perform to their listed U-value. PowerDOE would eliminate the need for such a substantial safety margin by modeling the exact heat transfer through the windows. Referred to as the *construction by layer* approach, PowerDOE models the delay in heat transfer through each component of the window unit according to the conductivity values it has for each material: glass, gas, aluminum, fiberglass, etc. The program even accommodates for the air film that naturally develops on the exterior face of windowpanes. Although somewhat tedious, the detail ensures that an engineer can trust the reading rather than apply excessive safety factors.

The tenets of Green Architecture are sufficient for an architect just setting off on building design. The fine-tuning facilitated by PowerDOE is helpful to the architect later in the process when, for example, low-e coatings and window unit construction must be specified. At this point, the engineer is involved with the project and can answer many of the concerns an architect would have in relation to building energy loads at the level of detail PowerDOE requires. Such a cooperation between the engineer and architect is fundamental to the design of energy efficient buildings. As stated in the Architectural Record:

> ..the architect determines many of a building's thermal properties by selecting its shape, color, layout, and composition. Engineers, who are not consulted on these decisions, may find themselves literally boxed into designing the size and capacity of heating and cooling system based on the architect's selections. But developing a mutually challenging

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[76] David Houghton, Building Comfort with Less HVAC, Architectural Record: Dec. 1998: p. 132.

partnership… means the team works together from the beginning to optimize the building's design.[77]

[77] David Houghton, Building Comfort with Less HVAC, Architectural Record: Dec. 1998: p. 131.

Conclusion

Although I was unsuccessful in running the model to arrive at an exact low-e coating specification, I feel confident that Carr House should incorporate a low solar heat gain coefficient on the eastern, western, and southern exposures. The potential for passive winter heating is low at Carr House due to the proximity of neighboring structures, while the cost of removing heat is high for Brown University. Fortunately for the facilitation of selecting a particular low-e coating, window manufacturers only provide a limited sample of the endless specifications available. Therefore, the stipulation for a minimum solar heat gain coefficient, within the confines of normal (70 – 80 percent) visible transmittance is adequate guidance for the contractor. The issue then, becomes one of choosing the window construction and manufacturer.

I recommend that Brown University extend the offer to bid on projects to manufacturers outside of the realm of wood and mass-marketed aluminum windows. High efficiency aluminum and fiberglass windows have been denied access to the Brown University market in spite of their superior thermal performance and guarantee for occupant comfort. Expanding the University's scope on windows would also allow for greater incorporation of technological advances as they develop in the field. The lack of stipulation for argon and warm-edge spacers reflects the dated nature of the University's window specifications.

However, as important as the logistics of fenestration are to achieving good building design, they should not overshadow what lies at the heart of an ideal window. In the words of a green builder:

> But for me what really matters is that we're using windows to make places fit for human beings. Windows in just the right spot, perhaps with a seat, and a pleasing view… where you feel at home curling up with a book or having a cup of tea… For example do you know that it's possible (although very, very hard) to make a building which makes you feel the way you do when a loved one smiles at you, or when a child holds your hand. That you have the power to make a place that you could love as much as standing in a meadow of flowers? Just writing about it sounds silly, but… I just want to remind folks- without that quality, we will not achieve a sustainable built environment.[78]

David Foley, " GBList: Windows- What Really Matters," Online Posting, 15 January 1999, Green Building List Serve <greenbuilding@crest.org>.

Bibliography

Books and Journals

A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures. Energy Information Administration.

Consumers Union of United States. Replacement Windows. Consumer Reports, 58(100): Oct.1993: 664-67.

Consumers Union of United States. Weather Stripping. Consumer Reports, 58(10): Oct.1993: 650.

Cooperative Extension of University of Massachusetts. Windows. Super Good Cents Program Manual, 1987: ch. 5.3.

Energy Crafted Home. (A project managed by Conservation Services Group and sponsored by utilities in the Northeast). 15 June 1990.

Fauteux, Andre. Letter. Environmental Building News, 5(3): May/June 1996: 2-3.

Houghton, David. Building Comfort with Less HVAC. Architectural Record, Dec. 1998: 131-136.

Houghton, David. The E SOURCE Columbine Building. E Source, PE TU-95(15): Nov. 1995: 22.

Howard, Bion. Putting the Byte into your Analysis Toolkit. Home Energy, 15(5): Sept/Oct. 1998: 25-32.

Krigger, John. Residential Energy, Cost Savings and Comfort for Existing Buildings. Quality Books Inc., Thomson-Shore Inc., 1994.

Wilson, Alex. Construction Detail: Light Shelves Increase Daylight Penetration. Environmental Building News, 4(3): May/June 1995: 10.

Wilson, Alex. Keeping the heat out. Environmental Building News, 3(3): May/June 1994: 1, 13-17.

Wilson, Alex. Windows: Looking through the Options, Environmental Building News, 5(2): March/April 1996: 1, 10-17.

_____. Should We Phase Out PVC. Environmental Building News, 3(1): Jan/Feb 1994.

Web Pages

"Weather Stripping." E Source Online. 5 April 1999 <www.esource.com>.

Efficient Windows. Efficient Windows Collaborative. 27 Jan. 1999 <http://www.efficientwindows.org/energycosts.html>.

Commercial Buildings Characteristics. Energy Information Association. 14 Aug. 1997 <http://www.eia.doe.gov/emeu/cbecs/char95/ex_sum.html>.

Overview of Commercial Buildings Energy Consumption and Expenditures, 1995. Energy Information Association. 18 Feb. 1999 <http://www.eia.doe.gov/emeu/cbecs/ce95/c&e_rept.html>.

EREC Brief: Energy Efficiency and Renewable Energy in Buildings. Energy Efficiency and Renewable Energy Network (EREN), US Department of Energy. 23 July 1998 <http://www.eren.doe.gov/consumerinfo/refbriefs/tpbldgs.html>.

Jackson, Mark A. "Superwindows, Retrofit Show Significant Energy Savings." Home Energy Magazine Online. Sept/Oct 1994 <http://www.homeenergy.org.eehem/94/940910.html>

PVC Plastic: a Looming Waste Crisis. Greenpeace. Undated <http://www.greenpeace.org/~comms/pvctoys/reports/loomingsummary.html>.

Types of Passive Solar. Passive Solar Industries Council (PSIC). 18 March 1999 <http://www.psic.org>.

Press Releases. Pella Window Corporation. undated <http://www.pella.com/about/pressREleases/precisionFit.asp?userType=remodeler>.

Thermotech Windows. 5 March 1999 <http://www.thermotechwindows.com/col2.htm>.

United States. United States Energy Information Administration. 26 Feb. 1999 <http://www.eia.doe.gov/emeu/cabs/usa.html>.

Architectural Documents

CSI Short Form Guide Specification (ANSI/AAMA 101-88 Format). Section 08520, ALUMINUM WINDOWS. Part: 2.02 Materials [Single Hung Windows], E. 1.

G.R.G Vanderweil Engineers, Inc. HVAC System Options Life Cycle Cost Analysis for Addition and Renovations to Brown University. 3 March 1999.

Koetter, Kim and Associates, Inc. GMP Package. Brown University Macmillan Hall. 16 Aug. 1996.

Lerner|Ladds Architects, Inc.. Project Manual, Brown University Carr House English Department. March 1999. Section 08520, ALUMINUM WINDOWS. Part: 2.02 Materials [Single Hung Windows] E, 1.

Other

What's Working and E Build, Inc. “Windows and Doors,” Environmental Building News™ Product Catalog. 1998.

Energy Efficiency and Renewable Energy Clearinghouse, Cooling Your Home Naturally (DOE/CH10093-221 FS186) Oct. 1991.

Foley, David. "GBList: Windows- What Really Matters." Online posting. 15 January 1999. Green Building List Serve <greenbuilding@crest.org>.

Hesse, Paul. “Reference for (non)-EREC statistic.” 17 March 1999.

Loewen Promotional Spec Sheet. Loewen Windows: PO225 ENG0896/50)

Windows 1998. Loewen Windows: P0081.

Pella Corporation: PPP Flyer 1998.

Longo , Peter. (RICKETSON Sash & Door Company Inc.) Re: Budget Quote, Windows and Doors.

English Department Building. Brown University. 6 Nov. 1998.

swiftjr@NU.com. "GB: solar angles based on location." Online posting. 2 May 1999. Green Building List Serve <greenbuilding@crest.org>.

terrain@cow-net.com. "GBList Re: windows." Online posting. 12 January 1999. Green Building List Serve <greenbuilding@crest.org>.

Appendix A

Weather Stripping

Weather stripping comes in a wide variety of materials and constructions. The Consumer Report team found 69 products on their retail-shopping excursion, ranging from 20 cents to more than a dollar per foot. For the most part, all the products were variations on four basic designs: foam or rubber tape, plain or reinforced with a strip of wood; a tubular plastic gasket, plain or reinforced; felt, plain or reinforced and bent plastic or metal. The accepted standards for good weather stripping is that it be easy to cut and install (or stick), resilient to repetitive rubbing, durable to extreme weather conditions and non- interfering with the normal operation of the window.[79] Bent brass and aluminum are considered the most durable, but also the most expensive, both initially and through the heat that they conduct. Though reliable once properly installed, the relative complication of doing so lends the material to being bent the wrong way or being poorly installed. Bent plastics are similar to bent metals in every way but price and, intuitively, durability. Rubber and foam plastics win out by both remaining flexible and effective over time. Consumer Report recommendations for general use went with nonporous EPDM rubber and foam tapes, and for plastic V-strip or bronze tension seal when specifically sealing the space between the window sash and frame for double hung windows.[80] Other weather stripping options may of course be better for other sash designs and applications.

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[79] Consumers Union of United States, Weather Stripping, Consumer Reports: 58(10): Oct.1993: pp. 650.

E Source Online, "Weather Stripping," 5 April 1999, <www.esource.com>

[80] E Source Online, "Weather Stripping," 5 April 1999, <www.esource.com>

Appendix B

Window Replacement Options

Window replacement tends to have a long payback period, however they are certainly a crucial step when overhauling the thermal envelope of a structure. Replacing windows tends to be an arduous affair principally because of the difficulty in finding windows to fit the building's existing rough openings. There are three approaches to fulfilling the task:

Custom frames

The most popular choice, this approach involves completely knocking out the original window frame and starting from scratch with the rough opening. Vinyl, fiberglass and aluminum windows are typically offered in one inch-incremented sizes, facilitating a custom fit. Unfortunately wood window manufacturers are not so accommodating, and so the rough opening must usually tucked and stuffed a tad to fit the standard size offerings.

Custom Opening

A big and arduous task, some chose to remove the entire existing window and frame and then begin hacking away at the rough opening to fit a larger standard sized window. Obviously this is extremely labored intensive and costly, as a new header beam must be installed, not to mention new outdoor siding and indoor paint or wallpaper work. This approach, clearly, only makes sense if the damage or decay has extended past the confines of the window into the building its self, in which case cleaning up the rough opening might as well entail making it appropriate for an enlarged but standard fitting.

Bi-Glass

The latest technique on the market, Bi-Glass has received a lot of press recently with a spotlight on This Old House and in other Building publications. The system uses the original frame and sash, provided they are in good shape, but replaces the inefficient true lites with a single plate of insulated glass. Efficient to a science, the window replacement specialist first removes the sash from the frame and takes it outside into his truck, where most of the work is completed. Using a special machine, the glass is cut out of the sash, with special attention paid to maintaining the integrity of the external grill. The sash must usually be expanded a tad to make room for the insulated glass, but the replacement's fit is tight and just. The grill is then glued on top so that the window looks the same as its traditional forefather, in spite of its vast thermal improvement. The final step, before the sash is reinstalled, is to insulate the typically hollow frame and insert new jamb liners, between the sash and frame, to ensure maximum air tightness. <http://www.bi-glass.com >

Appendix C

Energy Design Tools

A list of energy design software that analyzed, at least in part, energy transfer through fenestration was compiled from computer modeling tools highlighted in the September/October 1998 issue of Home Energy magazine[81], http://www.efficientwindows.org and http://www.eren.doe.gov/buildings/tools_directory/index.cgi. A short spec on all those considered is included below. Mention is made only to those features of the tools deemed relevant to my work.

Model	DOE-2
Web address	http://eande.lbl.gov/btp/srg.html
Contact person	Kathy Ellington Fax: 510 486 4089
Price	$300-$2000
Demo (Y/N)	No
Description	Hourly, whole-building energy analysis program calculating energy performance and life-cycle cost of operation.
Input and output of interest	Regards all aspects of building and therefore very complicated and data hungry.
Pros, cons and conclusion	Would require training or help, neither of which is readily available. One desire for this thesis is that architects hired by Brown will follow my method of analysis, making use of energy modeling tools. Recommending a complicated modeling tool will not encourage greater use.

Model	ADELINE (Advanced Day and Electric Lighting Integrated New Environment) Incorporates the capabilities of RADIANCE and SUPERLITE energy tools.
Web address	http://radsite.lbl.gov/adeline/HOME.html
Contact person	Charles Ehrlick CKEhrlick@lbl.gov
Price	$450
Demo (Y/N)	Yes, but poor and uninformative
Description	Concerned with day lighting, electric lighting and whole building analysis.
Input and output of interest	User fills description for surface reflectance, aperture, transmittance and luminance of fenestration and lighting situation. Renders CAD 3-D models of a space and the interior illumination level and hotspots to be expected.
Pros, cons and conclusion	Requires just average PC computer literacy and therefore accessible to all. However, would prefer model with more emphasis on how the sun hits the windows, with concern for the shading effect of neighboring structures.

[81] Bion Howard, Putting the Byte into your Analysis Toolkit, Home Energy, 15(5) Sept/Oct. 1998: pp. 25-32.

Model	FRAME 4
Web address	http://www.enermodal.com/frameplustoolkit.html
Contact person	Direct questions to Enermodal Engineering at frame@enermodal.com
Price	$295
Demo (Y/N)	Yes
Description	Evaluates heat transfer across surfaces to generate energy ratings for window components and unit.
Input and output of interest	A parallel model to the THERM-2 and WINDOW 4.1 team, FRAME 4 evaluates heat transfer across the unit to calculate thermal property values such as U-value, local heat flow, temperature, etc. User input takes the form of a cross-sectional sketch of the window unit. The model displays the results of its analysis in the form of isotherm plots superimposed upon the cross-sectional sketch. Results may be directly transferred into Vision 4 for heat transfer through the glazing and further analysis of solar optical properties.
Pros, cons and conclusion	Rejected for the same reasons as was WINDOW 4.1.

Model	ENER-WIN
Web address	http://archone.tamu.edu/~energy/enerwin.htm
Contact person	Larry Degelman larry@archone.tamu.edu
Price	$20 for Architectural schools and $50 for all other full-time students
Demo (Y/N)	Trial available for download
Description	Calculates transient heat flows, daylighting, energy consumption, demand charges, lifecycle costs and floating temperatures in unconditioned zones.
Input and output of interest	Graphic entry of building plans through a sketch interface with attention paid to the thermal properties of the building envelope. Input requirements also include hourly use profiles and indoor temperature settings. The output consists of tabular reports and graphs for monthly, annual and peak loads, electric displacement by day lighting and life cycle costs.
Pros, cons and conclusion	Sketch format of input is ideal. Unfortunately, input specific to fenestration consists solely of area, blinds, transmissivity and reflectance, which is inadequate for the level of accuracy and specificity this thesis hopes to attain for each building project.

Model	Softdesk Energy
Web address	None, though basic description available at: http://www.eren.doe.gov/buildings/tools_directory/software/softdesk.htm
Contact person	Developer: G. Z. Brown GZBrown@aaa.uoregon.edu For info on availability: Majorie Matty MJM@softdesk.com
Price	No price given
Demo (Y/N)	No
Description	Provides energy load analysis on buildings drawn using AutoCAD.
Input and output of interest	Input includes an AutoCAD drawing of the structure, site orientation, location (nearest city), building materials, occupancy, ventilation, thermostat and equipment schedule. Output, either in graphical or text form, provides a summary of annual or even monthly estimations of heat loss and gain by building component.
Pros, cons and conclusion	As architects generally have a working knowledge of CAD, the input format would be fairly straightforward for all. However, the program distinguishes between windows solely on a factor of R-value and shading coefficient. In addition, the software has only a limited capability is assessing the effects of daylighting and extreme solar gain, a focus of my thesis.

Model	Sunday
Web address	None, though basic description available at: http://www.eren.doe.gov/buildings/tools_directory/software/sunday.htm
Contact person	Kaija Berleman, Office Manager for Ecotope Inc. Tel: 206 322 3753 Fax: 206 325 7270
Price	No price given
Demo (Y/N)	No
Description	Simulates heating and cooling requirements of small commercial buildings on a daily basis using weather data typical of the area. Considers the contributions of solar energy, internal gains, nighttime setback and the building's glazing and (thermal storage) mass.
Input and output of interest	Model heavily reliant upon assumptions, requesting from user only parameters on building components, weather data, and related information.
Pros, cons and conclusion	Although imbedded assumptions make for a less complicated model, when great in number, they prevent the level of accuracy and specificity this thesis looks to attain. The lack of a web address discourages the further research necessary for greater consideration of this model.

Model	HEAT 3
Web address	http://www.blocon.se
Contact person	Direct questions to info@blocon.se
Price	Licenses typically run around $200-$500, though an educational discount is available
Demo (Y/N)	Yes
Description	Considering the building's geometry, thermal characteristics, exterior and interior loads and heat sources, the program constructs a 3-D model of the building, upon which isotherm plots of predicted temperature variation and heat flow are superimposed.
Input and output of interest	Due to the MatLab interface, the input format for the above building properties is fairly graphical and mathematical in nature. (Step by step instruction is provided in the user manual, however, which should help the less mathematically-minded.)
Pros, cons and conclusion	The scope of the model is too limited for entire building analysis such that this thesis requires. In addition the program's graphical nature and price tag would be alienating to any building committee.

Model	RESFEN
Web address	http://windows.lbl.gov/software/resfen/resfen.html
Contact person	None given
Price	Free
Demo (Y/N)	Can view input and output screens as they would appear
Description	Computes energy consumption and associated cost implications due to heating, cooling and peak demands.
Input and output of interest	Many assumptions regarding structure's layout and size (that of a standard house), glazing as a percentage of building envelope and exposure to sun have been pre-programmed. User simply picks closest location city, orientation and electricity and gas costs.
Pros, cons and conclusion	RESFEN is already known and used within the field and therefore lends itself to standardization within Brown building spec. Unfortunately, the assumptions inherent to the model are too general for the level of specificity and accuracy for which our project calls. Not to mention that they were made with a relatively small house in mind, quite unlike Carr House.

Model	Solar 5.4
Web address	http://www.aud.ucla.edu/energy-design-tools
Contact person	Murray Milne milne@ucla.edu
Price	Free
Demo (Y/N)	No
Description	Although not intended for equipment sizing, displays 3D plots of hourly energy performance for the entire building unit or any of 16 components. Models energy use from the roots of heat flow across building components to the environmental and economic costs, in terms of energy use, of running the HVAC system.
Input and output of interest	Model is flexible to any level of user control. From only floor area, number of stories, location and building type, the program designs a basic building, filling in hundreds of items of data. The user is then given the option to change all that data for which he/she has specific figures. From the final data, the program generates dozens of 3-D plots, tables, and reports dealing with heat flow across building components, HVAC output and building-wide energy consumption, to name but a few.
Pros, cons and conclusion	Due to its free cost and accessibility off the web, this model would be ideal if greater attention were paid to the effect of the fenestration in particular.

Model	WINDOW 4.1
Web address	http://windows.lbl.gov/software/window/window.html
Contact person	None given
Price	Free
Demo (Y/N)	No
Description	Calculates thermal performance figures such as U-value, solar gain coefficient, etc, for non-standard glazing systems.
Input and output of interest	
Pros, cons and conclusion	Thesis is concerned with evaluating the solar situation in order to optimize the fenestration design, not assess how fenestration will affect the situation.

Model	FenSpec
Web address	http://www.eneraction.com/skapp/FENSPEC.HTM
Contact person	Stephen Kapp skapp@eneraction.com
Price	$89
Demo (Y/N)	No
Description	A query field of window products that identifies the best style and manufacturer for a list of imputed features.
Input and output of interest	
Pros, cons and conclusion	Not relevant to Brown at current time as school sources manufacturers for reasons beyond that of product.

Model	Market Manager
Web address	http://www.src-systems.com
Contact person	None given
Price	$995-$4,495
Demo (Y/N)	Evaluation copy available for free download
Description	Simulates integrated building performance including load, system and plant calculations on an hourly basis. Models and evaluates the impacts of different rate structures including TOU, demand charges, load factors and ratchets.
Input and output of interest	Input includes building layout, HVAC, envelope, systems set-up, performance measures, rate tariff structures and weather data. Software projects building load and operating costs after applying local weather, utility performance measures, internal gains and other factors.
Pros, cons and conclusion	Models the interaction between lighting, heating, cooling and mechanical equipment. Such a capability would allow for the economic optimization of lighting load against cooling. However, breadth of model is beyond our needs, creating undue complication and confusion. In addition price tag is prohibitively high.

Model	THERM 2.0
Web address	http://windows.lbl.gov/software/therm/therm.html
Contact person	None given
Price	Free
Demo (Y/N)	Can view sample screen shots
Description	Models 2-D heat transfer across building components. Evaluates window's thermal performance under weather conditions typical of area.
Input and output of interest	Results can be directly transferred into Window 4.1 and RESFEN.
Pros, cons and conclusion	On its own, the scope of THERM 2.0 is insufficient for the needs of this project. When combined with WINDOWS 4.1 and RESFEN, the limiting simplicity of RESFEN still controls.

Model	PC-Solar 2.0
Web address	http://3dsoftware.com/solar/pcsolar/
Contact person	None given
Price	$55
Demo (Y/N)	Web page contains info sheets that walk you through examples
Description	Calculates solar angles, draws sun charts and displays shadows of overhangs and trees on building through the use of weather data affixed to the site's latitude input by the user.
Input and output of interest	At program prompt, user inputs wall edge dimensions. Program responds with a CAD sketch to which user can make changes to correct. Model then superimposes shading upon sketch for visual representation of results.
Pros, cons and conclusion	Clear and easy to use. Unfortunately, simplicity can only come with sacrifice. The model does not analyze the shading due to nearby structures so critical to the Carr House project. In addition, the model does not translate light and shading into building loads.

Model	Building Energy Modeling and Simulation- Self Learning Modules
Web address	http://www.strath.ac.uk/Departments/ESRU/courseware/Class-mod+sim
Contact person	Jan Hensen jan@esru.strath.ac.uk
Price	Free
Demo (Y/N)	No
Description	Intro: Why you should use building energy and environmental simulation. Practice: How to use real building energy modeling and simulation. Theory: How building energy modeling and simulation actually works.
Input and output of interest	None
Pros, cons and conclusion	Checked out and found overly simplified to be informative.

Model	EZDOE
Web address	http://www.elitesoft.com
Contact person	None given
Price	$1250
Demo (Y/N)	Demonstration copy may be downloaded
Description	A simplified IBM PC version of DOE-2, the program calculates hourly energy use and projects life cycle cost of building. Principally analyzes the contribution made by the air-handling system and thermal storage of the building materials to the building's energy loads.
Input and output of interest	EZDOE models up to 22 air handling systems, created from any combination of chillers, pumps, boilers, furnaces, and cooling towers. Other input concerned with building's location, construction and use pattern.
Pros, cons and conclusion	The strength and specificity of the program is with the simulation of HVAC systems, not fenestration.

Appendix D

Selection of PowerDOE Input

Input Justification for Chiller

Location: Compression Chiller Data (double click on Chiller 1)

Type	Elec Hermetic Recip
	Spec Book; Section 15000, p.31
	Hermetic chillers cool their motors by having the refrigerant pass over it, on its way to the compressor. As a result, motor losses are transformed into heat in the condenser water. The fact that the motor heat increases the refrigerant temperature before it enters the compressor yields a hermetic chiller less energy efficient than a similar chiller with an open drive.
CHW Loop	DualTemp Loop
Condenser Type	*Water Cooled*
	Spec Book; Section 15000, p.31
CW Loop	Condenser Loop
Capacity	*0.274* (MBtu/hr) .
	The nominal cooling capacity of the chiller is listed as 103.7 tons in the Mechanical Schedule
Capacity Ratio	n/a
	Defined as the fraction of the design loop cooling capacity that the chiller can provide. Yet only relevant to PowerDOE if the user has not explicitly specified the capacity of the chiller.
Elec Input Rat	.225
	The Electric Input Ratio is the dimensionless ratio of the electric input power to the nominal capacity of the equipment. The Mechanical Engineer in the Carr House project defined the efficiency of the chiller using the units KW. The conversion factor for EIR=KW/ton * .284
Auxiliary Kw	0.00
	The control panels for the chiller might be connected to an uninterruptible electricity supply in the form of a battery, but Carr House has no formal auxiliary power loop**.**
Elec To Condenser	**1**
	Used to estimate the efficiency of the compressor motor, the Electricity to Condenser fraction denotes that portion's chiller's electrical power input that is rejected to the condenser as heat. According to PowerDOE help, this value should always be 1 for electric hermetic chillers and for all fuel-consuming chillers as all the motor power must be rejected through the condenser.
Electric Meter	**NOT YET DONE**
	The electric meter assigned to measure the electric consumption of the chiller. As the focus of this study is total cooling load, rather than the efficiency of any one piece of equipment, the building-level Master Cooling Electric Meter has been assigned.

Chiller Recirculation Loops	
CHW Pump	Undefined
CW Pump	Undefined
	Attaching a pump directly to the chiller's evaporator (Chilled Water Pump) or condenser (Condensed Water loop) indicates a decoupling of the flow to that part from the principle loop. A designer may create such a situation when the principle loop is variable flow, but the flow through the chiller is constant. As all the pumps on DualTemp and Condenser Loops are single speed, the mechanical engineer has not called for such a decoupling. Hence both pumps remain "undefined" to indicate a lack of existance.

Location: Basic Specifications (Click on "More")

Loop Assignments	
HtRec	undefined
	2-pipe systems can not support a Heat Recovery Loop. Therefore "undefined" denotes lack of existance.
Equipment Capacity	
Min Ratio	0.25 (default)
	The minimum fraction of the nominal capacity at which an Electric Hermetic Reciprocating Chiller operates continually is defaulted by PowerDOE as 0.25. This models the unit as cycling on and off for demand less than one quarter of maximum capacity. I have no information inciting me to override
Max Ratio	1.0 (default)
	Electric Hermetic Reciprocating Chillers are not typically designed to be able to operate beyond their nominal capacity, therefore PowerDOE defaults to a ratio of 1.
HGB Ratio	UKNOWN
	The fraction of the design capacity below which electric and engine chiller use hot-gas bypass.

Location: Miscellaneous (Click on "More")

Start-Up and shut-Down Times	
Start-UP	UKNOWN
	"The equivalent full-load time (in hours) required to bring the chiller on-line. For example, if it takes the equivalent of 15 minutes of full load fuel consumption to bring an absorption chiller on-line, then this entry should be 0.25 (hours). If a chiller is to operate in the current hour, but did not operate the previous hour, then a start-up load is presumed to exist. The equivalent full-load run time added to the current hour's load varies according to how many hours the chiller has been shut down: · 1 hour 50% of this value · 2 hours 80% of this value · 3 or more hours 100% of this value"

Input Justification for Condenser Loop Pumps

Location: Miscellaneous (Click on "More")

Pump	CD Pumps
Head	92 feet
	Mechanical Equipment Schedule
Flow	
	Professional help from PowerDOE recommended that I input either Head or Flow and allow PowerDOE to size the other accordingly. Inputting both would confuse the program.
Head Ratio	N/a
Flow Ratio	1 (default)
	If allowed to size the pump itself, PowerDOE will oversize the design flow rate of the pump using this ratio. As we wish PowerDOE to come up with the same pump as already specified by the Carr House project mechanical engineer, who has already incorporated safety over-sizing factors, we will maintain the default value.
Head Setpoint	Only applies to situations in which the pumps have been attached directly to the equipment and not the loop itself. Therefore by keeping this square open, we instruct PowerDOE to default to the head setpoint of the primary loop.
Head Setpoint Ratio	Only applies to situations in which the pumps have been attached directly to the equipment and not the loop itself. Therefore by keeping this square open, we instruct PowerDOE to default to the head setpoint of the primary loop.
Pump Head F(Flow)	Pump-Head-Fflow **NOT YET CONFIRMED**
Pump Power F(Flow)	Pump-Power-Fflow **NOT YET CONFIRMED**
Electric Meter	EM1 **NOT YET INPUT**
Number	2
Pump Energy	Can input the design power consumption of the pump only if you have specified the corresponding flow rate. As we are letting PowerDOE dictate the flow rate, we leave this square open.
Motor Efficiency	As the Carr House project Mechanical Engineer has not specified the efficiency of the pump motor, by leaving this space open I alert PowerDOE to make its own estimation of the efficiency through the Pump Power and Motor Class.
Mech Efficiency	0.77 **NOT YET CONFIRMED**
	The mechanical efficiency of the pump impeller.
Min Speed	N/a
Motor Class	Premium
	Section 15500, p. 36/43
Capacity Ctrl	One-Speed Pump
	In lieu of any mention of variable speed motors by the Mechanical Engineer, the assumption is that all motors are one-speed.
Max Pump Ratio	1.3
	When two or more pumps are used in parallel, as in the case of the Carr House Project, a pump can typically move more fluid than the design rate as the fluid head is lower than the design value. PowerDOE defaults this ratio at 1.3 and strongly recommends against increasing it unless quite sure of accuracy. As I have no information to recommend any ratio number, I defer to the default.
Pump Power Exponent	3.05

	As an ideal pump would have an exponant of three to depict the variance of horsepower with speed, PowerDOE strongly recommends an exponent of 3.05 for all real world pumps.

Input Justification for DualTemp Loop Pumps

Location: Miscellaneous (Click on "More")

Pump	DT Pumps
Head	57.5 feet
	Mechanical Equipment Schedule
Flow	
	Professional help from PowerDOE recommended to input only one of the design Head or Flows, and allow PowerDOE to size the other accordingly. Otherwise program will be confused.
Head Ratio	N/a
Flow Ratio	1 (default)
	If allowed to size the pump itself, PowerDOE will oversize the design flow rate of the pump using this ratio. As we wish PowerDOE to come up with the same pump as already specified by the Carr House project mechanical engineer, who has already incorporated safety over-sizing factors, we will maintain the default value.
Head Setpoint	Only applies to situations in which the pumps have been attached directly to the equipment and not the loop itself. Therefore by keeping this square open, we instruct PowerDOE to default to the head setpoint of the primary loop.
Head Setpoint Ratio	Only applies to situations in which the pumps have been attached directly to the equipment and not the loop itself. Therefore by keeping this square open, we instruct PowerDOE to default to the head setpoint of the primary loop.
Pump Head F(Flow)	Pump-Head-Fflow **NOT YET CONFIRMED**
Pump Power F(Flow)	Pump-Power-Fflow **NOT YET CONFIRMED**
Electric Meter	EM1 **NOT YET INPUT**
Number	2
Pump Energy	Can input the design power consumption of the pump only if you have specified the corresponding flow rate. As we are letting PowerDOE dictate the flow rate, we leave this square open.
Motor Efficiency	As the Carr House project Mechanical Engineer has not specified the efficiency of the pump motor, by leaving this space open I alert PowerDOE to make its own estimation of the efficiency through the Pump Power and Motor Class.
Mech Efficiency	0.77 **NOT YET CONFIRMED**
	The mechanical efficiency of the pump impeller.
Min Speed	N/a
Motor Class	Premium
	Section 15500, p. 36/43
Capacity Ctrl	One-Speed Pump
	In lieu of any mention of variable speed motors by the Mechanical Engineer, the assumption is that all motors are one-speed.
Max Pump Ratio	1.3

	When two or more pumps are used in parallel, as in the case of the Carr House Project, a pump can typically move more fluid than the design rate as the fluid head is lower than the design value. PowerDOE defaults this ratio at 1.3 and strongly recommends against increasing it unless quite sure of accuracy. As I have no information to recommend any ratio number, I defer to the default.
Pump Power Exponent	3.05
	As an ideal pump would have an exponent of three to depict the variance of horsepower with speed, PowerDOE strongly recommends an exponent of 3.05 for all real world pumps.