HISTORIC WINDOWS AND SUSTAINABILITY:
A COMPARISON OF HISTORIC AND REPLACEMENT WINDOWS
BASED ON ENERGY EFFICIENCY, LIFE CYCLE ANALYSIS,
EMBODIED ENERGY, AND DURABILITY
A THESIS
SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE IN HISTORIC PRESERVATION
BY
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Chapter 1
Introduction

Historic preservation and environmentalism are often understood as unrelated or even opposing disciplines. Environmentalism is seen as dealing with the future while historic preservation is only concerned with the past. Popular perception is that only new buildings constructed using the latest green products are sustainable. Historic preservationists have long argued that historic buildings are inherently green because the energy required in their construction has already been expended. While this embodied energy is certainly a consideration, thorough research on whether historic buildings are sustainable in other ways has not been conducted.

Windows were chosen as the focus of this study due to their frequent replacement as well as their importance to the exterior of a building. Historic windows are often replaced due to their perceived energy inefficiency and poor appearance and/or functionality. Window companies often promise huge energy savings for replacement windows. Replacement is often easier than repair with the added incentive of improved energy efficiency. Building owners believe they are acting “green” when they replace their drafty, old windows with modern efficient units. This thesis attempts to discover if replacing historic windows is a sustainable practice.
Preservationists will always advocate for saving historic windows. As prominent elements of a building’s exterior, windows are character defining features. According to the National Park Service, character-defining elements “…include the overall shape of the building, its materials, craftsmanship, decorative details, interior spaces and features, as well as the various aspects of its site and environment.” Character-defining features are essential to a building’s style. Windows, more than any other architectural feature, create the essential style of a building by their size, shape, and number. They are crucial to identifying the period of a building’s construction. Loss of these features results in damage to a building’s integrity, affecting its eligibility for listing on the National Register of Historic Places or inclusion in a locally designated historic district.

Methodology

In researching this thesis, only published material was consulted. Time and funding constraints did not allow for field studies to be performed. Every attempt was made to consult all available relevant sources. Only studies performed by respected laboratories, universities, or individuals were referenced.

Literature Review

Sustainability and preservation are two seemingly different causes that in fact share many goals. Historic building techniques were inherently ‘green,’ not because sustainability was trendy but because our predecessors had to make the most of the

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limited energy that was available to them. Reusing an existing building usually requires less energy than constructing a new one. Preservation and sustainability were initially linked in the late 1970s. While preservation has been quick to promote sustainable practices, “green” architecture often ignores the role historic buildings can play in creating a healthier environment.

One of the earliest publications to link preservation and sustainability was assembled in 1980. *New Energy From Old Buildings*, edited by Diane Maddex, is the product of the “Preservation: Reusing America’s Energy” Symposium, held in May 1980. The symposium and the resulting collection of papers represent the advent of the linking of sustainability and preservation. The papers cover a range of topics, from the inherent sustainable characteristics of the historic houses, the benefits of revitalizing historic downtowns, to specific energy savings recommendations based on different climate zones. The book is important as a pioneering work but contains some inaccuracies and outdated information.

“Green Building Practices and the Secretary of the Interior’s Standards for Historic Preservation: A White Paper prepared in advance of the 2008 Pocantico Symposium” examines the relationship between green building and The Secretary of the Interior’s Standards for the Treatment of Historic Buildings. Specifically, the paper discusses the conflicts between LEED and the Standards, perceived and actual. There are relatively few green strategies that the Standards prevent, and the paper concludes that with creative design, green techniques can be applied to historic buildings. The paper contains very
little specific information, but it is a good summary of the current issues facing preservation within the sustainability movement.

Architect Mike Jackson argues that the embodied energy of existing buildings should be given more weight in evaluating their sustainability in “Embodied Energy and Historic Preservation: A Needed Reassessment.” He argues that the 1976 report *Energy Use for Building Construction*, is an important tool preservationists should take advantage of. Jackson feels that the report is fairly comprehensive but excludes some historic materials such as stone and plaster. Jackson’s article is useful source for analyzing historic buildings based on embodied energy values.

There are many different meanings of sustainability and green within architecture. Stephen A. Mouzon addresses both concepts in his book *The Original Green: Unlocking the Mystery of True Sustainability*. He relates the current green movement to historic architectural practices. In order to achieve true sustainability, we must make significant changes in our society and the way we design our buildings. Architecture should be driven by practical factors rather than being ruled by aesthetics. In order to return to living traditions, we must design based on practical reasons or as Mouzon explains, “we do this because…” To Mouzon, longevity, environmental health, and love-ability are what create sustainability. Mouzon includes the love-ability requirement because he believes that regardless of a building’s performance, if is not loved, it will not endure.

Mouzon feels we need to change our behavior as well as our building products. Energy efficiency and low carbon footprints in themselves do not lead to sustainability. While both are beneficial, it does not encourage us to change our behavior. Mouzon
recommends that in order to be more green we need to address both city and rural settings, design and use objects that have many uses, produce things locally, learn to tolerate variations in temperature better, and share knowledge so everyone can be involved. This will create not only a healthier environment but healthier people as well.

Mouzon writes in a very accessible way. His use of specific examples, including illustrations and images, make his ideas easy to understand. His ideas about sustainability were very helpful in forming a comprehensive yet clear definition of what it means to be sustainable for this thesis.

In 2002, architect William McDonough and chemist Michael Braungart addressed sustainability in *Cradle to Cradle*, a book that calls for people to rethink the way we produce everything. McDonough and Braungart argue that energy efficiency and recycling are not sufficient. Because our systems are flawed, efficiency within them means little. Recycling is actually “downcycling,” reducing the quality of the material over time. McDonough and Braungart propose we emulate nature and create products that can be reused. In addition to making large scale recommendations, the authors provide criteria for evaluating individual materials. Their arguments are well made though the book does not provide much guidance on how to achieve their ambitious goals.

Information on the sustainability of specific materials is generally difficult to find in a single source. Bjorn Berg’s *The Ecology of Building Materials, Second Edition*, published in 2009, is a thorough examination of the materials that make up buildings. Berg evaluates building components based on the raw materials, energy, and pollution
that are needed or result from their production. His goal is to give professionals in the building industry a tool for creating environmental requirements. He considers a material’s renewability, durability, disposal (recycling/reuse), embodied energy, pollution produced by the material during its processing and use, and its chemical and physical properties. Berg discusses individual raw materials such as stone, metals, and wood, as well as entire building components. Brief histories of most materials are also included. All the materials used in windows are discussed in addition to a separate section on windows as a building component. Berg gives an example of what he considers the modern sustainable window. The book is a detailed, well-researched, and comprehensive resource.

There is a good deal of literature available on historic windows, from articles for the general public to highly technical studies testing the energy performance of historic windows and replacement windows. Walter Sedovic and Jill H. Goffhelf, in “What Replacement Windows Can’t Replace: The Real Cost of Removing Historic Windows,” published in 2005, argue that historic windows have many benefits, including being sustainable. They are crucial to the character of a building, were constructed with superior wood and craftsmanship than used in modern windows, and can easily be retrofitted. The article provides a thorough examination of the advantages of historic windows and offers several alternatives to replacement.

“Testing the Energy Performance of Wood Windows in Cold Climates,” a report compiled for the State of Vermont Division for Historic Preservation in 1996, is a seminal study, referenced by many subsequent articles. The study tested the hypothesis
that historic windows can be upgraded to a level of thermal efficiency similar to replacement units. 151 windows located in northern and central Vermont were field tested and thermal losses were calculated using WINDOW 4.1 (software developed by Lawrence Berkeley National Laboratory). Both non-upgraded and upgraded windows were tested. The upgrades included different types of weatherstripping and storm windows. The upgraded windows were also tested against a modern replacement window. The study found that sash leakage was greatly reduced by any of the upgrade methods tested and that replacement windows did not necessarily reduce energy costs more than an upgrade. It is one of the earliest studies that specifically examines historic windows.

“Measured Winter Performance of Storm Windows,” by J. H. Klems, published in 2002, compares a single-glazed wood window (similar in construction to historic wood windows) with an insulated replacement window. The single-glazed window was tested with and without a storm window. Measurements were made using an accurate calorimetric facility with the windows facing north. Each window was tested for at least four days during the winter months. Heat flows due to air infiltration were found to be small. Prime window/low-E storm window combinations performed very closely to the replacement window.

William Hill’s “An Evaluation of Indiana’s Energy Conservation Financial Assistance Program (ECFAP),” published in 1991, summarizes a study that examined different home upgrades that aimed to improve energy efficiency. These upgrades included replacement windows, new heating systems, and additional insulation. Data
obtained from each home’s gas meter (gathered one year before and one year after installation of the upgrades) was analyzed with PRISM software (Princeton Scorekeeping Method) in order to calculate energy savings. The study found that replacing the windows provided the least amount of energy savings, while new insulation was the most effective.

“Technical Paper 1: Thermal Performance of Traditional Windows,” published in 2008, reports on a study performed by Glasgow Caledonian University in Scotland that tested a traditional window fitted with various options to improve its thermal performance, including different window treatments and a secondary glazing system (storm window). The window was also re-glazed with low-E double glazing and tested. The tests determined the reduction in heat loss and the U-value for each option. The study found that air-tightness did not have a significant effect on the U-value. Several of the tested configurations produced U-values similar to modern windows.

“Field Evaluation of Low-E Storm Windows,” published in 2007 by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), compares the performance of low-E storm windows to standard clear storm windows as well as to no storm windows. The study was conducted in a cold climate over the period of one heating season. Annual energy savings were calculated in comparison with the cost of the storm windows. The homes with low-E storm windows had a payback period of less than five years while the clear storm windows resulted in approximately 10 years payback.
“To Storm or Not to Storm: Measurement Method to Quantify Impact of Exterior Envelope Airtightness on Energy Usage Prior to Construction,” published in 1998, reports on a study that tested the air leakage of several types of wall systems with and without storm windows. The study utilized historic windows and aluminum storm windows. The application of storm windows was found to reduce air infiltration. The purpose of the study was to create a methodology for taking data from hot box tests. Due to the limited number of window types tested, the paper concludes that more studies using the proposed methodology need to be conducted.

Commercial steel windows have also been studied. “An Analysis of the Thermal Performance of Repaired and Replacement Windows,” published in 2009, summarizes a window study of the Lafayette Building in Washington D.C. The building was scheduled to undergo extensive renovations, including either replacement or repair of the original steel windows. Because it is a federal building, the windows needed to be upgraded for blast resistance. In order to determine if replacement or repair was the best option, in-situ mock-ups were installed in the building. The windows were analyzed based on thermal performance, constructability, cost, and aesthetics. Data was collected over a period of five months. The repaired window experienced more solar heat gain during morning and early afternoon hours than the replacement. The replacement window experienced more heat loss through the glass and frame during evening and early morning hours. The repaired window actually provides the superior heat-loss performance because solar heat gain can be addressed with low-e coatings while heat loss through the frame cannot.
The Empire State Building has recently undergone a “green” retrofit. Sudip Bose, in “The Height of Sustainability,” reports on the work that began in 2009 and will be completed in 2013. The Empire State Building is an important example of a green historic building because of its size and iconic image. The biggest changes to the building are an update of its chill cooler and other mechanical, electrical, and plumbing systems and replacing the window panes with insulated glass. The windows remain operable. Offices will also be fitted with motion sensors that turn off the lights after 15 minutes of inaction. While the article does not contain much specific information, it illustrates that historic commercial buildings can also be “greened.” Dana Schneider and Paul Rode offer a more detailed overview of the project in "Energy Renaissance: Empire State Building." The authors explain each aspect of the project and how it will affect the energy efficiency of the building. The article includes charts on energy use, cost and projected energy savings. The Empire State Building is setting an important precedent in greening historic buildings.

In addition to energy performance, life cycle analysis is an important tool in evaluating sustainability. “Life Cycle of Window Materials—A Comparative Assessment,” a study performed in 2002 at Napier University in Edinburgh, Scotland, examines the materials most commonly used for window frames. These materials include aluminum, PVC, aluminum-clad timber, and timber. Materials were analyzed based on the energy used in production, maintenance required, and disposal methods. As part of the study, a survey was performed to determine the average life-span of each window type. Accelerated aging tests were also carried out. Aluminum windows were
found to have the highest embodied energy, followed by PVC, Aluminum-clad timber, and timber windows. Aluminum-clad windows performed the best under the aging tests, while PVC, untreated wood, and uncoated aluminum were more sensitive. The study is a comprehensive look at all the elements that make up a window’s life-cycle.

There are very few works that primarily address the history of windows. Most literature on windows includes only a brief section on the development of windows over time. *Windows: History, Repair, and Conservation*, edited by Michael Tutton and Elizabeth Hirst, is a collection of papers that deal with the history, policy and conservation of windows. The conservation section covers wood, metal, stone, and stained glass windows. The information presented deals primarily with British history and policy. The policy section details preservation practices and laws in Britain. There is one chapter on windows and sustainability. It details techniques for improving the energy efficiency of historic windows. While comprehensive in terms of British windows, the work does not cover international window history or conservation policy.

The National Park Service’s Technical Preservation Services has published preservation briefs that address the repair and upgrading of historic wood and steel windows. *Preservation Brief 9: The Repair of Historic Wooden Windows* and *Preservation Brief 13: The Repair and Thermal Upgrading of Historic Steel Windows* cover evaluation, maintenance, repair, weatherization, and replacement for each window type. Repair and thermal upgrading are discussed in detail. The briefs were written to serve as guides for both home owners and building professionals.
Information on modern windows is available in several texts. *Windows Systems for High Performance Buildings* and *Residential Windows: A Guide to New Technologies and Energy Performance* are comprehensive resources on windows and their energy performance. Both are written by teams led by John Carmody, Stephen Selkowitz, and Dariush Arasteh and serve as guides for choosing windows. *Window Systems* deals with commercial windows and is written for professionals in the building industry. The authors detail the purpose of windows, criteria for choosing windows, characteristics of window system materials, as well as how to design window placement for specific climates and building types. Energy performance of individual materials as well as the window unit as a whole is the focus. The physical properties of windows are described in detail. U-values and solar heat gain coefficient, and air infiltration are explained and the latest technologies to address these aspects of energy performance are discussed.

*Residential Windows* is written for both professionals and lay people. It deals with the same content as *Window Systems* but at a less comprehensive scale.

There are many journal articles that deal with a specific building or building component within the field of sustainable preservation. There is also a focus on the “greening” of historic homes. In particular, historic commercial buildings are not adequately addressed. The preservation field is missing a current definitive and comprehensive source on the connections between sustainability and preservation.

Individual elements of historic buildings have not been compared to their modern equivalents in terms of sustainability. Without this knowledge, environmentalists and historic preservations will continue to argue their respective sides instead of
acknowledging how each can help the other and work together. There are many different variations on the definition of sustainability from a variety of sources. Companies, governments, rating systems, and individuals have all given their own definition of what makes a building, component, or product sustainable. Through examining the various ideas about sustainability, a clear definition emerges. This study/thesis will evaluate historic windows and their modern replacements based on materials, energy efficiency, life cycle, and durability. Using various studies comparing historic and replacement window performance and the inherent qualities of window materials, the thesis will determine which window types are sustainable.
Chapter 2
Defining Sustainability

According to Random House Webster’s Dictionary, to sustain is “to endure without giving way or yielding.”\(^3\) Today, the term sustainability is used primarily in reference to the natural environment and our relationship to it. In its 1987 report Our Common Future, the World Commission on Environment and Development defined sustainability as “…meeting the needs of the present without compromising the ability of future generations to meet their own needs.”\(^4\) Sustainable practices harvest or use a resource without depleting or permanently damaging it. Consequently, we must take care to not deplete or permanently damage our resources. Sustainability is harder to define in terms of real world applications. “Green” and sustainable have become buzz words used by many companies as marketing strategies. Claims of sustainability are often made with no clear explanation of what exactly it means to be sustainable. In opposition to the advertising fluff, there are many organizations and individuals who are attempting to give sustainability true meaning. Rating systems have been developed in an effort to create truly sustainable buildings. LEED and Green Globes are two well-known programs that certify buildings as green at various levels. The International Living Building Institute has also created a very comprehensive set of guidelines called the Living

Building Challenge. Specialized professional groups, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers, have published very specific requirements for green buildings. Individual architects, such as William McDonough and Stephen Mouzon, have outlined their own definitions of sustainability. From these varied sources, there are many similar requirements for sustainability but also some surprising differences.

Leadership in Energy and Environmental Design (LEED) is a rating system that evaluates new and existing buildings. Developed by the United States Green Building Council (USGBC), the system has been in use since 1998 and is widely recognized in the U.S. The USGBC’s goal is to transform the built environment by maximizing economic and environmental performance. The LEED Rating Systems aim to provide a definitive guideline for what constitutes a green building. There are rating systems for new construction, existing buildings, commercial interiors, core and shell, schools, retail, healthcare, homes, and neighborhood development. The rating standards are based on energy and environmental principles. Points are assigned based on the environmental or human effects of the design, construction, operation, and maintenance of the building. These include greenhouse gas emissions, fossil fuel use, toxins and carcinogens, air and water pollutants, and indoor environmental conditions. Point values are created using a combination of energy modeling, life-cycle assessment, and transportation analysis. For LEED for New Construction 2009, at least 40 out of 100 possible points must be earned for a building to be LEED Certified. Above that, a building may receive Silver, Gold, or Platinum designation. The evaluation is broken down into: Sustainable Sites (26 possible
points); Water Efficiency (10 possible points); Energy and Atmosphere (35 possible points); Materials and Resources (14 possible points); Indoor Environmental Quality (15 possible points); Innovation in Design (6 possible points); and Regional Priority (4 possible points). LEED for Existing Buildings 2009 differs from LEED for New Buildings in a few ways. Water efficiency is given 14 rather than 10 possible points, and materials and resources is worth only 10 rather than 14 possible points. There are slight differences in most of the remaining categories, but otherwise the systems are nearly identical. The LEED system emphasizes site selection (alternative transportation, development density, and environmentally sensitive site development) and energy efficiency in its definition of green. Interestingly, there are no requirements or recommendations for the life span of the building.

Green Globes is a rating system that evaluates new construction and existing buildings’ environmental performance. Created in 2000, it evolved out of the Canadian Building Research Establishment’s Environmental Assessment Method. The evaluation system is currently used in Canada as well as the U.S. The Green Building Initiative (GBI) oversees the system in the U.S. GBI is an accredited standards developer under the American National Standards Institute. Buildings are assessed based on several categories, including energy, indoor environment, site, water, resources, emissions, and project/environmental management. Buildings must receive at least 350 points out of the possible 1,000 to be certified. They are then given a rating of one to four globes. Evaluation encompasses the entire building process, from predesign to construction and commissioning. The most points can be earned through the energy category; by
optimizing performance, utilizing renewable energy sources, and reducing demand. Conservation of natural resources and reduced emission of pollutants (greenhouse gases, airborne particulates, liquid effluents, and solid waste) are also emphasized. As in LEED, there is no requirement for building longevity.

In addition to rating systems, guidelines and standards for sustainability have been written. The Living Building Challenge is a set of guidelines for truly sustainable buildings created by the International Living Building Institute, a non-profit organization dedicated to creating a truly sustainable built environment. The Institute was founded in May 2009 by the Cascadia Green Building Council. Cascadia was incorporated as a 501(c)(3) in December 1999 and is one of the three original chapters of the USGBC. The Living Building Challenge calls for humanity to unite to “reconcile the built environment with the natural environment, into a civilization that creates greater biodiversity, resilience and opportunities for life with each adaptation and development.” The Challenge can be applied to any project type, from renovation to new construction, as well as landscapes and neighborhoods. The Challenge ambitiously calls for the built environment to increase biodiversity and soil health; create a deeper understanding of climate, culture, and place; and to realign our food and transportation systems. Its trademark is “Socially Just, Culturally Rich and Ecologically Benign.” The Challenge is divided into seven performance areas or ‘Petals’; site, water, energy, health, materials, equity, and beauty. Petals are subdivided into a total of twenty Imperatives. The imperatives are: limits to growth; urban agriculture; habitat exchange; car free living; net

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zero water; ecological water flow; net zero energy; civilized environment; healthy air; biophilia (design elements that use natural shapes, forms, patterns, or processes); red list (a list of toxins); embodied carbon footprint; responsible industry; appropriate sourcing; conservation and reuse; human scale and humane places; democracy and social justice; rights to nature; beauty and spirit; and inspiration and education.

Project evaluation begins with categorizing the site, based on six “Living Transect” categories: Natural Habitat Preserve; Rural Agricultural Zone; Village or Campus Zone; General Urban Zone; Urban Center Zone; and Urban Core Zone. The site must be separated a minimum distance from wetlands, primary dunes, old-growth forests, virgin prairie, prime farmland, and outside the 100-year flood plain. Certain percentages of the project area must be used for food production and natural habitat. Projects should increase density, contributing to a pedestrian-oriented community. Water must come from captured precipitation or closed loop systems. Storm water, if not captured for use, must be directed to return to the earth as groundwater. Energy must be supplied by on-site renewable energy.

Materials used in construction are the next category. They should be non-toxic and not include any of the elements included on the “Red List,” a comprehensive list of toxins that includes asbestos, chlorofluorocarbons, and polyvinyl chloride. Raw materials, such as stone, rock, metal, and wood, should be extracted using sustainable and fair labor practices. Materials, products, and services should be sourced from the local region. All projects must create a material conservation management plan that illustrates
how the project will strive to eliminate waste. Percentages of certain materials must be diverted from landfills.

The project cannot restrict access to fresh air, sunlight and natural waterways for the surrounding developments. Beauty is included as a requirement because it will encourage people to protect and maintain a project over time. Depending on the category of the project, certain imperatives are waived. For example, renovations do not have to meet the urban agriculture or car free living imperatives under the site requirements. The guidelines recognize the current limitation to each imperative. The ideal water usage is not always attainable because of current health, land use, and building code regulations. Buildings must be operational for at least twelve consecutive months before being evaluated, ensuring their level of performance is real rather than modeled.

Approximately 80 projects have been certified since the Challenge was first issued in May 2006. The Living Building Challenge has created a very comprehensive definition of sustainability. The inclusion of beauty in the requirements is unique but important. Humans value beauty and are more likely to retain what is beautiful. However, like LEED and Green Globes, the life span of materials and buildings is not one of the many imperatives required by the Challenge.

High performance design is also used by the architectural industry to refer to sustainable or green design. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has teamed with the USGBC and the Illuminating Engineering Society (IES) to create the Standard 189: Standard for the Design of High-Performance, Green Buildings, published in 2009. The Standard’s goal is to set
minimum requirements for high-performance buildings that can be incorporated into existing building codes. A *high-performance green building* is defined as:

[A] building designed, constructed, and capable of being operated in a manner that increases environmental performance and economic value over time, seeks to establish an indoor environment that supports the health of occupants, and enhances satisfaction and productivity of occupants through integration of environmentally preferable building materials and water-efficient and energy-efficient systems.\(^6\)

The Standard outlines requirements for site sustainability, water use efficiency, energy efficiency, indoor environment quality and the building’s impact on the atmosphere, materials, and resources. The Standard also sets minimum service life spans for buildings. A medium life is considered 25 years minimum and a long life is 50 years minimum. The Standards are a comprehensive tool to evaluate buildings, from energy and water efficiency to building lifespan.

Whole Building Design Guide is an online resource that provides guides based on various design objectives, including designing for sustainability.\(^7\) The sustainability guide defines sustainable design as an integrated, synergistic approach that considers all phases of the facility’s life cycle, resulting in an optimal balance of cost, environmental, societal, and human benefits. The main objectives the guide outlines are as follows: to avoid resource depletion of energy; water, and raw materials; prevent environmental degradation caused by facilities and infrastructure throughout their life cycle; and create built environments that are livable, comfortable, safe, and productive. To achieve these

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objectives, there are six fundamental principles: optimize site/existing structure potential; optimize energy use; protect and conserve water; use environmentally preferable products; enhance indoor environmental quality; and optimize operational and maintenance practices. In addition to these requirements, sustainable buildings should be adaptable to multiple uses and different environments and conditions. This stipulation implies that buildings should be able to last longer than their initial use demands, though the guide does not explicitly address building lifespan. The Whole Building Design Guide does not introduce any ideas that differ from LEED or Green Globes, focusing again on energy efficiency and conservation of water and raw materials.

Individuals in the field of architecture have also attempted to define sustainability. William McDonough is an award winning architect and author and former dean of the University of Virginia’s School of Architecture. In 1992, his firm, William McDonough + Partners, set out to create a set of sustainable design guidelines for the 2000 World’s Fair in Hannover, Germany. The so-called Hannover Principles specified that every element of a material should be considered, from its extraction, manufacture, transformation, and degradation, in addition to its embodied energy, toxicity, off-gassing, maintenance requirements, and recyclability. In 2002, William McDonough and Michael Braungart further developed the idea of sustainability in Cradle to Cradle, a book that calls for people to rethink the way we produce everything. McDonough and Braungart argue that when companies improve their manufacturing techniques, they are not actually creating good practices but simply ‘less bad’ ones. We need to aim for eco-efficiency instead of just energy-efficiency. McDonough and Braungart argue, “…efficiency has no
independent value: it depends on the value of the larger system of which it is a part.”

Because our systems are bad, efficiency within the system is meaningless. They also question the effectiveness of recycling, referring to it as “down-cycling” because it reduces the quality of the material over time. Recycling can even create greater harm to the environment when the recycling process produces harmful emissions or requires the addition of chemicals. Economically, recycling is also harmful because it increases operating costs. McDonough and Braungart propose we up-cycle instead by manufacturing goods that are designed to be reused without any loss of quality.

Ultimately, all our systems need to be recreated to emulate nature. In nature, any waste is actually food for something else. Therefore, any waste we create in manufacturing and construction should be able to be returned to the earth as nutrients (or at the very least be harmless.)

In addition to these society altering ideas, McDonough and Braungart outline criteria for evaluating materials. These include: oral or inhalative toxicity; chronic toxicity; whether the material is a strong sensitizer, known carcinogen, mutagen, teratogen or endocrine disruptor; bioaccumulative; its toxicity to water organisms; biodegradability; its potential for ozone-layer depletion; and whether the by-products are also safe. Based on the ideas in the Hannover Principles and Cradle to Cradle, sustainability is defined as causing no harm to the natural environment along with the ability to return to the earth after the component’s useful life is over. Up-cycling, a form of longevity, is emphasized.

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Stephen A. Mouzon attempts to define sustainability in his book *The Original Green: Unlocking the Mystery of True Sustainability*. Because the term is used by many different people in many different ways, Mouzon argues sustainability is currently meaningless and used simply as a marketing strategy. There is a need for a simple and clear definition. To him, sustainability is “keeping things going in a healthy way long into an uncertain future.” In other words, something is sustainable when it achieves longevity without causing harm. Most definitions of sustainability focus on carbon emissions and energy efficiency. Mouzon argues that carbon is only one part of sustainability and that emphasizing carbon footprints can actually lead to less sustainable buildings. For example, a carbon neutral building located on the outskirts of town and only accessible by car is not very sustainable overall. Energy efficiency in itself does not lead to sustainability. While efficiency is beneficial, it does not encourage us to change our behavior. If anything, energy efficient machines lead us to increase our energy use because we can get more while paying less.

Like McDonough and Braungart, Mouzon also calls for significant change in our society. Rather than a consuming economy, we should aim for a conserving one where things are made to last and planned obsolescence is no longer the norm. Many of today’s buildings are throw-aways and not expected to last. While they may be inexpensive to build, they are not sustainable. Discarding a building, even if its parts can be recycled, is

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less sustainable than keeping a building. Mouzon feels that durability is essential to sustainability.\textsuperscript{10}

Our society needs to return to building based on regional conditions, climate, and culture. We currently live in the “Thermostat Age” where mechanical equipment has replaced natural methods of conditioning buildings. These natural methods are what Mouzon refers to as the “Original Green.” To stay warm in winter and cool in summer, humans learned to harness nature. People practiced sustainability because it was essential to their survival not because it was better for the environment. Architecture has forgotten its living traditions and become defined by style and aesthetics. In order to return to living traditions, we must design based on practical reasons or as Mouzon explains, “we do this because…” For example, areas that experience heavy snowfall should have buildings with steeply pitched roofs that shed snow. If our buildings are constructed of purposeful elements, they will be more useful and more loveable. Mouzon includes a love-ability requirement because he believes that regardless of a building’s performance, if it is not loved, it will not endure. To Mouzon, longevity, environmental health, and love-ability are what create sustainability.

Sustainability is much more than high energy efficiency and low carbon emissions. The true meaning of the word has been manipulated by advertisers into whatever best fits their campaign. Sustainability and “green” architecture are related terms but have different meanings. Green products and buildings are less environmentally harmful alternatives. Green is a short term solution while sustainability

\textsuperscript{10} Ibid, 222.
is for the long term. Most of the current rating systems (with the exception of the Living Building Challenge) do very little to return sustainability to its roots. They continue to operate within a flawed system and therefore can only produce flawed ratings.

McDonough and Mouzon have focused on the larger issues and created a more comprehensive idea of what creates sustainability. For the purposes of this thesis, a sustainable product will be defined as one that lasts multiple generations without causing harm to the environment, either in its production, maintenance, or disposal. To determine which window types are sustainable, window materials will be evaluated based on their life span, life cycle analysis, energy efficiency, maintenance, and disposal.
Chapter 3
History of Windows

Windows provide three things to a building’s interior; light, air, and views. The word *window* comes from the Old English *vindauga*, or “wind eye.” Depending on climate, available technology, and prevailing style, windows have served various functions in human history.

**Light**

Window openings can be found in the architecture of the ancient Egyptians, Sumerians, and Greeks (Figure 3.1). Daylight was usually admitted through slits at the roof line and large openings were rare due to the

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hot climate. During the Roman Empire, windows became an important element of a building’s façade. Unlike in ancient Egypt, important buildings were open to the public, requiring their interiors to be well-lit. Roman window types included bay and pivot or swivel windows. While the Romans had access to glass, the warm climate did not necessitate its frequent use in windows. If necessary, animal skins were used to keep out the elements. Wealthy citizens used thin sheets of mica or even small sections of cast glass. Shutters provided shade and security. Early Christian churches contained windows but they were simple and not focal points of the building’s façade. It was not until the Gothic period that windows played a dominant role in church architecture.

Air

In northern Europe, the earliest windows were holes that exhausted smoke out and allowed fresh air in. Skins, mats, or fabric were used to control air flow. The holes’ ability to let in light was a secondary function that eventually became important. The construction method of the building determined the size of the windows. Stone buildings generally had small windows because long pieces of stone, required to frame the window, were rare. Wood buildings had the capacity for larger windows. Oiled paper and cloth were the first translucent materials used to allow light in while keeping out the elements.

13 Ibid, 118.
14 Ibid.
15 Rees, 10; Tutton and Hirst, 65.
16 Beckett and Godfrey, 118.
17 Rees, 10.
Later, thin slices of translucent horn were placed within a wood lattice.\textsuperscript{18} Eventually these membranes were installed in a movable sash that allowed more control over ventilation.

As window technology progressed, typical windows (see Figure 3.2) were composed of a simple rectangular grid of mullions (vertical structural elements that divide openings) and transoms (horizontal structural elements). Elizabethan and Jacobean builders used iron for the frames and lead for the cames (the slender rods that hold the panes in place), but the windows were not very weathertight.\textsuperscript{19} In Continental Europe, wood frames were the standard.\textsuperscript{20} Wooden casement windows were used in England as early as the thirteenth century, but lead-glazed iron remained the most widely used frame type in Britain.\textsuperscript{21} Around the fourteenth century, the bay window, with its increased views and light, came into use in banqueting halls in wealthy homes.\textsuperscript{22}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{window_diagram.png}
\caption{Window diagram showing the location of mullions and transoms. Source: Linda Hall, \textit{Early Casement Window Furniture, The Building Conservation Directory 2001}.}
\end{figure}

\textsuperscript{18} Ibid, 12.
\textsuperscript{20} Ibid, 174.
\textsuperscript{21} Tutton and Hirst, 58.
Prior to the sixteenth century, glass was used only in churches and homes of the very wealthy. The first “window-walls” were installed in churches during the late-medieval period, like King’s College Chapel in Cambridge (Figure 3.3).23 In England, large windows became more common place in non-religious structures as society became progressively less secularized and as glass production expanded during the sixteenth century.24 The English used glass enthusiastically, in great country homes such as Hardwick Hall, which was said to be “more glass than wall” (Figure 3.4).25 This trend clashed with the strict proportion and symmetry of the Renaissance’s Classically inspired architecture.

Classical architecture and the fireproofing movement that began even before London’s Great Fire of 1666 led to the increased use of brick in urban settings in Britain. Wood framed window were the standard

22 Rees, 12.
23 Tutton and Hirst, 20.
24 Ibid, 9 & 20.
25 Ibid, 10.
window type used with the new brick buildings. Eventually the frame became non-loadbearing, allowing the window and the wall to become separate architectural components.26

In the 1670s, the sash window, a counterbalanced, wooden vertically sliding window, was developed (Figure 3.5).27 During this time, London was an international center for wood joinery and glassmaking.28 The sliding window invented by the French in the early fifteenth century was improved with a counterbalancing system of cords, pulleys and weights.29 Sash is a derivation of the French word chassis, or frame. Though a single inventor is impossible to identify, the architect Christopher Wren was instrumental in its development and popularity. The boom in country house construction in the 1680s allowed craftsmen to perfect their skills and further develop the sash window.30 The sash window’s ability to be prefabricated allowed them to be mass produced. One of the sash window’s greatest advantages over casements was its ability to be opened varying degrees.31 Sash windows could also be constructed much taller than their precursors. By the early eighteenth century, sash windows tall enough to also serve as doors were common in country houses as an alternative to ‘French window,’ a door height casement window.32
The double-hung (moveable upper and lower sashes) sash window was probably introduced in the 1690s but was not widely used until the mid-eighteenth century. The ability to open both sashes allowed inhabitants to take advantage of the stack effect. Because warm air rises naturally, the lower and upper sashes of windows could be strategically opened or closed to draw cool air in through the lower opening while forcing hot air out through the higher opening. By the 1720s, sash windows were considered selling points in houses throughout England. The sash window is well suited to varied climates due to its ability to closely control the amount of ventilation. Casement windows are better suited to warm, stable climates because they allow the most unobstructed air into the interior. While sash windows became the dominant window style in Britain, the wooden casement was the window of choice in France, Germany, and Italy.

In 1695, England passed a tax on windows. Any house with more than six windows had to pay a tax for each additional window. As a result, existing windows were often boarded up and false windows were employed to retain the symmetry of the façade. The result was fewer windows in England than the rest of Europe. The glass duty was not repealed until 1845, followed by the abolishment of the window tax in 1851. Technology and the repealed window tax resulted in an increased use of glass in the mid-nineteenth century. The increased transparency of glass led shop owners to advertise their wares through large picture windows. The technological advances made in glass and iron were dramatically illustrated in the Crystal Palace at the Great

33 Ibid, 16.
34 Louw and Crayford, “Part 2”, 175.
35 Tutton and Hirst, 16.
Exhibition of the Industry of All Nations in London in 1851 (Figure 3.6). Due to the improved quality in glass, windows were eventually used to create a link to the outdoors. The Picturesque movement in particular used windows to create calculated views to the landscape.

**Style**

Eventually windows were used to express architectural style in addition to performing their practical duties of providing light, air, and views. Classicism mandated exact proportions on a building’s façade, with a balanced solid to void ratio. Window size was based on the floor area and sometimes even the volume of the spaces it lit. Rectangular windows typically had a width-to-
height ratio of 1:2 with six lights (panes) over six (Figure 3.7).\textsuperscript{36} In the early eighteenth century, rounded, pointed, and ogee arch sash windows were used in Gothic Revival and Rococo buildings. The Picturesque movement brought the popularity of bowed windows and exotic influences. French windows became popular in England since they allowed direct access to the outdoors. Window placement was determined by the rooms they lit rather than the strict symmetry required of Classicism. In the late nineteenth century, architects used light to manipulate the mood of interior spaces. Proponents of the Arts and Crafts movement, such as William Morris, objected to the use of large plate glass. Instead, Arts and Crafts designers like Morris revived the historically Gothic leaded-light iron casement window. A variety of windows configurations were used in a free form composition of the building’s exterior (Figure 3.8).

Steel windows became available in the 1860s but did not become widely used until after 1890. Technological advances in the rolled steel industry allowed mass production, making metal windows more cost competitive with wood windows. After devastating fires in Boston, Baltimore, Philadelphia, and San Francisco, strict fire codes were adopted for industrial and multi-story commercial and office buildings. Steel windows had the advantage of being fire resistant. The strength of steel allowed for larger windows, ultimately changing the architecture of industrial and commercial buildings in the late

\textsuperscript{36} Ibid, 28.
The thin profiles of steel windows were ideal for the streamlined appearance of Art Deco, Art Moderne, and International buildings of the early twentieth century.

Ribbon windows and curtain walls became hallmarks of the International or Modernist style (Figures 3.9 and 3.10). Creating volume instead of mass became the design imperative. Window frames once again became load-bearing.

Steel windows were used in a range of buildings, from industrial to luxury commercial and apartment buildings. In addition to being extremely durable and easy to transport, steel windows became standardized in size. Prefabricated steel-framed windows became popular in the 1920s. Steel is the most common window framing material in commercial buildings today due to its strength and stiffness. After World War II, cheap, non-
corroding aluminum windows became popular in residential construction. Polyvinyl chloride (PVC) frames first became available in the U.S. in the 1960s. More recent frame types include wood clad in aluminum, vinyl, and fiberglass.

Windows’ energy efficiency became a priority in the late twentieth century. Previously, a separate sash, called a storm window, was seasonally installed over the original window to improve its thermal performance. The single-pane and storm window configuration evolved into a single unit that contained two glazing layers. Sealed, double glazed windows were developed in the 1960s. Triple and quad glazed windows were built in response to the energy crisis of the 1970s, and are becoming more popular today. Glass tints and coatings were also used to improve a window’s energy efficiency.

Eventually, an inert gas was injected between the panes of glass in multi-paned units. Emerging glazing technologies include even greater insulated units and ‘smart’ windows that respond to environment conditions. Aerogel, honeycombs, and capillary tubes can be placed between glazing layers, resulting in highly insulated windows. The insulation is not completely transparent and results in diffused light. “Smart” windows, like photochromic and thermochromic windows, adjust their transparency in response to changes in light or heat. Electrochromic windows use an electric current to change the color of the glazing from clear to blue-tinted, allowing the heat transfer to be modulated. Researchers are also attempting to produce insulating window units that contain a vacuum instead of an inert gas, known as evacuated windows.

Today we expect windows to be high performing components of our buildings, designed to contribute to a building’s energy efficiency rather than diminishing it, while
still performing the basic functions of light, ventilation, and views. Windows have evolved from simply providing light and ventilation to expressing a building’s style and even serving as walls in modern buildings. Today, a window’s primary task is to provide daylight. Natural light is more than desirable; studies have shown that daylight is essential to our emotional and psychological health.\(^{37}\) Access to natural light has also been shown to increase retail sales and student performance. Besides affecting our health, windows play an important role in architectural history. Windows can aid historians in determining the period of a building. Construction techniques and distinctive style markers are clear and simple tools for dating a structure (Figure 3.11).

![Figure 3.11. Windows representing various architectural styles. From left, Georgian, Italianate, Neo-classical, and Craftsman. Source: Heritage Education: They Story of American Homes by Maurie Van Buren (Architectural Images, Digital Media Repository, Bracken Library, Ball State University, Muncie, IN).](image)

Chapter 4
Window Materials

Windows are made up of two main components; the glass and the frame. While there have been many technological advances in glass production, its composition has essentially remained the same. Frames can be constructed from a variety of materials, but the most common are wood, steel, aluminum, and polyvinyl chloride (PVC). Newer and less common types include fiberglass and wood clad in aluminum.

Glass

Glass production is thought to have originated in Syria and eventually spread north into Europe.\textsuperscript{38} Early glass was used in jewelry. The Romans were able to produce glass (and did occasionally use it in windows) but it did not become an architectural staple. Glass was not used prominently in architecture until the twelfth century. Even then it was only used in monumental buildings like cathedrals. Silica and an alkali (such as sodium or potassium oxide) are the two basic ingredients required to make glass. The sand mixture is heated until molten. Early glass was formed into sheets through blowing. Glass could also be poured onto a flat stone slab and manipulated into a rectangle with iron tools. The color tended to be greenish due to iron present in the silica, with an uneven surface.

\textsuperscript{38} Tutton and Hurst, 121.
By the tenth century, the Venetian island of Murano had become the major center of glass making. Glass was produced through the crown and cylinder methods. Both processes began by blowing a large glass sphere. For crown glass the sphere was stuck to a rod called a punty. The blowpipe was then removed and the punty was spun while the glass was reheated, causing the bubble to open up into a circular disk, or crown. Up to 750 millimeters in diameter, the disc was cut into panes. Over time, the maximum diameter increased, until the mid-nineteenth century when discs 132 cm in diameter were routinely produced. The punty left a circular indentation in the center of the disc, referred to as the bullseye or bottle glass, and was considered the lowest grade glass. Cylinder glass was made by swinging the blown glass sphere in a wide arc to extend the glass into a cylindrical shape. The cylinder was then split and transferred to a flattening kiln, where it was reheated and flattened with a wooden block. Finally the glass was slowly cooled to produce a stress-free piece. Crown glass was preferred to cylinder glass because of its smooth and brilliant surface. Cylinder glass was more economical to produce but its surface was often marred by irregularities or dirt from the surface on which it was flattened.

The French excelled at plate glass production. Plate glass was initially produced for use as mirrors in the seventeenth century. Molten glass was poured onto a polished iron table and then rolled out. It then was ground and polished on both sides by hand, making plate glass very expensive. Polished plate glass was considered the highest quality glass for the next 350 years.

40 Tutton and Hurst, 132.
Access to fuel changed glass production. In the early seventeenth century, glassmakers in Britain were banned from using wood to fire their furnaces. Coal was the alternative fuel and glass operations were relocated to areas where coal was plentiful. The higher temperatures produced by coal fires led to the creation of the English glasshouse furnace, a conical brick structure over a hundred feet high. The increase in size and efficiency in turn increased the size of the window panes produced.\footnote{Ibid, 125.} In the early nineteenth century, the high price of wood in France led glass blowers to develop a technique for making cylinder glass longer rather than wider. The resulting glass was produced more quickly and with less waste.\footnote{Ibid, 138.}

Further innovation came with the use of natural gas powered furnaces. In Germany in 1869, the Siemens brothers built a furnace that could produce glass continuously. Around 1900, J. H. Lubber patented a device in the U. S. that drew molten glass up through a 40 foot tall tower, producing sheets of glass 12 feet by 5 feet. The Lubber machine was used until about 1930. However, bubbles, waviness, and foreign matter entering the glass were all issues. Mass produced glass was still considered lower in quality than hand-blown cylinder glass. The cylinder method was eventually replaced by processes that drew the glass instead of blowing it. The Fourcault method, developed in Belgium in 1916, was one such drawn glass process. Glass could be drawn vertically or horizontally. Grinding and polishing were mechanized. In the 1920s, Henry Ford, founder of Ford Motor Company, needed plate glass for windshields and partnered with the Pilkington Brothers Ltd., a British company, to develop a continuous casting process.
Eventually they could produce ribbons of glass 100 inches wide. Pilkington cast glass was considered the highest quality glass at the time.\(^{43}\) All these methods were virtually replaced in the 1950s by float glass.

Today, glass is produced primarily through the float technique. Developed by the Pilkington Brothers, Ltd. in 1959, molten glass is floated over a bed of molten tin, where it hardens, creating an extremely flat surface of uniform thickness. Float tanks are typically made of fireproof stone and can produce 200 to 300 tons per day. Used continuously, tanks usually last only two to three years. The technique was eventually licensed to other glassmakers and was first used in the U. S. in 1963.\(^{44}\)

The essential components of glass have not changed over time. Modern glass is typically made up of 70% silicon dioxide in the form of quartz sand, 15% soda ash (sodium carbonate), and 15% limestone and dolomite.\(^{45}\) Glass will have a greenish tint unless it is produced with a reduced iron content. Lead glass is created by replacing the limestone with lead. Phosphorous pentoxide can be added to produce extremely translucent glass. Colored glass is created by adding metal oxides of tin, gold, iron, chrome, copper, cobalt, nickel, and cadmium. Metal oxides can be added to glass during production to improve its energy performance (known as low-emissivity or low-E glass). Other additives affect the production rather than the properties of the glass. Fluorine compound agents are added to decrease the viscosity and lower the melting point of

\(^{43}\) Ibid, 154.  
\(^{44}\) Allen and Iano, 646.  
glass, reducing energy used in production. Antimony trioxide improves malleability and arsenic trioxide acts as an oxidizing agent to remove air bubbles.

**Environmental Impacts**

Quartz sand, while regionally limited, has large reserves overall. A great deal of energy is required to produce glass. Particle pollution from quartz dust and calcium chloride can result from glass production. Hydrogen chloride and hydrogen fluoride are emitted when tin oxide is applied as a vapor. Metal oxides used to produce low-E glass have a high environmental impact in terms of resources and pollution.\(^46\) During use, glass does not emit pollution. After disposal, antimony trioxide and arsenic trioxide can seep out of the glass. Colored glass and metal-coated glass may contain heavy metal pigments that can wash out and therefore require controlled disposal.\(^47\) Clear glass can easily be recycled and new glass can contain up to 50% recycled glass.\(^48\) Recycled glass can also be reused as glasswool, foam glass and fiberglass. Laminated glass and glass coated with a metallic film cannot be recycled for reuse as window glass. They can, however, be ground down to be used in elastomeric roof coverings, bricks, tiles, and aggregate in asphalt or concrete.\(^49\) Low-E glass is difficult to recycle. The metallic coatings incorporated into the glass during the manufacturing process remain attached to

\(^{46}\) Ibid, 360.
\(^{47}\) Ibid, 103.
\(^{48}\) Ibid.
\(^{49}\) Ibid, 104.
the glass even after crushing and screening. The coatings act as a barrier to fusing, even at temperatures over 1700°F (927 °C).\textsuperscript{50}

\textbf{Frame Materials}

\textbf{Wood}

Wood consists mainly of cellulose and lignin, along with other organic substances such as protein, sugar, resin, and water. The composition differs based on the tree type. Trees are made up of long cells stretched vertically with pith divisions that run across the trunk, forming rectangular cells. This structure makes wood strong and elastic. Trees contain two types of wood: sapwood and heartwood. Sapwood contains the living cells of the tree. When sapwood dies, it becomes heartwood. Heartwood is extremely hard and resists shrinking, warping, and in some species even rot, mold, and insect attack. After being felled, tree trunks are milled. Prior to modern machinery, tree trunks were split along the grain using wedges, in a process called riving. It was much faster than sawing, required minimal equipment, and produced stronger sections of wood because the long fibers of the wood remained intact.

Today, trees are primarily milled through sawing. There are different techniques for sawing logs, depending on the quality desired. Plain sawing maximizes the amount of usable lumber. The wood grain produced is variable, with some grain running perpendicular to the face of the wood, some diagonal, and some parallel. Parallel grained wood is susceptible to cupping. Quarter sawn wood is first divided into four equal

sections and then cut diagonally. This method maximizes the amount of wood with perpendicular grain but results in a smaller amount of usable lumber. On average, half of each trunk is used for construction lumber and the rest is by-products or waste that can be used for paper, energy, or chemicals. After milling, wood is dried to remove 70-90% of its original moisture. Natural drying requires much less energy consumption than artificial drying but is time consuming. A year is required for each inch of thickness, in addition to one year for the whole plank thickness. In artificial drying, wood is dried in kilns where the temperature is slowly increased. Drying the wood artificially may not completely eliminate the sugars that can become a breeding ground for mold. Naturally dried wood does not have this issue.

**Environmental Impact**

Wood has the lowest thermal conductivity (and, thus, the highest thermal resistance) of all frame materials. It can easily be milled into complex shapes. Sustainable forest management can ensure that wood is a renewable resource. Certain species of wood can be useful for hundreds of years if not exposed to fire, insects, or mold. The maturity of a tree affects its quality. In the past, trees where harvested only when mature. For conifers, maturity means greater than 80-years-old, deciduous between 30 and 60 years, and beech and oak well over 100-years-old. The heartwood of spruce and pine does not begin to form until the tree is 30 or 40-years-old. Wood exposed to the

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51 Berg, 170.
52 Ibid, 171.
54 Ibid, 173.
55 Berg, 168.
elements must be protected by paint or varnish or it will rot. Due to the rarity of knot-free wood today, many modern wood windows are made of composite wood. Short lengths of defect-free wood finger jointed and glued, oriented strand lumber, and laminated veneer lumber are some of the composites used. These composites are often clad with wood veneer to improve their appearance. Wood is biodegradable and can be repurposed or recycled into various building boards or as a source of energy.

**Steel**

Steel is an iron alloy with a carbon content of less than 2%. Iron has been used since prehistoric times and iron smelting has been performed for at least 5000 years. Iron was first used in buildings in classical Greece as reinforcement for stone lintels and architraves. To convert iron to steel, the ore is first broken up and cleaned. The iron is then smelted and reduced in a blast furnace. Steel eventually replaced cast iron as a structural material with the introduction of the Bessemer process in the 1850s. Air was blown into a vessel of molten iron to burn out the impurities, producing steel very quickly. Today, most steel is produced using the basic oxygen process. A hollow lance is lowered into the molten iron and a stream of pure oxygen is blown into the iron at a very high pressure. The excess carbon and impurities are burned off. Steel can be alloyed with other elements to produce even greater strength. Nitrogen, aluminum, niobium, titanium, and vanadium alloys all form very strong steel.

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56 Allen and Iano, 684.
57 Berg, 76.
58 Allen and Iano, 370.
Environmental Impact

Steel has a moderate rate of thermal conductivity. It is strong and extremely durable but is susceptible to corrosion. Galvanizing or coating it with zinc, tin, aluminum, cadmium, chrome, or nickel (or a combination of these) protects steel from corroding. Galvanizing is an electrolytic process that applies a very thin layer of the protective metal onto the surface of the steel. Galvanizing emits organic solvents, cyanides, chrome, phosphates, and fluorides into the water used to clean the steel. The resulting sludge must be treated as hazardous waste. Iron ore is available all over the world but easily available reserves are diminishing rapidly. Mining iron produces 5 to 6 tons of waste for each ton of iron extracted. Mining and its waste can damage the groundwater and surrounding ecosystem. Steel production requires 440-600 tons of coal to produce 1 ton of iron. Large amounts of carbon dioxide, as well as sulfur dioxide, fluorine compounds, and a wide range of heavy metals are emitted during production. Large amounts of water are also used in the cooling process.

Aluminum

Aluminum is derived from the ore bauxite. It was first produced in 1850. Aluminum production is a highly technical process. The bauxite ore first undergoes calcination (heating it with sodium hydroxide and lime). It is then placed in an electrolytic bath with sodium and fluorides which extracts the pure aluminum. The aluminum is then formed into sheets.

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59 Berg, 78.
60 Ibid, 76.
61 Ibid, 77.
Environmental Impact

Aluminum is light, strong, durable, and can easily be extruded into complex shapes. It is highly resistant to most forms of corrosion due to self-passivation, the process by which a naturally occurring oxide film forms when aluminum reacts with oxygen. Bauxite is found in tropical areas of the world, as well as Russia. A significant portion of bauxite reserves is located in the rainforests of Brazil, Surinam, and Venezuela. Large amounts of carbon dioxide and perfluorocarbons, as well as sulfur dioxide, polyaromatic hydrocarbons, and fluorides are released during production. A great deal of water is also used in the process. However, aluminum can be readily recycled, requiring much less energy (as low as 7%) than needed for its initial production from ore.62 Anodized and factory-baked enamel finishes are very durable and low-maintenance. Aluminum’s greatest disadvantage as a window frame material is its high thermal conductance. The conductance can be improved through the use of a thermal break; the components of the frame are split between the exterior and interior and a less conductive material, such as plastic, is inserted between them.

Aluminum-Clad

Wood frames clad in aluminum are very durable and low-maintenance. The aluminum is powder coated or anodized to prevent corrosion.

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62 Ibid, 79.
Polyvinyl Chloride (PVC)

PVC is produced through a polymerization of vinyl chloride. It was discovered by accident by French chemist Henri Regnault in 1838. Commercial production of PVC did not begin until 100 years later. Vinyl chloride is composed of 51% chlorine and 43% ethylene. Additives can reduce brittleness or protect against heat, oxidation, and solar radiation degradation, increase flame retardation, reduce smoke, and add pigmentation.

Environmental Impact

PVC has good insulating properties (low thermal conductivity), high impact resistance, and is highly resistant to moisture, abrasion, corrosion, air pollutants, and termites. Frames made of PVC are considered low-maintenance because the color is integrated throughout the material. However, PVC has a very high coefficient of thermal expansion (meaning it greatly expands when hot and shrinks when cold). In order to combat this issue, PVC is usually formulated with a high proportion of inert filler material. Its thermal insulator properties are comparable to wood. PVC is not very strong, and large window units often require metal or wood stiffeners.

Extracting and refining the crude oil and natural gas used as raw materials for plastics greatly affects the environment. Cadmium, lead or tin, and chloroparaffins can be present in the additives. Plasticizers containing phthalates are also used in PVC. Chlorine gas, ethylene, dioxins, vinyl chloride, dichloroethane, and mercury are often extracted.

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63 Ibid, 148.
64 Allen and Iano, 685.
released during production. PVC has an anticipated lifespan of 8 to 30 years, depending on the temperatures and climatic conditions it is exposed to. PVC decomposes slowly and can release environmentally hazardous substances such as cadmium. If burned, it can form concentrated hydrochloric acid and dioxins, the most toxic of all chemical groups.

**Fiberglass**

Fiberglass or glass-fiber-reinforced polyester can be pultruded into lineal forms to create window frames. Fiberglass is made from silica sand, limestone, boric acid, and other ingredients that are melted and fed through tiny orifices. Continuous strands of glass are saturated in a thermoset resin, pulled through a heated die, and then molded into the desired shape. Pultruded fiberglass is different from the fiberglass used in pools, boats, and storage tanks.

**Environmental Impact**

Fiberglass requires relatively low energy to produce and can be made with recycled glass. Fiberglass has a high tensile strength and resists heat, fire, chemicals, and moisture. It also has low thermal conductivity and is a fairly good thermal insulator. Fiberglass frames are often insulated with polyurethane foam, further improving their thermal properties. It creates a stronger window frame than vinyl and has a very low rate of thermal conductivity.

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65 Berg, 154.
66 Ibid, 153.
68 Allen and Iano, 689.
Gas Fills

Insulated glass window units are multi-glazed windows, filled with an inert gas and sealed. They usually contain either krypton or argon gas. Krypton is superior to argon at reducing heat loss. However, according to Berg, the energy intensive production of krypton outweighs krypton’s energy saving benefits over the lifetime of a building.\(^{69}\)

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\(^{69}\) Berg, 360.
Chapter 5
Windows and Energy

Heat Transfer Through Windows

Windows admit daylight but also allow heat and cold into our buildings. Conduction, convection, radiation and infiltration are the heat transfer mechanisms that affect windows. Conduction requires surface contact. Convection occurs through the movement of gases or liquids. Radiation is the movement of energy through space that does not require contact or the movement of gases or liquids. Air leakage or infiltration is uncontrolled or unwanted ventilation. Heat transfer occurs when there is a temperature difference between the exterior and interior of a window. Conduction, convection, radiation, and infiltration cause heat loss in winter and heat gain in summer.

Heat Loss in Winter

Conduction takes place primarily through the glass and window frame. Glass is a good conductor of energy, and is therefore a poor insulator. However, the thin film of air that hugs each surface of the glass improves the glass’ ability to resist heat flow. The conduction level of the frame is dependent on the frame material. Metal is a much greater thermal conductor than wood, and therefore metal framed windows lose more heat than wood framed units. Convection affects heat transfer in three places; at the
exterior glazing surface, the air space between glazings (if there are multiple panes), and at the interior glazing surface. Wind blowing on the exterior of the window can replace the existing air film with colder air, causing the unit to experience a higher rate of heat loss. The air space between layers of glazing also allows convection currents to transfer heat. Adjusting the space and filling the gap with a gas that is a greater insulator than air can minimize heat transfer. The temperature of the glazing surface affects the temperature of the entire room through thermal radiation (MRT). Radiation occurs as long-wave and short-wave. Long-wave radiation occurs between objects at environmental temperatures in the range of 3-50 microns, while short-wave radiation comes from the sun in the 0.3-2.5 micron range. Ultraviolet, visible, and solar-infrared radiation fall into the short-wave category.

Infiltration occurs when air enters through cracks and holes in the building envelope. Cold air entering the building must be heated. Heated air can also leak out through exfiltration. In window units, air leaks occur around the frame, between movable sashes and the frame, and between sashes (as in double-hung windows). In order for infiltration to occur, a driving force must be present to move the air across the opening. Stack effect or chimney effect is usually the most influential driving force (and has a much greater effect on the air leakage in a building than the larger but intermittent pressure differences between the exterior and interior caused by wind). Stack effect produces a relatively small but constant pressure difference whenever there is a temperature difference between the exterior and interior of a building. In the winter, the warmer and more buoyant air inside a building creates positive pressure at on the top of
the conditioned space and negative pressure at the bottom. In the center there is zero pressure difference, or a neutral pressure plane. Stack effect is directly proportional to the temperature difference and the height of a building. Because of stack effect, it is most effectual to seal openings at the top and bottom of a building (such as attics and basements). Windows are usually located on the edge of or within the neutral pressure plane. Sealing around them would have little to no effect on air movement. Openings found in attics, crawlsspaces or basements, and at the intersections of walls and ceilings account for much more energy loss than a leaky window in the center of a wall.

Heat Gain in Summer

During warm months, keeping the heat out of a building becomes the greater concern. Heat is transferred by the same mechanisms as in winter except the heat flows in the opposite direction (into, rather than out of, a building). In order for a window to be energy efficient, it must reduce not only the heat flow in winter but also reduce heat gains in summer.

Windows allows heat gain through solar radiation. Solar heat gain is caused by the direct and diffuse radiation from the sun and sky. The combination of directly transmitted radiation and the inward flowing component of absorbed radiation raise the temperature of interior spaces. Solar heat gain can be minimized or maximized depending on the climate and design intent. Solar heat gain is measured through the solar heat gain coefficient (SHGC) and shading coefficient (SC). The SHGC is defined as the fraction of incident solar radiation that enters a building through the window assembly as heat gain. It refers to the total window system performance. SHGCs range from 0 to 1, with a low
coefficient indicating low heat gain. The SC represents the ratio of solar heat gain through the window system relative to that through 1/8-inch clear glass at normal incidence. The SHGC has largely replaced the SC. In general, reducing the SHGC of the glazing reduces cooling costs but can increase heating costs, due to the warming benefits of solar gain in winter.\(^{70}\) Therefore, a low SHGC is more effective at lowering energy costs in predominantly cooling climates.

**Thermal Comfort**

Windows directly affect the level of thermal comfort within a building. Convection and radiation are the mechanisms that have the greatest effect on occupant comfort. Convection currents caused by cold interior glazing surfaces can lead to occupants feeling a draft of cold air from the window. This cold interior surface affects thermal comfort in another important way. Occupants of a building radiate energy (heat) to any surface that is colder than their body temperature, and thus will feel colder sitting in front of a cold window because they are giving up energy to the cold glass through radiant heat transfer.

**Improving Energy Efficiency**

Glass is a poor insulator. The first method to combat this problem was to use multiple layers of glazing by installing a storm window. Double glazing was used by the French in the 1640s, and in England by the late seventeenth century.\(^{71}\) Storm windows double the number of air films in a window system, as well as create an air space between

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\(^{70}\) Carmody, *Residential*, 35.  

\(^{71}\) Louw and Crayford, "Part 2", 184.
glazings, reducing conductive losses by half. Eventually windows were constructed with
double panes. Also referred to as ‘thermalpane’ windows, these performed similarly to
storm windows, though the smaller air space between panes reduced their benefit
somewhat. A spacer at the edges of the glazing at the frame was required to separate the
multiple panes. If the spacer between panes was metal (typically aluminum), the window
frame was more conductive than a single paned wood window. Today, materials such as
silicone foam, vinyl, and fiberglass are used as alternatives to aluminum spacers.

Double glazing was further improved with the introduction of inert gases into the
air space between panes. Sealed, double glazed windows were developed in the 1960s.
Argon or krypton gas is typically used to fill the air space between panes. These gases
have much lower rates of thermal conductivity than air and therefore lower the amount of
heat the passes through the window unit. Both argon and krypton occur naturally in the
atmosphere and are inert, nontoxic, nonreactive, clear, and odorless. Triple and
quadruple glazed windows are also available. Besides adding weight and thickness, these
additional panes reduce the visible light transmitted and the solar heat gain coefficient.
Plastic films can be used for the inner layer of triple or quadruple glazed windows,
reducing the weight and thickness of the unit. The plastic films are treated to resist UV
degradation.

Glass can be treated with tints and coatings to reduce radiant heat transfer. Tints
absorb a portion of the solar heat and block some visible light. Tinted glazing is still
transparent though the color is altered. Gray, bronze, and blue-green are the most
common tint colors. Tinted glass is chemically different from clear glass. Inorganic
additives are added during the production process. Tints can be formulated to absorb solar energy across some or all of the solar spectrum. The absorbed energy is transformed into heat, raising the temperature of the glass. Tinted glazing is best used as the exterior pane on a multiple pane unit.\textsuperscript{72} Tinted glazing is commonly used in commercial windows.

The solar heat gain coefficient can also be reduced through the use of reflective coatings. Coatings can control the passage of either long-wave or short-wave radiation. A thin metallic or metal oxide layer is applied to the glazing. The coatings also reduce light transmittance. Some coatings are durable enough to be applied on the exterior while others must be protected within a multi-glazed unit. Reflective coatings are most often used in commercial buildings, in hot climates, or on windows that experience high solar heat gain.

One of the most important advancements in window technology is the use of low-E coatings. Low-E glass coatings reduce the emissivity of glass. Emissivity is the ability of a material to radiate energy.\textsuperscript{73} The emissivity of glass is an important heat transfer in both heating and cooling seasons. Solar energy absorbed by glass is either convected away by moving air or reradiated by the glass surface. During the winter, heat from the interior can also be blocked from escaping through the glass. Glass emits heat in the form of long-wave far-infrared energy. Reducing emissivity can greatly improve a window’s insulation properties.\textsuperscript{74} Low-E coatings can be formulated to reflect specific

\textsuperscript{72} Carmody, \textit{High Performance}, 86.
\textsuperscript{73} Ibid, 22.
\textsuperscript{74} Ibid.
portions of the visible and infrared spectrum for optimizing or reducing solar heating. Since only half of the sun’s energy is visible to the human eye, it is possible to block some of the energy without affecting the light transmitted. Coatings to enhance solar heating allow all of the solar spectrum to pass through the glass and block it from reradiating back out, keeping the heat inside. To minimize solar heating, the coating allows most of the visible light through while blocking the rest of the solar spectrum (such as ultraviolet and near-infrared radiation, and long-wave heat).

Low-E coatings are produced through either a sputtered or pyrolytic process. Sputtering is a multi-layered, low-temperature process. The coating is applied to the glazing in a vacuum chamber. Sputtered coatings often use silver which must be protected from humidity and physical contact. Sometimes referred to as a soft coat, sputtered coatings must be installed in a multi-paned unit. Pyrolytic coatings are deposited while the glass is still hot, creating a hard, durable layer. They typically consist of a metallic oxide and are referred to as hard coats. Sputtered coatings have lower emissivity than pyrolytic ones.

**U-Factor**

The energy efficiency of windows is based on two primary measurements: the U-factor and the solar heat gain coefficient. Conduction, convection, and radiation interact with both the glazing and the window frame in complex ways and therefore are not measured separately in reference to windows. Air leakage and condensation resistance are also included in the U-factor calculation (though they can each be measured independently). The U-factor indicates the insulating value, or the ability of the window
assembly to resist heat transfer.\textsuperscript{75} Insulating value refers to the amount of heat gained or lost when there is a temperature difference between the exterior and interior of the window. The U-factor is the reciprocal of the R-factor. R-factor measures the resistance to heat loss while U-factor measures the rate of heat transfer through a product.\textsuperscript{76} It represents the heat flow per hour measured in Btus (or Watts) through each square foot (or square meter) of window for a 1°F (or 1°C) temperature difference between the indoor and outdoor air temperature. The smaller the U-factor, the lower the rate of heat flow. The U-factor is affected not only by the properties of the window materials, but to a much lesser degree, weather conditions. Window manufacturers typically list the U-factor for harsh winter conditions: 15 mph (25 km/hr) wind, 70°F (20°C) indoors, 0°F (-18°C) outdoors. Unlike the SHGC, reducing the U-factor has a greater impact on reducing heating costs than cooling costs.\textsuperscript{77}

The National Fenestration Rating Council (NFRC) developed the current standard for rating windows in 1993. NFRC 100 “Procedures for Determining Fenestration Product U-Factors” established standardized environmental conditions, product sizes, and testing requirements. Windows can be broken up into three areas; the frame, center-of-glass, and edge-of-glass and each area can be given a separate U-factor. However, effectively comparing U-factors based on area can be challenging if the components are not thoroughly described. Therefore, the NFRC utilizes a total window U-factor. The U-factor is typically based on the unit being installed vertically.

\textsuperscript{75} Carmody, \textit{Residential Windows}, 25.
Total window U-factors for various window types (Btu/hr-ft²-°F):

Single-glazed, clear, aluminum frame: 1.25
Double glazed, clear, aluminum frame with break: 0.64
Double glazed, clear, wood/vinyl frame: 0.49
Double glazed, low-E (high solar gain), wood/vinyl frame: 0.36
Double glazed, low-E (low solar gain), wood/vinyl frame: 0.32
Triple glazed, low-E (high solar gain), insulated vinyl frame: 0.18\textsuperscript{78}

**Condensation Resistance**

Condensation can lead to thermal energy loss and damage to the window frame. Condensation occurs when the temperature of the glass is at or below the dew point of the air. Insufficiently insulated glass is susceptible to condensation. The National Fenestration Rating Council and the American Architectural Manufacturers Association have developed ratings for the ability of windows to resist condensation. The Condensation Resistance Factor ranges from 0 to 100, and the higher the number, the greater the resistance.

Windows are categorized as fixed (sashes do not move) or operable (sashes are moveable). Fixed windows perform slightly differently than operable ones. They have lower U-factors, lower air-leakage rates, and higher solar heat gain.\textsuperscript{79} Operable windows come in several forms. While all operable windows have similar U-factors and solar heat

\textsuperscript{78} Ibid, 12.
\textsuperscript{79} Ibid, 94.
gain, air leakage is affected by whether the window is hinged or sliding. Casements, awnings, and hoppers are examples of hinged windows and have lower air-leakage rates than sliding windows. Hinged sashes close by pressing against the frame, utilizing more effective compression weatherstripping. Sliding windows typically use brush-type weatherstripping that allows the sash to slide back and forth but allows for greater air leakage.

**Historic vs. Replacement Windows**

Due to the many advancements in window technology, historic windows are often replaced in an effort to reduce energy costs. Modern replacement window manufacturers often promise high energy savings. These purported savings claim to be anywhere from 15% to as high as 40% (from R9 by Serious Windows).80 Several studies have been conducted in the past twenty years testing historic windows against replacement windows in order to determine how both window types truly perform.

In 2002, the Lawrence Berkeley National Laboratory conducted a study measuring the energy performance of storm windows in winter conditions.81 The Windows and Daylighting Group of the Building Technologies Department tested a double-hung single-glazed wood window as the prime window against a single-hung (fixed top sash), low-E selective glazed, argon-filled sealed-insulated vinyl window, representative of a typical replacement window. The prime window was made

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intentionally leaky while the replacement window was weatherstripped. The windows had identical glass areas and rough openings. The prime window was tested in four configurations: without a storm window; with an uncoated exterior storm window; with a low-E coated exterior storm window; and with a low-E coated interior storm window. Without a storm window, the prime window had approximately twice the rate of heat loss of the replacement window at night.\textsuperscript{82} However, when a low-E storm was installed, the mean sample heat flows for the replacement window and prime window were nearly identical. The prime window/low-E exterior storm’s mean sample heat flow was -34 Watts (-116 Btu/hr) while the replacement had a flow of -30 Watts (-102 Btu/hr). The low-E interior storm performed even better with a heat flow of -42 Watts (-143 Btu/hr) in comparison to the replacement window’s flow of -43 Watts (-146.7 Btu/hr).\textsuperscript{83} (See Figure 5.1) The study found that, “[t]he two prime/low-E storm window combinations…give a net energy flow that is essentially indistinguishable from that of the replacement window.”\textsuperscript{84}

Using the data collected on heat flows, the team calculated the U-factors and solar heat gain coefficients for each window combination. Correcting for infiltration, the non-coated exterior storm and prime window configuration had a U-factor of 3.32 +/-0.01 W/m\(^2\)K (or 0.585 Btu/hr-ft\(^2\)-°F ) and a SHGC of 0.311 +/-0.004. The low-E exterior storm and prime window configuration had a U-factor of 3.04 +/-0.02 W/m\(^2\)K (or 0.535

\textsuperscript{82} Ibid, 6.  
\textsuperscript{83} Ibid, 9.  
\textsuperscript{84} Ibid.
Figure 5.1: Graphs from Lawrence Berkeley study charting the rate of heat loss through the various window configurations in Watts. Note how similar the black (representing the prime/storm configuration) and gray (representing the replacement window) readings are. (Source: Klems, 9).

Figure 5.2: Table from Lawrence Berkeley study showing the U-factors and solar heat gain coefficients for each window configuration for each test period. (Source: Klems, 10).

Table 3. Fitted Values of U-Factor and Solar Heat Gain Coefficient

<table>
<thead>
<tr>
<th>Test</th>
<th>Prime or Prime/Storm Combination</th>
<th>Replacement Window</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U-factor (W/m²K)</td>
<td>Solar Heat Gain Coefficient</td>
</tr>
<tr>
<td>Prime Only</td>
<td>4.72±0.04</td>
<td>0.535±0.017</td>
</tr>
<tr>
<td>Low-e Ext. Storm</td>
<td>3.04±0.02</td>
<td>0.360±0.006</td>
</tr>
<tr>
<td>Reg. Ext. Storm</td>
<td>3.32±0.01</td>
<td>0.311±0.004</td>
</tr>
<tr>
<td>Low-e Int. Storm</td>
<td>2.67±0.02</td>
<td>0.394±0.007</td>
</tr>
</tbody>
</table>

Figure 6. Performance of Prime/Storm Window Combinations. In each plot, the measured net heat flow through a prime/storm window combination (black dots) is compared with the simultaneously-measured net heat flow through the replacement window (gray dots). In addition, a continuous curve describes the calculated net heat flow through the prime window alone under the same instantaneous conditions. (a) Exterior low-e storm window tests. (b) Exterior uncoated storm window test. (c) Interior low-e storm window test.
Btu/hr-ft$^2$°F) and a SHGC of 0.360 +/-0.006. The low-E interior storm and prime window configuration had a U-factor of 2.67 +/-0.02 W/m$^2$K (or 0.47 Btu/hr-ft$^2$°F) and a SHGC of 0.394 +/-0.007.\(^{85}\) (See Figure 5.2) The study shows that the energy performance of historic windows can be improved to levels similar to modern replacement windows through the use of storm windows.

Lawrence Berkeley National Laboratory found that solar heat gain was a factor in winter conditions despite the windows being installed on the north side of the building. Because the SHGC varied widely between the replacement window and the prime/storm combinations, they conclude that “…comparison of performance is more complicated than straightforward comparison of U-factors…”\(^{86}\) Air leakage was also measured with surprising results. The air leakage rates were about ten times lower than expected for the prime window.\(^{87}\) While an inhabitant may feel an air flow due to infiltration, it was found to have little effect on the overall heat flow.\(^{88}\) As previously discussed, infiltration from windows is not as important to heat loss as perceived.

In 2011, the Center for ReSource Conservation published a study examining “The Effects of Energy Efficiency Treatments on Historic Windows.” Windows in a 108 year old home were retrofitted. Testing was also performed in a window laboratory facility developed for the study in order to more accurately measure U-factors and air leakage. Five of the historic windows were rebuilt using methods that retained their historic

\(^{85}\) Ibid, 10.  
\(^{86}\) Ibid, 14.  
\(^{87}\) Ibid, 13.  
\(^{88}\) Ibid.
character. After blower door tests revealed leakage at the weight pockets, the weights were removed and the pockets insulated and sealed. The authors contend that the weight pockets were a source of “…substantial convective and conductive energy losses…”, and were therefore removed.89 Insulating the pockets resulted in reduction of air flow by an average of 11% during the blow door tests.90 (Removal of the weight-pulley system does not follow the Secretary of the Interior’s Standard for Treatment of Historic Properties.)

Windows were fitted with a spring system in place of the counterweight system, then repaired and weatherstripped. Weatherstripping consisted of a silicone compression bulb on the horizontal rails and felt pile on the vertical parting bead and both interior and exterior sash stops. Three of the windows were outfitted with storm windows: one with a single-glazed storm; one with an insulated glass unit storm; and one with an insulated glass unit storm with an insulated frame. An original double-hung window and each storm (including an existing aluminum storm) were tested individually and then in combination. A new vinyl window was also tested. (The authors did not specify whether the window contained low-E glass or was insulated.)

Without a storm, the original window had an average U-factor of 0.78 Btu/hr-ft²-°F (or 4.4 W/m²-K) before repair and 0.48 Btu/hr-ft²-°F (or 2.7 W/m²-K) after repair. With a single-glazed wood storm, the window had an average U-factor of 0.33 Btu/hr-ft²-°F (or 1.8 W/m²-K), with the insulated storm achieved a U-factor of 0.19 Btu/hr-ft²-°F (or 1.07 W/m²-K), and with the insulated frame produced a U-factor of 0.17 Btu/hr-ft²-°F (or 0.96 W/m²-K). The vinyl window had an average U-factor of 0.36 Btu/hr-ft²-°F (or 2.04

90 Ibid, 3-7 and 3-8.
The team used RESFEN software developed by Lawrence Berkeley National Laboratory to estimate the summer and winter energy performance of the fenestration systems. Based on their estimates, the window retrofit would have payback period of anywhere from 19.9 (for Boston) to 63.1 (for Sacramento) years, depending on location and fuel/energy costs. The authors conclude that “…it is possible to improve the overall energy performance of existing window systems by over four fold…through repairs, sealing, and the installation of an excellent storm window.” While a wood storm window greatly improves the energy performance of a historic window, the study found a more efficient fiberglass framed storm would produce even greater energy savings (though fiberglass storms are not commercially available at this time).

In 2009, Glasgow Caledonian University conducted a study on the thermal performance of historic wood windows. Two 2-over-2 historic windows were tested in environmental chambers, one maintained at 2°C (35.6 °F) to simulate exterior winter conditions and the other held at 22°C (71.6°F) to represent interior conditions. Heat-flow tests were conducted with the windows as found, after repair, and after weatherproofing. Heat flux meters were attached to the centers of the top right and bottom left panes. The readings were averaged and the heat transfer rates were converted into U-factors for the glass. U-factors for the entire window assembly were estimated using the FRAME model. The FRAME software was developed in Canada and calculates heat transfer. A variety of different thermal improvements were made to the windows, from window

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92 Ibid, 4-8.
93 Ibid, 4-16.
94 Ibid, 5.
coverings to the use of low-E interior storm windows. Without any repairs or improvements, the window had a U-factor of 5.4 W/m²-K (or 0.951 Btu/hr-ft²-°F). With a low-E storm window, the window had a U-factor of 1.7 W/m²-K (or 0.299 Btu/hr-ft²-°F).\(^95\) (The use of well-fitting shutters or a reflective roller blind produced a U-factor of 1.8 W/m²-K and 1.9 W/m²-K respectively.) Air leakage (at an air flow rate of 50 Pa divided by 20) was reduced from 3.5 m³/h (or 0.19 ft³/min) to 0.5 m³/h (or 0.027 ft³/min) after the storm window was installed.\(^96\) In-situ measurements were also made during the winter at an historic apartment building. The windows were found to have a U-factor of 5.5 W/m²-K (0.969 Btu/hr-ft²-°F) for single glazing and 2.3 W/m²-K (0.423 Btu/hr-ft²-°F) for windows with low-E storms.\(^97\) This study affirms that storm windows can have a dramatic effect on the energy performance of historic windows, allowing them to approach the U-factors of modern insulated windows.

In 1996, a team of civil, energy, and environmental engineers produced a study entitled, “Testing the Energy Performance of Wood Windows in Cold Climates.”\(^98\) The goal of the study was to determine whether or not historic windows can be upgraded to approach the thermal efficiency of replacement windows. The study estimated energy savings as well as installation and material costs for retrofitting historic windows. 151 windows in 29 historic homes and one municipal building were tested. 64 windows were


\(^{96}\) Ibid, 17.

\(^{97}\) Ibid.

in their original, non-retrofitted condition and 87 had been improved through a variety of different upgrades. Thermal losses were measured through field testing and computer modeling. The team divided the thermal losses into two categories: infiltrative and non-infiltrative. Conduction, convection, and radiation fall into the latter category and were modeled using the WINDOW 4.1 computer program. WINDOW 4.1 was developed by Lawrence Berkeley National Laboratory’s Building Technologies Program and simulates fenestration thermal performance. Infiltrative thermal losses were determined by field testing the 151 windows, located primarily in northern and central Vermont.

Field testing produced a U-factor of 0.92 Btu/hr-ft² (or 5.2 W/m²-K) for a loose, single-glazed window without a storm. A single-glazed tight window with a storm had a U-factor of 0.51 Btu/hr-ft² (or 2.9 W/m²-K). Double-glazed insulated wood and vinyl sash units had U-factors of 0.49 Btu/hr-ft² (or 2.8 W/m²-K) and 0.47 Btu/hr-ft² (or 2.6 W/m²-K) respectively. Improving the tightness of a window along with the addition of a storm produced a U-factor very close to an insulated replacement window. Unlike the Lawrence Berkeley Lab study, the Vermont study found that air infiltration significantly contributed to the heat load of the window. The authors looked at leakage that occurred not only through the sash but also between the window frame and rough opening. Aluminum storm windows (triple track or fixed) reduced sash leakage by an average of 45%, while a triple track aluminum storm window caulked to the exterior trim reduced leakage by 75%, and interior storms reduced leakage an average of 96%. Simple window maintenance was also found to significantly reduce air leakage on loose

99 Ibid, 40.
100 Ibid, 69.
windows. Replacement window inserts did not always reduce exterior air infiltration as expected. The authors conclude that, “[b]ased on the range of estimated first year energy savings of window upgrades generated by the study as compared to an assumed typical window and those costs associated with upgrade purchase and installation, replacing a window solely due to energy considerations did not appear to be worthwhile…” and that “…window replacement will not necessarily reduce energy costs more than an upgrade utilizing the existing sash.” This study was one of the first to discover that replacing historic windows for energy savings was not cost effective.

In addition to laboratory and field testing, studies examining actual (as opposed to estimated) energy costs, have been conducted. In 1990, the American Council for an Energy-Efficient Economy (ACEEE) published a report on measured savings from 234 homes in a state energy conservation program in Indiana. Author Hill measured energy savings based on changes in metered fuel use before and after the houses were retrofitted to improve energy efficiency. Retrofits included new windows, new furnaces, and additional insulation. PRISM (the Princeton Scorekeeping Method, a standardized tool for estimating energy savings from billing data) was used to analyze the monthly meter data. Houses ranged in age from 6 to 135 years old and most were wood-frame construction. Hill found the houses that installed replacement windows had an energy

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102 Ibid, 44.
103 Ibid, iii.
104 Ibid, 70.
savings average of 1.4% +/- 1.2% (15 +/- 13 therms per year). The primary reason for the very low average savings was that most of the homes in the study had previously installed aluminum storms (and four had thermal pane windows). If the replaced window was single paned (wood or aluminum), the mean energy savings was 11.2% If the previous window systems had included a storm window, the energy savings from the new window were essentially zero. Replacement windows were found to have an average simple payback period (SPP) for the window investment of greater than 400 years. Houses that installed attic or wall insulation had a much higher rate of savings, with 64% achieving savings of 20% or better. In comparison to replacement windows, replacing the furnace had an SPP of 20 years while installing insulation had a SPP of only 8.5 years.

Hill noted that, “…from a heat transfer perspective, double pane windows would not be expected to perform better than primary windows in combination with storms. A primary with storm enclosing a four-inch air space has a slightly higher R-value than a double pane window alone.” Despite the argument that a reduction in air infiltration will result in energy savings, research has found that windows are not greatly important in terms of infiltrative energy losses because they are generally located in the neutral pressure plane, where there is very little driving force (due to stack effect). In addition,

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106 Ibid, 103.
111 Ibid.
storm windows provide a good air barrier which decreases any pressure differential caused by the wind. Without a pressure differential, there is no driving force and therefore no infiltration/exfiltration.\textsuperscript{112}

Metal framed windows have not been included in studies on energy efficiency, perhaps because they account for a small percentage of residential windows. Steel windows were popular in industrial and commercial buildings before World War II. The Lafayette Building in Washington, D.C., built in 1940, is an example of a commercial building with steel windows. It is a government building and therefore the windows required upgrading for blast resistance. In order to determine whether replacement or retrofitting was a better option, a joint team of architects and engineers undertook a performance monitoring study of an upgraded original window and a replacement window in-situ. In addition to blast-resistance, the owners wanted to improve the energy performance of the windows, have windows that are easily maintained, as well as preserving the original configuration and sight-lines of the original glazing. Cost was also considered. One of the original steel windows was repaired and fitted with an interior low-E coated storm window. The replacement window was thermally broken, aluminum-frame with 1-inch insulating low-E glazing. The windows were tested between March and July of 2006. The tested windows were installed on the east elevation because it would provide variable conditions, (as opposed to the diffuse solar radiation on the north or the intense solar radiation on the south and west elevations.) Surface temperatures, ambient conditions, and heat gain and loss were all measured.

\textsuperscript{112} Hill, “An Evaluation...”, 47.
Because of the in-situ restrictions, the measured heat flows could only be used for comparison between the two windows.

The windows were compared based on rates of solar heat gain and infiltration. The repaired window with an interior storm experienced 35% to 40% greater solar heat gain than the replacement window during the coldest week and 10% to 25% greater during the warmest week. 113 The replacement window lost more heat during the evening and early morning hours. The repaired window experienced nearly 70% less heat loss than the replacement window during the coldest week. 114 The repaired window experienced more solar heat gain during the morning and early afternoon than the replacement window. The team concluded that, “[b]ecause solar heat gain can be manipulated (e.g. through the use of low-E coatings) but heat loss through the frame cannot, the repaired window provides superior heat-loss performance and significantly greater potential for optimizing glazing and heat-gain performance…” 115 The repaired window was also found to have 50% less air infiltration than the replacement window. 116 Infiltration can be a significant source of heat loss in multi-story buildings, such as the Lafayette. The project team concluded that, “…the repaired window offers superior thermal performance…” over the replacement window, in addition to, “…minimiz[ing] material waste by maximizing efficient use of pre-existing embodied energy.” 117

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114 Ibid, 15.
115 Ibid, 17.
116 Ibid, 18.
117 Ibid.
on these findings, the modernization plan specified the refurbishment, rather than replacement, of the building’s windows.

Today’s windows have several technological advantages over historic windows. Multiple layers of glass or plastic improve thermal resistance and reduce heat loss due to convection between window layers. Low-emittance (low-E) coatings reflect long-wavelength infrared radiation which reduces heat transfer between glazing layers. Low-conductive gas fills in insulating glass units can also lower heat transfer between layers. However, multiple studies have shown that with the use of storm windows, particularly those with low-E glass, historic windows can be upgraded to perform nearly equal to replacement windows in terms of energy costs.
Chapter 6

Embodied Energy and Life Cycle Assessment

Embodied energy is the energy required to extract the raw materials from nature and as well as the energy used in primary and secondary manufacturing to create the final product.\textsuperscript{118} Transportation and installation energy is not necessarily included. There are several different methods used to calculate embodied energy. The most widely used are statistical analysis, input/output table analysis, and process analysis.\textsuperscript{119} Statistical analysis relies on available data from the whole economy or a particular industry. Input/output table analysis, originally developed by economists, can be used to determine indirect energy inputs and provide a more complete estimate of embodied energy.\textsuperscript{120} Tables of transactions between different industries are converted from monetary values to energy data. Process analysis is the most detailed method and is usually focused on an individual process or industry. Life cycle assessment is more comprehensive than embodied energy. Life cycle refers to the entire ‘life’ of a material, from ‘cradle-to-grave.’ Assessment includes resource extraction, manufacturing, on-site construction, occupancy/maintenance, demolition, and recycling/reuse/disposal. Embodied energy can


\textsuperscript{120} Ibid.
be considered one component of life cycle assessment. Embodied energy is useful for providing a quick comparison between materials or components, while life cycle assessment is more in-depth and multifaceted. Both concepts can be applied to buildings as a whole or to individual elements.

Embodied energy, though it has become a popular tool in recent years, is not a new concept. In 1981, the U. S. Department of Energy published the *Handbook of Energy Use for Building Construction*. The Stein Partnership and the Energy Research Group at the University of Illinois at Urbana used data from the Bureau of Economic Analysis (BEA) to produce values for over 400 materials used in construction. BEA’s data was in the form of economic input/output (I/O model) and was developed into an energy I/O model by the Energy Research Group. The Stein Partnership divided the data into 49 construction categories, including residential, commercial, and industrial buildings as well as railroads, roads and other non-building constructions. The *Handbook* compiled the data into energy values divided into different categories: by construction sectors; per square foot for new building construction; per unit of building material; and for typical building assemblies. Values for maintenance are also included. The values are based on national averages from 1967 and were not adjusted for regional differences. Table 6.1 shows the values for embodied energy by material and by window type for wood and aluminum. Values for polyvinyl chloride (PVC) and aluminum-clad wood are not included in the *Handbook*. By weight, wood has the lowest embodied energy by far. Aluminum has the highest embodied energy, both as a material and as a window type. Interestingly, there is not a significant difference between the embodied energy of
aluminum and wood framed windows. This implies that a great deal of a window’s embodied energy is in the glazing and other components.

**Table 6.1: U.S.D.O.E. Embodied Energy Estimates**

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Energy (kJ/kg)*</th>
<th>Embodied Energy (kJ)^</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (Soft)</td>
<td>819</td>
<td>1,279,621</td>
</tr>
<tr>
<td>Aluminum</td>
<td>44,122</td>
<td>1,698,550</td>
</tr>
<tr>
<td>Steel (Carbon)</td>
<td>10,863</td>
<td>n/a</td>
</tr>
<tr>
<td>Glazing (1/8” thick sheet)</td>
<td>24,815</td>
<td>n/a</td>
</tr>
</tbody>
</table>

*converted from Btu/lb  
^converted from Btu  

based on a residential grade 4’ x 4’ double glazed window  


In 2008, the University of Bath in England produced a database of carbon and energy associated with construction materials. The data is based on the input/output method. The inputs were taken from over 250 sources, such as peer-reviewed journal papers, technical reports, and monographs. The Inventory of Carbon Energy (ICE) is free and available to the public. Table 6.2 illustrates the embodied energy and carbon by material weight. Wood has the lowest embodied energy and carbon. Steel has the next lowest values, followed by PVC. Aluminum has the highest by far: nearly 20 times that of wood; 6 times that of steel, and 2 times that of PVC. The values produced by the ICE and the U.S.D.O.E. contain some dramatic differences, though the materials with the lowest and highest embodied energies are the same. Differences in embodied energy
could be due to the age of the D.O.E.’s data as well as the different geographical locations of the data sources.

### Table 6.2: ICE Embodied Energy by Material Weight

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Energy (kJ/kg)</th>
<th>Embodied Carbon kg CO2/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>7,800</td>
<td>0.47</td>
</tr>
<tr>
<td>Aluminium (extruded)</td>
<td>154,000</td>
<td>8.16</td>
</tr>
<tr>
<td>PVC</td>
<td>68,950</td>
<td>n/a</td>
</tr>
<tr>
<td>Steel (General)</td>
<td>24,400</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Source: Inventory of Carbon Energy Version 1.6a, University of Bath, UK

Embodied energy only follows a material from ‘cradle to gate,’ or from its extraction to when it is delivered to the construction site (excluding transportation). Life cycle assessment provides a more complete picture of a material’s environmental impact (‘cradle to grave’). The Athena Institute is a non-profit organization dedicated to evaluating the environmental impacts of new and existing buildings through life cycle assessment (LCA). The Institute provides software, databases, and consulting services. In association with the University of Minnesota and Morrison Hershfield Consulting Engineers, the Institute has developed the ATHENA® Impact Estimator for Buildings and ATHENA® EcoCalculator for Assemblies that are capable of modeling entire buildings or individual common building assemblies. The EcoCalculator was commissioned by the Green Building Initiative for use with the Green Globes rating system. Athena’s EcoCalculator is free to download from the Athena Institute’s website. It is available in both residential and commercial versions. The EcoCalculator can be
applied to new construction projects, retrofits, or major renovations, assemblies or entire buildings. Assemblies are divided into seven categories; foundations and footings, columns and beams, intermediate floors, exterior walls, windows, interior walls, and roofs. They are assessed based on a range of performance measures; fossil fuel consumption, weighted resource use, global warming potential, acidification potential, human health respiratory effects potential, eutrophication potential, ozone depletion potential, and smog potential. Eutrophication refers to the addition of artificial or natural substances to an aquatic system. The EcoCalculator takes into account resource extraction and processing, product manufacturing, on-site construction of assemblies, all related transportation, maintenance and replacement cycles over an assumed building service life, and structural system demolition and transportation to landfill. The EcoCalculator does not include energy required for operation. Both commercial and residential buildings are assumed to have a 60-year life span.

Using New York City as the selected location, the EcoCalculator produced the results shown in Tables 6.3 through 6.5. For all applications, wood and vinyl-clad wood windows have the lowest fossil fuel consumption, acidification potential, and ozone depletion potential. Vinyl windows had the lowest global warming potential but the highest ozone depletion potential for low-rise commercial. Aluminum windows use the greatest amount of fossil fuels, have the highest ozone depletion potential for residential, and greatest smog potential. While energy required in disposal is included in the evaluation criteria, the environmental effects of disposal are not addressed. Some materials are recyclable, such as aluminum, and that ability is important. Others release
toxins into the soil. Unfortunately, steel and aluminum-clad wood windows are not included in the EcoCalculator.

**Table 6.3 EcoCalculator Data for Residential Windows**

<table>
<thead>
<tr>
<th>Frame Type (all windows operable and assume double-paned, low-E, argon filled glazing)</th>
<th>Fossil Fuel Consumption per sq ft (kJ)</th>
<th>Weighted Resource Use per sq ft (kg)</th>
<th>Global Warming Potential per sq ft (kg CO2 eq)</th>
<th>Acidification Potential per sq ft (moles of H + eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>387.37</td>
<td>35.39</td>
<td>70.34</td>
<td>36.89</td>
</tr>
<tr>
<td>Aluminum</td>
<td>916.28</td>
<td>75.85</td>
<td>66.24</td>
<td>118.76</td>
</tr>
<tr>
<td>Vinyl</td>
<td>508.87</td>
<td>41.39</td>
<td>43.85</td>
<td>38.12</td>
</tr>
<tr>
<td>Vinyl-Clad Wood</td>
<td>385.10</td>
<td>34.01</td>
<td>65.29</td>
<td>34.74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frame Type</th>
<th>Human Health Respiratory Effects Potential per sq ft (g PM2.5 eq)</th>
<th>Eutrophication Potential per sq ft (mg N eq)</th>
<th>Ozone Depletion Potential per sq ft (mg CFC-11 eq)</th>
<th>Smog Potential per sq ft (g Nox eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>381.51</td>
<td>12084.55</td>
<td>0.07</td>
<td>210.57</td>
</tr>
<tr>
<td>Aluminum</td>
<td>921.94</td>
<td>24394.02</td>
<td>0.24</td>
<td>533.38</td>
</tr>
<tr>
<td>Vinyl</td>
<td>370.23</td>
<td>13008.52</td>
<td>0.23</td>
<td>196.61</td>
</tr>
<tr>
<td>Vinyl-Clad Wood</td>
<td>352.90</td>
<td>11364.42</td>
<td>0.10</td>
<td>194.86</td>
</tr>
</tbody>
</table>

Source: ATHENA EcoCalculator for Residential Assemblies v.1.1
### Table 6.4 EcoCalculator Data for Low-Rise Commercial Windows

<table>
<thead>
<tr>
<th>Frame Type (all windows assume double-paned, low-E, argon filled glazing)</th>
<th>Fossil Fuel Consumption per sq ft (kJ)</th>
<th>Weighted Resource Use per sq ft (kg)</th>
<th>Global Warming Potential per sq ft (kg CO₂ eq)</th>
<th>Acidification Potential per sq ft (moles of H⁺ eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>237.92</td>
<td>47.72</td>
<td>24.58</td>
<td>19.13</td>
</tr>
<tr>
<td>Aluminum</td>
<td>545.61</td>
<td>43.38</td>
<td>47.50</td>
<td>67.64</td>
</tr>
<tr>
<td>Vinyl</td>
<td>342.25</td>
<td>33.77</td>
<td>29.86</td>
<td>20.94</td>
</tr>
<tr>
<td>Vinyl-Clad Wood</td>
<td>238.19</td>
<td>44.29</td>
<td>23.45</td>
<td>18.19</td>
</tr>
<tr>
<td>Curtainwall viewable glazing</td>
<td>205.44</td>
<td>29.21</td>
<td>28.09</td>
<td>22.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Human Health Respiratory Effects Potential per sq ft (g PM2.5 eq)</th>
<th>Eutrophication Potential per sq ft (mg N eq)</th>
<th>Ozone Depletion Potential per sq ft (mg CFC-11 eq)</th>
<th>Smog Potential per sq ft (g NOx eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>258.11</td>
<td>8005.00</td>
<td>0.03</td>
<td>129.24</td>
</tr>
<tr>
<td>Aluminum</td>
<td>569.18</td>
<td>15017.00</td>
<td>0.13</td>
<td>329.31</td>
</tr>
<tr>
<td>Vinyl</td>
<td>252.60</td>
<td>9269.00</td>
<td>0.15</td>
<td>122.84</td>
</tr>
<tr>
<td>Vinyl-Clad Wood</td>
<td>238.66</td>
<td>7512.00</td>
<td>0.06</td>
<td>119.76</td>
</tr>
<tr>
<td>Curtainwall viewable glazing</td>
<td>339.13</td>
<td>8484.00</td>
<td>0.03</td>
<td>166.56</td>
</tr>
</tbody>
</table>

Source: ATHENA EcoCalculator for Commercial Assemblies v.3.6
### Table 6.5: EcoCalculator Data for Hi-Rise Commercial Windows

<table>
<thead>
<tr>
<th>Frame Type (all windows assume double-paned, low-E, argon filled glazing)</th>
<th>Fossil Fuel Consumption per sq ft (KJ)</th>
<th>Weighted Resource Use per sq ft (kg)</th>
<th>Global Warming Potential per sq ft (kg CO2 eq)</th>
<th>Acidification Potential per sq ft (moles of H + eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>545.61</td>
<td>43.38</td>
<td>47.50</td>
<td>67.64</td>
</tr>
<tr>
<td>Curtainwall viewable glazing</td>
<td>205.44</td>
<td>29.21</td>
<td>28.09</td>
<td>22.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frame Type (all windows assume double-paned, low-E, argon filled glazing)</th>
<th>Human Health Respiratory Effects Potential per sq ft (g PM2.5 eq)</th>
<th>Eutrophication Potential per sq ft (mg N eq)</th>
<th>Ozone Depletion Potential per sq ft (mg CFC-11 eq)</th>
<th>Smog Potential per sq ft (g Nox eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>569.18</td>
<td>15017.00</td>
<td>0.13</td>
<td>329.31</td>
</tr>
<tr>
<td>Curtainwall viewable glazing</td>
<td>339.13</td>
<td>8484.00</td>
<td>0.03</td>
<td>166.56</td>
</tr>
</tbody>
</table>

Source: ATHENA EcoCalculator for Commercial Assemblies v.3.6

In 2002, a team from the School of Engineering of Napier University in Edinburgh, Scotland conducted a study that focused on the life cycles of window materials. Aluminum, PVC, wood, and aluminum-clad wood were evaluated using embodied energy, acid potential, and global warming potential values. Table 6.6 contains the results of this study. Wood was found to have the lowest embodied energy, acid potential, and global warming potential while aluminum had the highest values in all three areas. PVC had the next highest values, followed by aluminum-clad wood. While the title of the study contains the phrase “life cycle,” it only took into account a few elements of a window’s life. The study did not include the environmental impacts of paintings and coatings on aluminum and wood, cleaning detergents for PVC, disposal of
windows and their generation of toxins. The values are for Europe and will vary for different countries.

Table 6.6: Napier University’s Life Cycle Assessment by Window Type

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Energy (kJ)</th>
<th>Acid Potential (g SO2 eq)</th>
<th>Global Warming Potential (g CO2 eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>995,000</td>
<td>1</td>
<td>116</td>
</tr>
<tr>
<td>Aluminum</td>
<td>6,000,000</td>
<td>60</td>
<td>11102</td>
</tr>
<tr>
<td>PVC</td>
<td>2,980,000</td>
<td>13</td>
<td>1400</td>
</tr>
<tr>
<td>Aluminum-clad Wood</td>
<td>1,460,000</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Based on a residential grade 4’ x 4’ double glazed window

Embodied energy is not an exact science. Different studies have produced widely different values, due to methodological differences in calculations, boundary conditions, and general assumptions. Embodied energy can also differ based on geographic location. While embodied energy values are not absolute, they can still serve as a useful method for comparing different window frame materials (Tables 6.8 and 6.9). Despite the variation in the numbers produced, studies have consistently shown that wood has the lowest embodied energy of window frame materials, followed by aluminum-clad wood, steel, PVC, and aluminum. Life cycle assessment considers the entire life of a material or product and therefore involves more factors than embodied energy. ATHENA’s EcoCalculator is a life cycle assessment tool that evaluates construction components.
based on eight different environmental impact factors. Determining which window type is least harmful to the environment is not black and white. The values for wood, vinyl-clad wood, and vinyl are similar enough that each could be considered the least harmful material depending on which factor is given more weight. Because embodied energy and life cycle analysis are variable, they should only be used as one of multiple criteria to determine a material’s potential to contribute to sustainability.

Table 6.8: Embodied Energy by Material Weight

<table>
<thead>
<tr>
<th>Material</th>
<th>U.S.D.O.E. Embodied Energy (KJ/Kg)*</th>
<th>University of Bath Embodied Energy (KJ/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>8</td>
<td>7,800</td>
</tr>
<tr>
<td>Aluminum(extruded)</td>
<td>44,122</td>
<td>154,000</td>
</tr>
<tr>
<td>PVC</td>
<td>n/a</td>
<td>68,950</td>
</tr>
<tr>
<td>Steel (General)</td>
<td>10,863</td>
<td>24,400</td>
</tr>
</tbody>
</table>

*converted from Btu/lb

Figure 6.9: Embodied Energy by Window Type

<table>
<thead>
<tr>
<th>Window Type</th>
<th>Embodied Energy (MJ)</th>
<th>U.S.D.O.E. Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>995</td>
<td>1,424</td>
</tr>
<tr>
<td>Aluminum</td>
<td>6000</td>
<td>1,700</td>
</tr>
<tr>
<td>PVC</td>
<td>2980</td>
<td>n/a</td>
</tr>
<tr>
<td>Aluminum-clad Wood</td>
<td>1460</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Chapter 7
Window Durability

Durability refers to a product’s ability to perform as intended over a period of time. A window’s durability is determined by the unit’s ability to resist condensation, air and water infiltration, exposure to moisture, temperature extremes, and exposure to ultraviolet radiation. \(^{122}\) Exposure to salts and other corrosive materials can significantly affect durability. Wood, aluminum, steel, polyvinyl chloride (PVC), and fiberglass are all affected by environmental factors depending on each material’s inherent weaknesses and strengths. Laboratory tests and field surveys can provide an estimate of their each window frame material’s expectancy.

As part of the life cycle window study conducted by the team at Napier University in Edinburg, Scotland, a survey was taken to investigate the performance of windows as a building component. The survey results were compiled to determine the mean service life for the four windows types examined: wood; PVC; aluminum; and aluminum-clad wood. In addition, accelerated aging tests were performed in a laboratory setting. Samples of the frame materials were subjected to immersion, dry-wet cycles, salt spray, humidity/temperature extremes, and ultraviolet radiation. The samples were then examined visually and with optical and atomic force microscopy. In 2002, the North

\(^{122}\) Carmody, *Window Systems*, 72.
American engineering firm Morrison Hershfield Limited conducted a window survey examining the replacement and maintenance requirements of building envelope materials, including windows. Single family residential, multi-unit residential (low-rise and high-rise), office, institutional, commercial, and industrial buildings were studied. Window types surveyed included wood, aluminum, PVC, and steel.

Wood

The Napier University survey found wood to have an average lifespan of 39.6 years. In laboratory testing, wood with surface treatments did not react to moisture or temperature and there experienced little discoloration. The Morrison Hershfield survey found that, “[w]ood-framed windows can survive the life of the building if properly maintained.” Wood windows require the most maintenance of all frame materials. They must be painted or stained every 5 to 7 years to protect the wood from water infiltration. Without maintenance, they usually require replacement after 16 years on average. History shows that wood can last for hundreds of years if protected. The Horiuji Temple in Japan was constructed of cypress in 607 A.D. and still stands today. Norwegian stave churches up to 900 years old are still in existence. Many historic buildings retain their original wood windows. In Lincolnshire, England, the Belshire House, constructed 1685-1688, still contains five of its original wood sash windows. Durability depends on the tree species. If kept dry, oak can last 300-800 years, pine 120-...

123 Asif, et al., 10.
125 Ibid, 36.
126 Ibid, 39.
127 Louw and Crayford, “Part 1”, 93.
1000 years, and spruce 120-900 years.\textsuperscript{128} Today, wood has decreased quality due the shortened growing times, resulting in a spongier, more porous wood.\textsuperscript{129} To compensate for these defects, wood is often impregnated with chemicals. Major window manufacturers offer anywhere from two to ten year warranties on wood windows. This short coverage period could be due to the poor quality of the wood used or the low expectation of maintenance being performed as required.

**Aluminum**

The Napier University survey found aluminum to have an average lifespan of 43.6 years.\textsuperscript{130} Coated aluminum was unaffected by moisture, temperature, and UV exposure in laboratory tests. Without coating, aluminum is susceptible to corrosion. Morrison Hershfield’s survey found that aluminum windows can last anywhere from 15 to 40 years, depending on the application.\textsuperscript{131} Aluminum requires little maintenance and only needs regularly cleaning to retain its appearance. Major window manufacturers offer 10 year warranties on aluminum windows.

**Polyvinyl Chloride (PVC)**

The Napier University survey found PVC windows to have an average lifespan of 24.1 years.\textsuperscript{132} In the laboratory, PVC was unaffected by humidity but experienced severe deterioration after exposure to temperature and UV radiation.\textsuperscript{133} PVC was found to be

\textsuperscript{128} Berg, 172. (See Appendix B)
\textsuperscript{129} Ibid.
\textsuperscript{130} Asif, et al., 10.
\textsuperscript{131} Morrison Hershfield Limited, 40.
\textsuperscript{132} Asif, et al., 10
\textsuperscript{133} Ibid., 11.
very sensitive to high temperatures and ultraviolet radiation, which can break down its molecular bonds and lead to embrittlement and discoloration.\textsuperscript{134} The Morrison Hershfield survey found that PVC-framed windows require replacement after 18 years on average.\textsuperscript{135} PVC requires regular cleaning to prolong its life. Major window manufacturers offer limited lifetime warranties on PVC windows. Limited lifetime warranties cover defects in material or workmanship, but do not apply to normal wear and tear, and are nontransferable.

\textbf{Aluminum-Clad Wood}

The Napier University survey found aluminum-clad wood windows to have an average lifespan of 46.7 years.\textsuperscript{136} Aluminum-clad wood window frames were unaffected by moisture, temperature, and UV exposure in laboratory tests. They require almost no external maintenance. Pella offers a twenty year warranty on aluminum-clad windows. If the frames are exposed to salt spray, the warranty falls to ten years.

\textbf{Steel}

While steel was not included in either survey, its durability can be evaluated based on the properties of the material. Steel is susceptible to corrosion. If protected from corrosion by galvanizing or some other protective coating, steel is extremely durable and strong. Evidence of steel’s durability as a window frame material can be found in the many buildings constructed in the early twentieth century that still retain their original steel windows.

\textsuperscript{134} Ibid, 5.
\textsuperscript{135} Morrison Hershfield Limited, 37.
\textsuperscript{136} Asif, et al., 10.
Fiberglass

Fiberglass is a relatively new window frame material and has not been included in any window studies thus far. In general, fiberglass is strong and resists warping. Pella provides a limited lifetime warranty on its Impervia fiberglass-resin framed windows against cracking, splitting, corroding and warping. Their other fiberglass-resin windows come with a ten year limited warranty. Marvin Windows offers a ten year limited warranty for their Integrity windows.

Window frame material deterioration may not always be the cause for replacement. Morrison Hershfield found that insulated glazing units typically fail (lose their gas seal) between 10 to 30 years after installation. This figure is disturbingly low. Most insulated glazing units cannot be easily repaired and instead are replaced after failure. Perhaps thirty years is the expected life span of buildings constructed today. For those buildings that aim to be in service for more than thirty years, insulated glazing units may not be the most durable option.

Some window frame materials are inherently more durable than others. Others can be augmented to improve their durability, such as steel that has been galvanized. Surface treatments can protect vulnerable materials allowing them to withstand exposure to the elements. According to studies performed by Napier University and Morrison Hershfield Limited, aluminum and aluminum-clad windows last the longest of the studied frame materials. Wood, with regular maintenance, has the next greatest lifespan. Historic wood windows offer proof that wood frames can last much longer than the forty

\[137\] Morrison Hershfield Limited, 35.
year lifespan produced by the Napier survey if made of quality material and regularly maintained. PVC was found to have the shortest performance life, around only twenty years. Unfortunately, steel and fiberglass windows were not included in either study. The survival of historic steel windows can attest to the material’s longevity. Fiberglass is a relatively new window frame material and more time is needed to determine how it holds up to environmental factors.
Chapter 8
Findings

Historic windows are arguably the most villainized component of historic buildings, subject to frequent replacement. Their loss impacts not only a building’s integrity but the natural environment as well. Based on the criteria of energy efficiency, life cycle, and durability, historic windows are equally, if not more, sustainable components than replacement windows. In general, wood windows are a highly sustainable window type. Historic wood windows are generally superior to modern equivalents, especially if constructed of old growth wood.138 Their energy performance can be improved with storm windows, their lifecycle is superior to replacement windows, and their durability has been proven.

**Historic vs. Replacement Windows**

Replacement windows’ greatest advantage over historic windows is their superior energy efficiency. However, storm windows can improve a historic single-paned window’s energy performance to be very close to that of a modern replacement window’s (see Figure 8.1). Energy efficiency is just one component of sustainability. While

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important, a component’s efficiency can only be used in comparison and means nothing as an independent value.\textsuperscript{139} Durability and life cycle are just as, if not more, important as energy efficiency. The continued survival of historic windows proves their durability. In the case of wood frames, historic frames are more durable than modern replacements due to the superiority of the historic wood. Historic windows also have the advantage of being easily repairable.\textsuperscript{140} Modern windows can be difficult or impossible to repair. Insulated glass units have a tendency to fail (lose their seals) after a relatively short amount of time and cannot be easily repaired. This results in a waste of energy, materials, and money. Regardless of frame material, historic windows have better life cycles than new ones. The energy needed to produce them has already been expended and can be deducted from the embodied energy of the frame.

\textbf{Figure 8.1 U-Values}

<table>
<thead>
<tr>
<th>Window Type</th>
<th>Typical NFRC Rating</th>
<th>Lawrence Berkeley Study</th>
<th>Glasgow Caledonia Univ. Study</th>
<th>Vermont Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazed, clear, wood/vinyl frame</td>
<td>0.50</td>
<td>n/a</td>
<td>n/a</td>
<td>0.49</td>
</tr>
<tr>
<td>Double glazed, insulated, low-E, wood/vinyl frame</td>
<td>0.33</td>
<td>0.438</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Triple glazed, insulated, low-E, wood/vinyl frame</td>
<td>0.22</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Historic window with storm window</td>
<td>n/a</td>
<td>0.585</td>
<td>n/a</td>
<td>0.51</td>
</tr>
<tr>
<td>Historic window with low-E exterior storm</td>
<td>n/a</td>
<td>0.535</td>
<td>0.299</td>
<td>n/a</td>
</tr>
<tr>
<td>Historic window with low-E interior storm</td>
<td>n/a</td>
<td>0.47</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

\textsuperscript{139} McDonough and Braungart, 65.  
\textsuperscript{140} See Appendix A.
Windows by Type

Wood

Wood has many qualities that make it a good window frame material. It is an excellent insulator, making wood window frames energy efficient. Wood can be extremely durable, lasting well over fifty years if protected from the elements by paint or varnish. Wood has the least harmful life cycle of all window frame materials. It requires a low amount of energy to harvest and mill, it can last a long time, and is recyclable and biodegradable. Historic wood frames were constructed of high quality wood, many with old growth wood. Old growth wood is extremely dense, strong, and resists warping. Because old growth forests have been depleted, old growth wood windows cannot be replaced with in-kind materials. Wood is a renewable resource if harvested from responsibly managed forests. The greatest disadvantage of wood frames is their need for frequent maintenance (every 5 to 7 years). Wood frames are readily available and priced in the mid-high range.

Steel

Steel is an extremely durable window frame material if protected from corrosion. Steel has a moderate conductive heat rate, making it relatively energy efficient. It is also recyclable. However, steel requires a great deal of energy to extract and produce. It is not a renewable resource. The galvanizing process produces air pollution and toxic sludge. Steel windows are produced by only a small number of companies and are relatively high priced.
Aluminum

Aluminum is an extremely durable window frame material, requiring no surface treatments. It is also easily recycled. But it requires a great deal of energy to extract. Aluminum is also a poor insulator, requiring a thermal break when used in window frames. While it is currently readily available, aluminum is a non-renewable resource. Aluminum frames are not widely produced. Their price is in the low-mid range.

Aluminum-Clad

Window frames made of wood clad with aluminum combine the durability of aluminum with the energy efficiency of wood. Their greatest advantage is the very low amount of maintenance required. However, clad windows are relatively new and their durability has not been proven. Clad windows require both high and low amounts of energy to produce due to the respective requirements of aluminum and wood. Clad frames are not widely available and are priced in the mid-high range.

Polyvinyl Chloride

Polyvinyl chloride (PVC) can produce window frames with good insulator qualities. While PVC resists moisture and insects, it is not very durable in the long term, with a lifespan of less than thirty years. Production of PVC creates a large amount of pollution, including chlorine gas, ethylene, dioxins, vinyl chloride, dichloroethane, and mercury. The raw materials required to make PVC are non-renewable. It is difficult to recycle and can release toxins into the soil when placed in a landfill. PVC frames are widely available and priced in the low-mid range.
Fiberglass

Fiberglass creates a strong window frame and has excellent insulator qualities if filled with polyurethane foam. Fiberglass can be produced with some recycled glass content and requires a comparatively low amount of energy to produce. Because it is a relatively new window frame material, its durability is unproven. Fiberglass frames are not widely available and are priced in the mid-high range.

Figure 7.1: Sustainability Criteria by Window Type

<table>
<thead>
<tr>
<th></th>
<th>Wood</th>
<th>Steel</th>
<th>Aluminum</th>
<th>Vinyl</th>
<th>Fiberglass</th>
<th>Aluminum-Clad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no/yes</td>
</tr>
<tr>
<td>Extraction Energy</td>
<td>Low</td>
<td>high</td>
<td>high</td>
<td>medium</td>
<td>low</td>
<td>high/low</td>
</tr>
<tr>
<td>Manufacture Energy</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>medium w/toxins</td>
<td>low</td>
<td>high/low</td>
</tr>
<tr>
<td>Maintenance</td>
<td>high (every 5-7 years)</td>
<td>low</td>
<td>extremely low</td>
<td>low</td>
<td>low</td>
<td>extremely low</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>good</td>
<td>fair</td>
<td>poor</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Life Span</td>
<td>40 years &amp; up</td>
<td>40 years &amp; up</td>
<td>40 years</td>
<td>24 years</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>Disposal</td>
<td>recyclable</td>
<td>recyclable</td>
<td>recyclable</td>
<td>landfill w/toxins</td>
<td>landfill</td>
<td>recyclable</td>
</tr>
<tr>
<td>Availability</td>
<td>good</td>
<td>poor</td>
<td>fair</td>
<td>good</td>
<td>poor</td>
<td>poor</td>
</tr>
<tr>
<td>Cost</td>
<td>mid-high</td>
<td>high</td>
<td>low-mid</td>
<td>low-mid</td>
<td>mid-high</td>
<td>mid-high</td>
</tr>
</tbody>
</table>

According to Bjorn Berg, author of *The Ecology of Building Materials*, the model for a modern sustainable window is a triple paned unit with separate inner and outer frames made of wood. The inner and outer most panes are clear glass and the center pane
is coated with a low-E film. The outer frame is constructed of mature oak and can be easily replaced when needed. A historic wood window with an external wood storm window is very similar to Berg’s modern sustainable window. The storm window protects the historic window from the harsh elements. As with the outer frame of Berg’s window, when the storm window wears out, it can be replaced without affecting the original window.

Historic preservationists and environmentalists need to realize they are natural allies. Historic structures are valuable not just for their beauty but for the embodied energy that they contain. Individual components, such as windows, may be more than or equally as sustainable as their modern counterparts. Further study is needed to determine what other components of historic buildings are also worth saving in terms of sustainability. Retention of historic windows is a highly sustainable practice. Wood’s need for frequent maintenance may still make many reluctant to choose it as a window frame material. But PVC can no longer be seen as a viable alternative to wood. The toxins produced in its production and disposal, along with its short life span, make PVC the least sustainable window frame material.

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141 Berg, 362-3.
Appendix A

Preservation Briefs: 9
The Repair of Historic Wooden Windows

John H. Myers

The windows on many historic buildings are an important aspect of the architectural character of those buildings. Their design, craftsmanship, or other qualities may make them worthy of preservation. This is self-evident for ornamental windows, but it can be equally true for warehouses or factories where the windows may be the most dominant visual element of an otherwise plain building (see figure 1). Evaluating the significance of these windows and planning for their repair or replacement can be a complex process involving both objective and subjective considerations. The Secretary of the Interior's Standards for Rehabilitation, and the accompanying guidelines, call for respecting the significance of original materials and features, repairing and retaining them wherever possible, and when necessary, replacing them in kind. This Brief is based on the issues of significance and repair which are implicit in the standards, but the primary emphasis is on the technical issues of planning for the repair of windows including evaluation of their physical condition, techniques of repair, and design considerations when replacement is necessary.

Much of the technical section presents repair techniques as an instructional guide for the do-it-yourselfer. The information will be useful, however, for the architect, contractor, or developer on large-scale projects. It presents a methodology for approaching the evaluation and repair of existing windows, and considerations for replacement, from which the professional can develop alternatives and specify appropriate materials and procedures.

Architectural or Historical Significance

Evaluating the architectural or historical significance of windows is the first step in planning for window treatments, and a general understanding of the function and history of windows is vital to making a proper evaluation. As a part of this evaluation, one must consider four basic window functions: admitting light to the interior spaces, providing fresh air and ventilation to the interior, providing a visual link to the outside world, and enhancing the appearance of a building. No single factor can be disregarded when planning window treatments; for example, attempting to conserve energy by closing up or reducing the size of window openings may result in the use of more energy by increasing electric lighting loads and decreasing passive solar heat gains.

Historically, the first windows in early American houses were casement windows; that is, they were hinged at the side and opened outward. In the beginning of the eighteenth century single- and double-hung windows were introduced. Subsequently many styles of these vertical sliding sash windows have come to be associated with specific building periods or architectural styles, and this is an important consideration in determining the significance of windows, especially on a local or regional basis. Site-specific, regionally oriented architectural comparisons should be made to determine the significance of windows in question. Although such comparisons may focus on specific window types and their details, the ultimate determination of significance should be made within the context of the whole building, wherein the windows are one architectural element (see figure 2).

After all of the factors have been evaluated, windows should be considered significant to a building if they: 1) are original, 2) reflect the original design intent for the building, 3) reflect period or regional styles or building practices, 4) reflect changes to the building resulting from major periods or events, or 5) are examples of exceptional craftsmanship or design. Once this evaluation of significance has been completed, it is possible to pro-
ceed with planning appropriate treatments, beginning with an investigation of the physical condition of the windows.

Physical Evaluation
The key to successful planning for window treatments is a careful evaluation of existing physical conditions on a unit-by-unit basis. A graphic or photographic system may be devised to record existing conditions and illustrate the scope of any necessary repairs. Another effective tool is a window schedule which lists all of the parts of each window unit. Spaces by each part allow notes on existing conditions and repair instructions. When such a schedule is completed, it indicates the precise tasks to be performed in the repair of each unit and becomes a part of the specifications. In any evaluation, one should note at a minimum, 1) window location, 2) condition of the paint, 3) condition of the frame and sill, 4) condition of the sash (rails, stiles and muntins), 5) glazing problems, 6) hardware, and 7) the overall condition of the window (excellent, fair, poor, and so forth).

Many factors such as poor design, moisture, vandalism, insect attack, and lack of maintenance can contribute to window deterioration, but moisture is the primary contributing factor in wooden window decay. All window units should be inspected to see if water is entering around the edges of the frame and, if so, the joints or seams should be caulked to eliminate this danger. The glazing putty should be checked for cracked, loose, or missing sections which allow water to saturate the wood, especially at the joints. The back putty on the interior side of the pane should also be inspected, because it creates a seal which prevents condensation from running down into the joinery. The sill should be examined to insure that it slopes downward away from the building and allows water to drain off. In addition, it may be advisable to cut a dripline along the underside of the sill. This almost invisible treatment will insure proper water run-off, particu-
Figure 3. Deterioration of poorly maintained windows usually begins on horizontal surfaces and at joints where water can collect and saturate the wood. The problem areas are clearly indicated by paint failure due to moisture. Photo: Baird M. Smith, AIA

The routine maintenance required to upgrade a window to "like new" condition normally includes the following steps: 1) some degree of exterior and interior paint removal, 2) removal and repair of sash (including reglazing where necessary), 3) repairs to the frame, 4) weatherstripping and reinstallation of the sash, and 5) repainting. These operations are illustrated for a typical double-hung wooden window (see figures 4a-4d), but they may be adapted to other window types and styles as applicable.

Historic windows have usually acquired many layers of paint over time. Removal of excess layers or peeling and flaking paint will facilitate operation of the window and restore the clarity of the original detailing. Some degree of paint removal is also necessary as a first step in the proper surface preparation for subsequent refinishing (if paint color analysis is desired, it should be conducted prior to the onset of the paint removal). There are several safe and effective techniques for removing paint from wood, depending on the amount of paint to be removed. Several techniques such as scraping, chemical stripping, and the use of a hot air gun are discussed in "Preservation Briefs: 10 Paint Removal from Historic Woodwork" (see Additional Reading section at end).

Paint removal should begin on the interior frames, being careful to remove the paint from the interior stop and the parting bead, particularly along the seam where these stops meet the jamb. This can be accomplished by running a utility knife along the length of the seam, breaking the paint bond. It will then be much easier to remove the stop, the parting bead and the sash. The interior stop may be initially loosened from the sash side to avoid visible scarring of the wood and then gradually pried loose using a pair of putty knives, working up and down the stop in small increments (see figure 4b). With the stop removed, the lower or interior sash may be withdrawn. The sash cords should be detached from the sides of the sash and their ends may be pinned with a nail or tied in a knot to prevent them from falling into the weight pocket.

Removal of the upper sash on double-hung units is similar but the parting bead which holds it in place is set into a groove in the center of the stile and is thinner and more delicate than the interior stop. After removing any paint along the beam, the parting bead should be carefully pried out and worked free in the same manner as the interior stop. The upper sash can be removed in the same manner as the lower one and both sash taken to a convenient work area (in order to remove the sash the interior stop and parting bead need only be removed from one side of the window). Window openings can be covered with polyethylene sheets or plywood sheathing while the sash are out for repair.

The sash can be stripped of paint using appropriate techniques, but if any heat treatment is used (see figure 4c), the glass should be removed or protected from the sudden temperature change which can cause breakage. An
Figure 4a. The following series of photographs of the repair of a historic double-hung window use a unit which is structurally sound but has many layers of paint, some cracked and missing putty, slight separation at the joints, broken sash cords, and one cracked pane. Photo: John H. Myers

Figure 4b. After removing paint from the seam between the interior stop and the jamb, the stop can be pried out and gradually sorted bone using a pair of putty irons or shears. To avoid visible scoring of the wood, the sash can be raised and the stop pried loose initially from the outer side. Photo: John H. Myers

Figure 4c. Sash can be removed and repaired in a convenient work area. Paint is being removed from this sash with a hot air gun while an asbestos sheet protects the glass from sudden temperature change. Photo: John H. Myers

Figure 4d. Replacing or replacement of the putty requires that the existing putty be removed manually, the glazing points be extracted, the glass removed, and the back putty scraped out. To replace, a bead of putty is laid around the perimeter of the rebate. The pane is pressed into place, glazing points are inserted to hold the pane (shown), and a final bead of putty is beaded around the edge of the glass. Photo: John H. Myers

Figure 4e. A common repair is the replacement of broken sash cords with new cords (shown) or with chains. The weight pocket is often accessible through a removable plate in the jamb, or by removing the interior trim. Photo: John H. Myers

Figure 4f. Following the relatively simple repairs, the window is weather-tight, like new in appearance, and serviceable for many years to come. Both the historic material and the detailing and craftsmanship of this original window have been preserved. Photo: John H. Myers
overlay of aluminum foil on gypsum board or asbestos can protect the glass from such rapid temperature change. It is important to protect the glass because it may be historic and often adds character to the window. Deteriorated putty should be removed manually, taking care not to damage the wood along the rabbet. If the glass is to be removed, the glazing points which hold the glass in place can be extracted and the panes numbered and removed for cleaning and reuse in the same openings. With the glass panes out, the remaining putty can be removed and the sash can be sanded, patched, and primed with a preservative primer. Hardened putty in the rabbets may be softened by heating with a soldering iron at the point of removal. Putty remaining on the glass may be softened by soaking the panes in linseed oil, and then removed with less risk of breaking the glass. Before reinserting the glass, a bead of glazing compound or linseed oil putty should be laid around the rabbet to cushion and seal the glass. Glazing compound should only be used on wood which has been brushed with linseed oil and primed with an oil based primer or paint. The pane is then pressed into place and the glazing points are pushed into the wood around the perimeter of the pane (see figure 4d). The final glazing compound or putty is applied and beveled to complete the seal. The sash can be refinished as desired on the inside and painted on the outside as soon as a “skin” has formed on the putty, usually in 2 or 3 days. Exterior paint should cover the beveled glazing compound or putty and lap onto the glass slightly to complete a weathertight seal. After the proper curing times have elapsed for paint and putty, the sash is ready for reinstallation.

While the sash are out of the frame, the condition of the wood in the jamb and sill can be evaluated. Repair and refinishing of the frame may proceed concurrently with repairs to the sash, taking advantage of the curing times for the putty used on the sash. One of the most common work items is the replacement of the sash cords with new rope cords or chains (see figure 4e). The weight carrying capacity is frequently accessible through a door on the face of the frame near the sill, but if no door exists, the trim on the interior face may be removed for access. Sash weights may be increased for easier window operation by elderly or handicapped persons. Additional repairs to frame and sash may include consolidation or replacement of deteriorated wood. Techniques for these repairs are discussed in the following sections.

The operations just discussed summarize the efforts necessary to restore a window with minor deterioration to “like new” condition (see figure 4f). The techniques can be applied by an unskilled person with minimal training and experience. To demonstrate the practicality of this approach, and photograph it, a Technical Preservation Services staff member repaired a wooden double-hung, two over two window which had been in service over ninety years. The wood was structurally sound but the window had one broken pane, many layers of paint; broken sash cords and inadequate, worn-out weatherstripping. The staff member found that the frame could be stripped of paint and the sash removed quite easily. Paint, putty and glass removal required about one hour for each sash, and the reinstalling of both sash was accomplished in about one hour. Weatherstripping of the sash and frame, replacement of the sash cords and reinstallation of the sash, parting bead, and top required an hour and a half. These times refer only to individual operations; the entire process took several days due to the drying and curing times for putty, primer, and paint, however, work on other window units could have been in progress during these lag times.

Repair Class II: Stabilization

The preceding description of a window repair job focused on a unit which was operationally sound. Many windows will show some additional degree of physical deterioration, especially in the vulnerable areas mentioned earlier, but even badly damaged windows can be repaired using simple processes. Partially decayed wood can be waterproofed, patched, built-up, or consolidated and then painted to achieve a sound condition, good appearance, and greatly extended life. Three techniques for repairing partially decayed or weathered wood are discussed in this section, and all three can be accomplished using products available at most hardware stores.

One established technique for repairing wood which is split, checked or shows signs of rot, is to: 1) dry the wood, 2) treat decayed areas with a fungicide, 3) waterproof with two or three applications of boiled linseed oil (applications every 24 hours), 4) fill cracks and holes with putty, and 5) after a “skin” forms on the putty, paint the surface. Care should be taken with the use of fungicide which is toxic. Follow the manufacturers’ directions and use only on areas which will be painted. When using any technique of building up or patching a flat surface, the finished surface should be sloped slightly to carry water away from the window and not allow it to puddle. Caulking of the joints between the sill and the jamb will help reduce further water penetration.

When sills or other members exhibit surface weathering they may also be built-up using wood putties or homemade mixtures such as sawdust and resorcinol glue, or whiting and varnish. These mixtures can be built up in successive layers, then sanded, primed, and painted. The same caution about proper slope for flat surfaces applies to this technique.

Wood may also be strengthened and stabilized by consolidation, using semi-rigid epoxies which saturate the porous decayed wood and then harden. The surface of the consolidated wood can then be filled with a semi-rigid epoxy patching compound, sanded and painted (see figure 5). Epoxy patching compounds can be used to build up...
missing sections or decayed ends of members. Profiles can be duplicated using hand molds, which are created by pressing a ball of patching compound over a sound section of the profile which has been rubbed with butcher's wax. This can be a very efficient technique where there are many typical repairs to be done. Technical Preservation Services has published *Epoxies for Wood Repairs in Historic Buildings* (see Additional Reading section at end), which discusses the theory and techniques of epoxy repairs. The process has been widely used and proven in marine applications; and proprietary products are available at hardware and marine supply stores. Although epoxy materials may be comparatively expensive, they hold the promise of being among the most durable and long lasting materials available for wood repair.

Any of the three techniques discussed can stabilize and restore the appearance of the window unit. There are times, however, when the degree of deterioration is so advanced that stabilization is impractical, and the only way to retain some of the original fabric is to replace damaged parts.

**Repair Class III: Splices and Parts Replacement**

When parts of the frame or sash are so badly deteriorated that they cannot be stabilized there are methods which permit the retention of some of the existing or original fabric. These methods involve replacing the deteriorated parts with new matching pieces, or splicing new wood into existing members. The techniques require more skill and are more expensive than any of the previously discussed alternatives. It is necessary to remove the sash and/or the affected parts of the frame and have a carpenter or woodworking mill reproduce the damaged or missing parts. Most millwork firms can duplicate parts, such as muntins, bottom rails, or sills, which can then be incorporated into the existing window, but it may be necessary to shop around because there are several factors controlling the practicality of this approach. Some woodworking mills do not like to repair old sash because nails or other foreign objects in the sash can damage expensive knives (which cost far more than their profits on small repair jobs); others do not have cutting knives to duplicate muntin profiles. Some firms prefer to concentrate on larger jobs with more profit potential, and some may not have a craftsman who can duplicate the parts. A little searching should locate a firm which will do the job, and at a reasonable price. If such a firm does not exist locally, there are firms which undertake this kind of repair and ship nationwide. It is possible, however, for the advanced do-it-yourselfer or craftsman with a table saw to duplicate moulding profiles using techniques discussed by Gordie Whittington in "Simplified Methods for Reproducing Wood Mouldings," *Bulletin* of the Association for Preservation Technology, Vol. III, No. 4, 1971, or illustrated more recently in *The Old House*, Time-Life Books, Alexandria, Virginia, 1979.

The repairs discussed in this section involve window frames which may be in very deteriorated condition, possibly requiring removal; therefore, caution is in order. The actual construction of wooden window frames and sash is not complicated. Pegged mortise and tenon units can be disassembled easily, if the units are out of the building. The installation or connection of some frames to the surrounding structure, especially masonry walls, can complicate the work immeasurably, and may even require dismantling of the wall. It may be useful, therefore, to take the following approach to frame repair: 1) conduct regular maintenance of sound frames to achieve the longest life possible, 2) make necessary repairs in place wherever possible, using stabilization and splicing techniques, and 3) if removal is necessary, thoroughly investigate the structural detailing and seek appropriate professional consultation.

Another alternative may be considered if parts replacement is required, and that is sash replacement. If extensive replacement of parts is necessary and the job becomes prohibitively expensive it may be more practical to purchase new sash which can be installed into the existing frames. Such sash are available as exact custom reproductions, reasonable facsimiles (custom windows with similar profiles), and contemporary wooden sash which are similar in appearance. There are companies which still manufacture high quality wooden sash which would duplicate most historic sash. A few calls to local building suppliers may provide a source of appropriate replacement sash, but if not, check with local historical associations, the state historic preservation office, or preservation related magazines and supply catalogs for information.

If a rehabilitation project has a large number of windows such as a commercial building or an industrial complex, there may be less of a problem arriving at a solution. Once the evaluation of the windows is completed and the scope of the work is known, there may be a potential economy of scale. Woodworking mills may be interested in the work from a large project; new sash in volume may be considerably less expensive per unit. Crews can be assembled and trained on site to perform all of the window repairs; and a few extensive repairs can be absorbed (without undue burden) into the total budget for a large number of sound windows. While it may be expensive for the average historic home owner to pay seventy dollars or more for a mill to grind a custom knife to duplicate four or five bad muntins, that cost becomes negligible on large commercial projects which may have several hundred windows.

Most windows should not require the extensive repairs discussed in this section. The ones which do are usually in buildings which have been abandoned for long periods or have totally lacked maintenance for years. It is necessary to thoroughly investigate the alternatives for windows which do require extensive repairs to arrive at a solution which retains historic significance and is also economically feasible. Even for projects requiring repairs identified in this section, if the percentage of parts replacement per window is low, or the number of windows requiring repair is small, repair can still be a cost effective solution.

**Weatherization**

A window which is repaired should be made as energy efficient as possible by the use of appropriate weather-stripping to reduce air infiltration. A wide variety of products are available to assist in this task. Felt may be fastened to the top, bottom, and meeting rails, but may have the disadvantage of absorbing and holding moisture, particularly at the bottom rail. Rolled vinyl strips may also be tacked into place in appropriate locations to reduce infiltration. Metal strips or new plastic spring strips may be used on the rails and, if space permits, in
the channels between the sash and jamb. Weatherstripping is a historic treatment, but old weatherstripping (felt) is not likely to perform very satisfactorily. Appropriate contemporary weatherstripping should be considered an integral part of the repair process for windows. The use of sash locks installed on the meeting rail will insure that the sash are kept tightly closed so that the weatherstripping will function more effectively to reduce infiltration. Although such locks will not always be historically accurate, they will usually be viewed as an acceptable contemporary modification in the interest of improved thermal performance.

Many styles of storm windows are available to improve the thermal performance of existing windows. The use of exterior storm windows should be investigated whenever feasible because they are thermally efficient, cost-effective, reversible, and allow the retention of original windows (see "Preservation Briefs: 31"). Storm window frames may be made of wood, aluminum, vinyl, or plastic; however, the use of unfinished aluminum storm windows should be avoided. The visual impact of storms may be minimized by selecting colors which match existing trim color. Arched top storms are available for windows with special shapes. Although interior storm windows appear to offer an attractive option for achieving double glazing with minimal visual impact, the potential for damaging condensation problems must be addressed. Moisture which becomes trapped between the layers of glazing can condense on the colder, inner prime window, potentially leading to deterioration. The correct approach to using interior storms is to create a seal on the interior storm while allowing some ventilation around the prime window. In actual practice, the creation of such a durable, airtight seal is difficult.

Window Replacement

Although the retention of original or existing windows is always desirable and this Brief is intended to encourage that goal, there is a point when the condition of a window may clearly indicate replacement. The decision process for selecting replacement windows should not begin with a survey of contemporary window products which are available as replacements, but should begin with a look at the windows which are being replaced. Attempt to understand the contribution of the window(s) to the appearance of the facade including: 1) the pattern of the openings and their size; 2) proportions of the frame and sash; 3) configuration of window panes; 4) muntin profiles; 5) type of wood; 6) paint color; 7) characteristics of the glass; and 8) associated details such as arched tops, hoods, or other decorative elements. Develop an understanding of how the window reflects the period, style, or regional characteristics of the building, or represents technological development.

Armed with an awareness of the significance of the existing window, begin to search for a replacement which retains as much of the character of the historic window as possible. There are many sources of suitable new windows. Continue looking until an acceptable replacement can be found. Check building supply firms, local woodworking mills, carpenters, preservation oriented magazines, or catalogs or suppliers of old building materials, for needed information. Local historical associations and state historic preservation offices may be good sources of information on products which have been used successfully in preservation projects.

Consider energy efficiency as one of the factors for replacements, but do not let it dominate the issue. Energy conservation is no excuse for the wholesale destruction of historic windows which can be made thermally efficient by historically and aesthetically acceptable means. In fact, a historic wooden window with a high quality storm window added should thermally outperform a new double-glazed metal window which does not have thermal breaks (insulation between the inner and outer frames intended to break the path of heat flow). This occurs because the wood has far better insulating value than the metal, and in addition many historic windows have high ratios of wood to glass, thus reducing the area of highest heat transfer. One measure of heat transfer is the U-value, the number of Btu's per hour transferred through a square foot of material. When comparing thermal performance, the lower the U-value the better the performance. According to ASHRAE 1977 Fundamentals, the U-values for single glazed wooden windows range from 0.88 to 0.90. The addition of a storm window should reduce these figures to a range of 0.44 to 0.49. A non-thermal break, double-glazed metal window has a U-value of about 0.6.

Conclusion

Technical Preservation Services recommends the retention and repair of original windows whenever possible. We believe that the repair and weatherization of existing wooden windows is more practical than most people realize, and that many windows are unfortunately replaced because of a lack of awareness of techniques for evaluation, repair, and weatherization. Wooden windows which are repaired and properly maintained will have greatly extended service lives while contributing to the historic character of the building. Thus, an important element of a building’s significance will have been preserved for the future.

Additional Reading


Ferro, Maximilian. Preservation: Present Pathway to Fall River’s Future. Fall River, Massachusetts: City of Fall River, 1979 (chapter 7).


1981
PRESERVATION BRIEFS

The Repair and Thermal Upgrading of Historic Steel Windows

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Windows are among the most vulnerable features of historic buildings undergoing rehabilitation. This is especially the case with rolled steel windows, which are often mistakenly not deemed worthy of preservation in the conversion of old buildings to new uses. The ease with which they can be replaced and the mistaken assumption that they cannot be made energy efficient except at great expense are factors that typically lead to the decision to remove them. In many cases, however, repair and retrofit of the historic windows are more economical than wholesale replacement, and all too often, replacement units are unlike the originals in design and appearance. If the windows are important in establishing the historic character of the building (see fig. 1), insensitively designed replacement windows may diminish—or destroy—the building's historic character.

This Brief identifies various types of historic steel windows that dominated the metal window market from 1890-1950. It then gives criteria for evaluating deterioration and for determining appropriate treatment, ranging from routine maintenance and weatherization to extensive repairs, so that replacement may be avoided where possible. This information applies to do-it-yourselfers and to large rehabilitations where the volume of work warrants the removal of all window units for complete overhaul by professional contractors.

This Brief is not intended to promote the repair of ferrous metal windows in every case, but rather to insure that preservation is always the first consideration in a rehabilitation project. Some windows are not important elements in defining a building's historic character; others are highly significant, but so deteriorated that repair is infeasible. In such cases, the Brief offers guidance in evaluating appropriate replacement windows.

Fig. 1 Often highly distinctive in design and craftsmanship, rolled steel windows play an important role in defining the architectural character of many later nineteenth and early twentieth century buildings. Art Deco, Art Moderne, the International Style, and Post World War II Modernism depended on the slim profiles and streamlined appearance of metal windows for much of their impact. Photo: William G. Johnson.

1The technical information given in this Brief is intended for use with ferrous (or magnetic) metals, particularly rolled steel. While stainless steel is a ferrous metal, the cleaning and repair techniques outlined here must not be used on it as the finish will be damaged. For information on cleaning stainless steel and non-ferrous metals, such as bronze, Monel, or aluminum, refer to Metals in America's Historic Buildings (see bibliography).
HISTORICAL DEVELOPMENT

Although metal windows were available as early as 1860 from catalogues published by architectural supply firms, they did not become popular until after 1890. Two factors combined to account for the shift from wooden to metal windows at that time. Technology borrowed from the rolling industry permitted the mass production of rolled steel windows. This technology made metal windows cost competitive with conventional wooden windows. In addition, a series of devastating urban fires in Boston, Baltimore, Philadelphia, and San Francisco led to the enactment of strict fire codes for industrial and multi-story commercial and office buildings.

As in the process of making rails for railroads, rolled steel windows were made by passing hot bars of steel through progressively smaller, shaped rollers until the appropriate angled configuration was achieved (see fig. 2). The rolled steel sections, generally 1/8” thick and 1 1/2” wide, were used for all the components of the windows: sash, frame, and subframe (see fig. 3). With the addition of wire glass, a fire-resistant window resulted. These rolled steel windows are almost exclusively found in masonry or concrete buildings.

A byproduct of the fire-resistant window was the strong metal frame that permitted the installation of larger windows and windows in series. The ability to have expansive amounts of glass and increased ventilation dramatically changed the designs of late 19th and early 20th century industrial and commercial buildings.

The newly available, reasonably priced steel windows soon became popular for more than just their fire-resistant qualities. They were standardized, extremely durable, and easily transported. These qualities led to the use of steel windows in every type of construction, from simple industrial and institutional buildings to luxury commercial and apartment buildings. Casement, double-hung, pivot, projecting, austral, and continuous windows differed in operating and ventilating capacities. Figure 4 outlines the kinds and properties of metal windows available then and now. In addition, the thin profiles of metal windows contributed to the streamlined appearance of the Art Deco, Art Moderne, and International Styles, among others.

The extensive use of rolled steel metal windows continued until after World War II when cheaper, non-corroding aluminum windows became increasingly popular. While aluminum windows dominate the market today, steel windows are still fabricated. Should replacement of original windows become necessary, replacement windows may be available from the manufacturers of some of the earliest steel windows. Before an informed decision can be made whether to repair or replace metal windows, however, the significance of the windows must be determined and their physical condition assessed.

Fig. 2. The process of rolling a steel bar into an angled section is illustrated above. The shape and size of the rolled section will vary slightly depending on the overall strength needed for the window opening and the location of the section in the assembly: subframe, frame, or sash. The 1/8” thickness of the metal section is generally standard. Drawing: A Metal Window Dictionary. Used with permission.

Fig. 3 A typical section through the top and bottom of a metal window shows the three component parts of the window assembly: subframe, frame, and sash. Drawings: Catalogue No. 15, January 1931, International Casement Co., Inc. (now Hope’s Architectural Products, Inc.), Jamestown, NY. Used with permission.

Cover Illustration: from Hope’s Metal Windows and Casements: 1863-1956, currently Hope’s Architectural Products, Inc. Used with permission.

2
EVALUATION

Historic and Architectural Considerations

An assessment of the significance of the windows should begin with a consideration of their function in relation to the building’s historic use and its historic character. Windows that help define the building’s historic character should be preserved even if the building is being converted to a new use. For example, projecting steel windows used to introduce light and an effect of spaciousness to a warehouse or industrial plant can be retained in the conversion of such a building to offices or residences.

Other elements in assessing the relative importance of the historic windows include the design of the windows and their relationship to the scale, proportion, detailing and architectural style of the building. While it may be easy to determine the aesthetic value of highly ornamented windows, or to recognize the importance of streamlined windows as an element of a style, less elaborate windows can also provide strong visual interest by their small panes or projecting planes when open, particularly in simple, unadorned industrial buildings (see fig. 5).

One test of the importance of windows to a building is to ask if the overall appearance of the building would be changed noticeably if the windows were to be removed or radically altered. If so, the windows are important in defining the building’s historic character, and should be repaired if their physical condition permits.

Physical Evaluation

Steel window repair should begin with a careful evaluation of the physical condition of each unit. Either drawings or photographs, liberally annotated, may be used to record the location of each window, the type of operability, the condition of all three parts—sash, frame and sub-frame—and the repairs essential to its continued use.

Specifically, the evaluation should include: presence and degree of corrosion; condition of paint; deterioration of the metal sections, including bowing, misalignment of the sash, or bent sections; condition of the glass and glazing compound; presence and condition of all hardware, screws, bolts, and hinges; and condition of the masonry or concrete surrounds, including need for caulking or resetting of improperly sloped sills.

Corrosion, principally rusting in the case of steel windows, is the controlling factor in window repair; therefore, the evaluator should first test its presence. Corrosion can be light, medium, or heavy, depending on how much the rust has penetrated the metal sections. If the rusting is merely a surface accumulation or flaking, then the corrosion is light. If the rust has penetrated the metal (indicated by a bubbling texture), but has not caused any structural damage, then the corrosion is medium. If the rust has penetrated deep into the metal, the corrosion is heavy. Heavy corrosion generally results in some form of structural damage, through delamination, to the metal section, which must then be patched or spliced. A sharp probe or tool, such as an ice pick, can be used to determine the extent of corrosion in the metal. If the probe can penetrate the surface of the metal and brittle strands can be dug out, then a high degree of corrosive deterioration is present.

In addition to corrosion, the condition of the paint, the presence of bowing or misalignment of metal sections, the amount of glass needing replacement, and the condition of the masonry or concrete surrounds must be assessed in the evaluation process. These are key factors in determining whether or not the windows can be repaired in place. The more complete the inventory of existing conditions, the easier it will be to determine whether repair is feasible or whether replacement is warranted.

Rehabilitation Work Plan

Following inspection and analysis, a plan for the rehabilitation can be formulated. The actions necessary to return windows to an efficient and effective working condition will fall into one or more of the following categories: routine maintenance, repair, and weatherization. The routine maintenance and weatherization measures described here are generally within the range of do-it-yourselfers. Other repairs, both moderate and major, require a professional contractor. Major repairs normally require the removal of the window units to a workshop, but even in the case of moderate repairs, the number of windows involved might warrant the removal of all the deteriorated units to a workshop in order to realize a more economical repair price. Replacement of windows should be considered only as a last resort.

Since moisture is the primary cause of corrosion in steel windows, it is essential that excess moisture be eliminated and that the building be made as weathertight as possible before any other work is undertaken. Moisture can accumulate from cracks in the masonry, from spalling mortar, from leaking gutters, from air conditioning condensation runoff, and from poorly ventilated interior spaces.

Finally, before beginning any work, it is important to be aware of health and safety risks involved. Steel windows have historically been coated with lead paint. The removal of such paint by abrasive methods will produce toxic dust. Therefore, safety goggles, a toxic dust respirator, and protective clothing should be worn. Similar protective measures should be taken when acid compounds are used. Local codes may govern the methods of removing lead paints and proper disposal of toxic residue.

ROUTE MAINTENANCE

A preliminary step in the routine maintenance of steel windows is to remove surface dirt and grease in order to ascertain the degree of deterioration, if any. Such minor cleaning can be accomplished using a brush or vacuum followed by wiping with a cloth dampened with mineral spirits or denatured alcohol.
Double-hung industrial windows duplicated the look of traditional wooden windows. Metal double-hung windows were early examples of a building product adapted to meet stringent new fire code requirements for manufacturing and high-rise buildings in urban areas. Soon supplanted in industrial buildings by less expensive pivot windows, double-hung metal windows regained popularity in the 1940s for use in speculative suburban housing.

Austral windows were also a product of the 1920s. They combined the appearance of the double-hung window with the increased ventilation and ease of operation of the projected window. (When fully opened, they provided 70% ventilation as compared to 30% ventilation for double-hung windows.) Austral windows were often used in schools, libraries and other public buildings.

Pivot windows were an early type of industrial window that combined inexpensive first cost and low maintenance. Pivot windows became standard for warehouses and power plants where the lack of screens was not a problem. The window shown here is a horizontal pivot. Windows that turned about a vertical axis were also manufactured (often of iron). Such vertical pivots are rare today.

Casement windows adapted the English tradition of using wrought iron casements with leaded came for residential use. Rolled steel casements (either single, as shown, or paired) were popular in the 1920s for cottage style residences and Gothic style campus architecture. More streamlined casements were popular in the 1930s for institutional and small industrial buildings.

Projecting windows, sometimes called awning or hopper windows, were perfected in the 1920s for industrial and institutional buildings. They were often used in “combination” windows, in which upper panels opened out and lower panels opened in. Since each movable panel projected to one side of the frame only, unlike pivot windows, for example, screens could be introduced.

Continuous windows were almost exclusively used for industrial buildings requiring high overhead lighting. Long runs of clerestory windows operated by mechanical tension rod gears were typical. Long banks of continuous windows were possible because the frames for such windows were often structural elements of the building.

Fig. 4 Typical rolled steel windows available from 1890 to the present. The various operating and ventilating capacities in combination with the aesthetics of the window style were important considerations in the selection of one window type over another. Drawings: Sharon C. Park, AIA.

If it is determined that the windows are in basically sound condition, the following steps can be taken: 1) removal of light rust, flaking and excessive paint; 2) priming of exposed metal with a rust-inhibiting primer; 3) replacement of cracked or broken glass and glazing compound; 4) replacement of missing screws or fasteners; 5) cleaning and lubrication of hinges; 6) repainting of all steel sections with two coats of finish paint compatible with the primer; and 7) caulking the masonry surrounds with a high quality elastomeric caulk.

Recommended methods for removing light rust include manual and mechanical abrasion or the application of chemicals. Burning off rust with an oxy-acetylene or propane torch, or an inert gas welding gun, should never be attempted because the heat can distort the metal. In addition, such intense heat (often as high as 3800°F) vaporizes the lead in old paint, resulting in highly toxic fumes. Furthermore, such heat will likely result in broken glass. Rust can best be removed using a wire brush, an aluminum oxide sandpaper, or a variety of power tools.

Fig. 5 Windows often provide a strong visual element to relative simple or undecorated industrial or commercial buildings. This design element should be taken into consideration when evaluating the significance of the windows. Photo: Michael Auer
adapted for abrasive cleaning such as an electric drill with a wire brush or a rotary whip attachment. Adjacent sills and window jams may need protective shielding.

Rust can also be removed from ferrous metals by using a number of commercially prepared anti-corrosive acid compounds. Effective on light and medium corrosion, these compounds can be purchased either as liquids or gels. Several bases are available, including phosphoric acid, ammonium citrate, oxalic acid and hydrochloric acid. Hydrochloric acid is generally not recommended; it can leave chloride deposits, which cause future corrosion. Phosphoric acid-based compounds do not leave such deposits, and are therefore safer for steel windows. However, any chemical residue should be wiped off with damp cloths, then dried immediately. Industrial blow-dryers work well for thorough drying. The use of running water to remove chemical residue is never recommended because the water may spread the chemicals to adjacent surfaces, and drying of these surfaces may be more difficult. Acid cleaning compounds will stain masonry; therefore plastic sheets should be taped to the edge of the metal sections to protect the masonry surrounds. The same measure should be followed to protect the glazing from etching because of acid contact.

Measures that remove rust will ordinarily remove flaking paint as well. Remaining loose or flaking paint can be removed with a chemical paint remover or with a pneumatic needle scaler or gun, which comes with a series of chisel blades and has proven effective in removing flaking paint from metal windows. Well-bonded paint may serve to protect the metal further from corrosion, and need not be removed unless paint build-up prevents the window from closing tightly. The edges should be feathered by sanding to give a good surface for repainting.

Next, any bare metal should be wiped with a cleaning solvent such as denatured alcohol, and dried immediately in preparation for the application of an anti-corrosive primer. Since corrosion can recur very soon after metal has been exposed to the air, the metal should be primed immediately after cleaning. Spot priming may be required periodically as other repairs are undertaken. Anti-corrosive primers generally consist of oil-alkyd based paints rich in zinc or zinc chromate. Red lead is no longer available because of its toxicity. All metal primers, however, are toxic to some degree and should be handled carefully. Two coats of primer are recommended. Manufacturer’s recommendations should be followed concerning application of primers.

REPAIR

Repair in Place

The maintenance procedures described above will be insufficient when corrosion is extensive, or when metal window sections are misaligned. Medium to heavy corrosion that has not done any structural damage to the metal sections can be removed either by using the chemical cleaning process described under “Routine Maintenance” or by sandblasting. Since sandblasting can damage the masonry surrounds and crack or cloud the glass, metal or plywood shields should be used to protect these materials. The sandblasting pressure should be low, 80-100 pounds per square inch, and the grit size should be in the range of #10-#45. Glass peening beads (glass pellets) have also been successfully used in cleaning steel sections. While sandblasting equipment comes with various nozzle sizes, pencil-point blasters are most useful because they give the operator more effective control over the direction of the spray. The small aperture of the pencil-point blaster is also useful in removing dried putty from the metal sections that hold the glass. As with any cleaning technique, once the bare metal is exposed to air, it should be primed as soon as possible. This includes the inside rabbeted section of sash where glazing putty has been removed. To reduce the dust, some local codes allow only wet blasting.

In this case, the metal must be dried immediately, generally with a blow-drier (a step that the owner should consider when calculating the time and expense involved). Either form of sandblasting metal covered with lead paints produces toxic dust. Proper precautionary measures should be taken against toxic dust and silica particles.

Bent or bowed metal sections may be the result of damage to the window through an impact or corrosive expansion. If the distortion is not too great, it is possible to realign the metal sections without removing the window to a metal fabricator’s shop. The glazing is generally removed and pressure is applied to the bent or bowed section. In the case of a muntin, a protective 2 x 4 wooden bracing can be placed behind the bent portion and a wire cable with a winch can apply progressively more pressure over several days until the section is realigned. The 2 x 4 bracing is necessary to distribute the pressure evenly over the damaged section. Sometimes a section, such as the bottom of the frame, will bow out as a result of pressure exerted by corrosion and it is often necessary to cut the metal section to relieve this pressure prior to pressing the section back into shape and making a welded repair.

Once the metal sections have been cleaned of all corrosion and straightened, small holes and uneven areas resulting from rusting should be filled with a patching material and sanded smooth to eliminate pockets where water can accumulate. A patching material of steel fibers and an epoxy binder may be the easiest to apply. This steel-based epoxy is available for industrial steel repair; it can also be found in auto body patching compounds or in plumber’s epoxy. As with any product, it is important to follow the manufacturer’s instructions for proper use and best results. The traditional patching technique—melting steel welding rods to fill holes in the metal sections—may be difficult to apply in some situations; moreover, the window glass must be removed during the repair process, or it will crack from the expansion of the heated metal sections. After these repairs, glass replacement, hinge lubrication, painting, and other cosmetic repairs can be undertaken as necessary.

Refer to Table IV, Types of Paint Used for Painting Metal in Merril in America’s Historic Buildings, p. 139. (See bibliography).
To complete the checklist for routine maintenance, cracked glass, deteriorated glazing compound, missing screws, and broken fasteners will have to be replaced; hinges cleaned and lubricated; the metal windows painted, and the masonry surrounds caulked. If the glazing must be replaced, all clips, glazing beads, and other fasteners that hold the glass to the sash should be retained, if possible, although replacements for these parts are still being fabricated. When bedding glass, use only glazing compound formulated for metal windows. To clean the hinges (generally brass or bronze), a cleaning solvent and fine bronze wool should be used. The hinges should then be lubricated with a non-greasy lubricant specially formulated for metals and with an anti-corrosive agent. These lubricants are available in a spray form and should be used periodically on frequently opened windows.

Final painting of the windows with a paint compatible with the anti-corrosive primer used should proceed on a dry day. (Paint and primer from the same manufacturer should be used.) Two coats of finish paint are recommended if the sections have been cleaned to bare metal. The paint should overlap the glass slightly to insure weathertightness at that connection. Once the paint dries thoroughly, a flexible exterior caulk can be applied to eliminate air and moisture infiltration where the window and the surrounding masonry meet.

Caulking is generally undertaken after the windows have received at least one coat of finish paint. The perimeter of the masonry surround should be caulked with a flexible elastomeric compound that will adhere well to both metal and masonry. The caulk used should be a type intended for exterior application, have a high tolerance for material movement, be resistant to ultraviolet light, and have a minimum durability of 10 years. Three effective compounds (taking price and other factors into consideration) are polyurethane, vinyl acrylic, and butyl rubber. In selecting a caulk material for a window retrofit, it is important to remember that the caulk compound may be covering other materials in a substrate. In this case, some compounds, such as silicone, may not adhere well. Almost all modern caulk compounds can be painted after curing completely. Many come in a range of colors, which eliminates the need to paint. If colored caulk is used, the windows should have been given two coats of finish paint prior to caulking.

As part of the orderly removal of windows, each window should benumbered and the parts labelled. The operable metal sash should be dismantled by removing the hinges; the fixed sash and, if necessary, the frame can then be unbolts or unscrewed. (The subframe is usually left in place. Built into the masonry surrounds, it can only be cut out with a torch.) Hardware and hinges should be labelled and stored together.

The two major choices for removing flaking paint and corrosion from severely deteriorated windows are dipping in a chemical bath or sandblasting. Both treatments require removal of the glass. If the windows are to be dipped, a phosphoric acid solution is preferred, as mentioned earlier. While the dip tank method is good for fairly evenly distributed rust, deep set rust may remain after dipping. For that reason, sandblasting is more effective for heavy and uneven corrosion. Both methods leave the metal sections clean of residual paint. As already noted, after cleaning has exposed the metal to the air, it should be primed immediately after drying with an anti-corrosive primer to prevent rust from reoccurring.

Sections that are seriously bent or bowed must be straightened with heat and applied pressure in a workshop. Structurally weakened sections must be cut out, generally with an oxy-acetylene torch, and replaced with sections welded in place and the welds ground smooth. Finding replacement metal sections, however, may be difficult. While most rolling mills are producing modern sections suitable for total replacement, it may be difficult to find an exact profile match for a splicing repair. The best source of rolled metal sections is from salvaged windows, preferably from the same building. If no salvaged windows are available, two options remain. Either an ornamental metal fabricator can weld flat plates into a built-up section, or a steel plant can mill bar steel into the desired profile.

While the sash and frame are removed for repair, the subframe and masonry surrounds should be inspected. This is also the time to reset sills or to remove corrosion from the subframe, taking care to protect the masonry surrounds from damage.

Missing or broken hardware and hinges should be replaced on all windows that will be operable. Salvaged windows, again, are the best source of replacement parts. If matching parts cannot be found, it may be possible to adapt ready-made items. Such a substitution may require filling existing holes with steel epoxy or with plug welds and tapping in new screw holes. However, if the hardware is a highly significant element of the historic window, it may be worth having reproductions made.

Following are illustrations of the repair and thermal upgrading of the rolled steel windows in a National Historic Landmark (fig. 6). Many of the techniques described above were used during this extensive rehabilitation. The complete range of repair techniques is then summarized in the chart titled Steps for Cleaning and Repairing Historic Steel Windows (see fig. 7).

Repair in Workshop

Damage to windows may be so severe that the window sash and sometimes the frame must be removed for cleaning and extensive rust removal, straightening of bent sections, welding or splicing in of new sections, and reglazing. These major and expensive repairs are reserved for highly significant windows that cannot be replaced; the procedures involved should be carried out only by skilled workmen. (See fig. 6a–6f.)
Fig. 6 a. View of the flanking wing of the State Capitol where the riveted steel casement windows are being removed for repair.

Fig. 6 b. View from the exterior showing the deteriorated condition of the lower corner of a window prior to repair. While the sash was in relatively good condition, the frame behind was rusted to the point of inhibiting operation.

Fig. 6 c. View of the rusted frame which was unscrewed from the subframe and removed from the window opening and taken to a workshop for sandblasting. In some cases, severely deteriorated sections of the frame were replaced with new sections of milled bar steel.

Fig. 6 d. View looking down towards the sill. The subframes appeared very rusted, but were in good condition once debris was vacuumed and surface rust was removed, in place, with chemical compounds. Where necessary, epoxy and steel filler was used to patch depressions in order to make the subframe serviceable again.

Fig. 6 e. View looking down towards the sill. The channel frame was reused in the window opening. The frame was screwed to the refurbished subframe at the jamb and the head only. The screw holes at the sill, which had been the cause of much of the earlier rusting, were infilled. Vinyl weatherstripping was added to the frame.

Fig. 6 f. View from the outside of the completely refurbished window. In addition to the steel repair and the installation of vinyl weatherstripping, the exterior was caulked with polyurethane and the single glass was replaced with individual lights of thermal glass. The repaired and upgraded windows have comparable energy efficiency ratings to new replacement units while retaining the historic steel sash, frames and subframes.

Fig. 6. The repair and thermal upgrading of the historic steel windows at the State Capitol, Lincoln, Nebraska. This early twentieth century building, designed by Bertram Goodhue, is a National Historic Landmark. Photos: All photos in this series were provided by the State Building Division.
### STEPS FOR CLEANING AND REPAIRING HISTORIC STEEL WINDOWS

<table>
<thead>
<tr>
<th>Work Item</th>
<th>Recommended Techniques</th>
<th>Tools, Products and Procedures</th>
<th>Notes</th>
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<tbody>
<tr>
<td><em>(Must be done in a workshop)</em></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1. Removing dirt and grease from metal</td>
<td>General maintenance and chemical cleaning</td>
<td>Vacuum and bristle brushes to remove dust and dirt; solvents (denatured alcohol, mineral spirits), and clean cloths to remove grease.</td>
<td>Solvents can cause eye and skin irritation. Operator should wear protective gear and work in ventilated area. Solvents should not contact masonry. Do not flush with water.</td>
</tr>
<tr>
<td>2. Removing Rust/Corrosion</td>
<td>Light</td>
<td>Manual and mechanical abrasion</td>
<td>Wire brushes, steel wool, rotary attachments to electric drill, sanding blocks and disks.</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>Sandblasting/abrasive cleaning</td>
<td>Low pressure (80-100 psi) and small grit (#10-#45); glass peening beads. Pencil blaster gives good control.</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>*Chemical dip tank</td>
<td>Metal sections dipped into chemical tank (phosphoric acid preferred) from several hours to 24 hours.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Sandblasting/abrasive cleaning</td>
<td>Low pressure (80-100 psi) and small grit (#10-#45).</td>
</tr>
<tr>
<td></td>
<td>Mechanical abrasion</td>
<td>Pneumatic needle gun chisels, sanding disks.</td>
<td>Protect operator; have good ventilation. Well-bonded paint need not be removed if window closes properly.</td>
</tr>
<tr>
<td>4. Aligning bent, bowed metal sections</td>
<td>Applied pressure</td>
<td>Wooden frame as a brace for cables and winch mechanism.</td>
<td>Remove glass in affected area. Realignment may take several days.</td>
</tr>
<tr>
<td></td>
<td>*Heat and pressure</td>
<td>Remove to a workshop. Apply heat and pressure to bend back.</td>
<td>Care should be taken that heat does not deform slender sections.</td>
</tr>
<tr>
<td>Work Item</td>
<td>Recommended Techniques</td>
<td>Tools, Products and Procedures</td>
<td>Notes</td>
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<tr>
<td><em>(Must be done in a workshop)</em></td>
<td></td>
<td>Epoxy fillers with high content of steel fibers; plumber's epoxy or autobody patching compound.</td>
<td>Epoxy patches generally are easy to apply, and can be sanded smooth. Patches should be primed.</td>
</tr>
<tr>
<td>5. Patching depressions</td>
<td>Epoxy and steel filler</td>
<td></td>
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<tr>
<td></td>
<td><em>Welded patches</em></td>
<td>Weld in patches using steel rods and oxy-acetylene torch or arc welder.</td>
<td>Prime welded sections after grinding connections smooth.</td>
</tr>
<tr>
<td>6. Splicing in new metal sections</td>
<td><em>Cut out decayed sections and weld in new or salvaged sections</em></td>
<td>Torch to cut out bad sections back to 45° joint. Weld in new pieces and grind smooth.</td>
<td>Prime welded sections after grinding connection smooth.</td>
</tr>
<tr>
<td>7. Priming metal sections</td>
<td>Brush or spray application</td>
<td>At least one coat of anti-corrosive primer on bare metal. <em>Zinc-rich primers are generally recommended.</em></td>
<td>Metal should be primed as soon as it is exposed. If cleaned metal will be repaired another day, spot prime to protect exposed metal.</td>
</tr>
<tr>
<td>8. Replacing missing screws and bolts</td>
<td>Routine maintenance</td>
<td>Pliers to pull out or shear off rusted heads. Replace screws and bolts with similar ones, readily available.</td>
<td>If new holes have to be tapped into the metal sections, the rusted holes should be cleaned, filled and primed prior to redrilling.</td>
</tr>
<tr>
<td>9. Cleaning, lubricating or replacing hinges and other hardware</td>
<td>Routine maintenance, solvent cleaning</td>
<td>Most hinges and closure hardware are bronze. Use solvents (mineral spirits), bronze wool and clean cloths. Spray with non-greasy lubricant containing anti-corrosive agent.</td>
<td>Replacement hinges and fasteners may not match the original exactly. If new holes are necessary, old ones should be filled.</td>
</tr>
<tr>
<td>10. Replacing glass and glazing compound</td>
<td>Standard method for application</td>
<td>Pliers and chisels to remove old glass, scrapeputty out of glazing rabbit, save all clips and beads for reuse. Use only glazing compound formulated for metal windows.</td>
<td>Heavy gloves and other protective gear needed for the operator. All parts saved should be cleaned prior to reinstallation.</td>
</tr>
<tr>
<td>11. Caulking masonry surrounds</td>
<td>Standard method for application</td>
<td>Good quality (10 year or better) elastomeric caulk suitable for metal.</td>
<td>The gap between the metal frame and the masonry opening should be caulked; keep weepholes in metal for condensation run-off clear of caulk.</td>
</tr>
<tr>
<td>12. Repainting metal windows</td>
<td>Spray or brush</td>
<td>At least 2 coats of paint compatible with the anti-corrosive primer. Paint should lap the glass about 1/8&quot; to form a seal over the glazing compound.</td>
<td>The final coats of paint and the primer should be from the same manufacturer to ensure compatibility. If spraying is used, the glass and masonry should be protected.</td>
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Fig. 7. STEPS FOR CLEANING AND REPAIRING HISTORIC STEEL WINDOWS. Compiled by Sharon C. Park, AIA.
WEATHERIZATION

Historic metal windows are generally not energy efficient; this has often led to their wholesale replacement. Metal windows can, however, be made more energy efficient in several ways, varying in complexity and cost. Caulking around the masonry openings and adding weatherstripping, for example, can be do-it-yourself projects and are important first steps in reducing air infiltration around the windows. They usually have a rapid payback period.

Other treatments include applying fixed layers of glazing over operable storm windows, adding operable storm windows, or installing thermal glass in place of the existing glass. In combination with caulking and weatherstripping, these treatments can produce energy ratings rivaling those achieved by new units.¹

Weatherstripping

The first step in any weatherization program, caulking, has been discussed above under “Routine Maintenance.” The second step is the installation of weatherstripping where the operable portion of the sash, often called the vent, and the fixed frame come together to reduce perimeter air infiltration (see fig. 8). Four types of weatherstripping appropriate for metal windows are spring-metal, vinyl strips, compressible foam tapes, and sealant beads. The spring-metal, with an integral friction fit mounting clip, is recommended for steel windows in good condition. The clip eliminates the need for an applied glue; the thinness of the material insures a tight closure. The weatherstripping is clipped to the inside channel of the rolled metal section of the fixed frame. To insure against galvanic corrosion between the weatherstripping (often bronze or brass), and the steel window, the window must be painted prior to the installation of the weatherstripping. This weatherstripping is usually applied to the entire perimeter of the window opening, but in some cases, such as casement windows, it may be best to avoid weatherstripping the hinge side. The natural wedging action of the weatherstripping on the three sides of the window often creates an adequate seal.

Vinyl weatherstripping can also be applied to metal windows. Folded into a “V” configuration, the material forms a barrier against the wind. Vinyl weatherstripping is usually glued to the frame, although some brands have an adhesive backing. As the vinyl material and the applied glue are relatively thick, this form of weatherstripping may not be appropriate for all situations.

Compressible foam tape weatherstripping is often best for large windows where there is a slight bending or distortion of the sash. In some very tall windows having closure hardware at the sash mid-point, the thin sections of the metal window will bow away from the frame near the top. If the gap is not more than 1/4", foam weatherstripping can normally fill the space. If the gap exceeds this, the window may need to be realigned to close more tightly. The foam weatherstripping comes either with an adhesive or plain back; the latter variety requires application with glue. Compressible foam requires more frequent replacement than either spring-metal or vinyl weatherstripping.

A fourth type of successful weatherstripping involves the use of a caulking or sealant bead and a polyethylene bond breaker tape. After the window frame has been thoroughly cleaned with solvent, permitted to dry, and primed, a neat bead of low modulus (firm setting) caulk, such as silicone, is applied. A bond breaker tape is then applied to the operable sash covering the metal section where contact will occur. The window is then closed until the sealant has set (2-7 days, depending on temperature and humidity). When the window is opened, the bead will have taken the shape of the air infiltration gap and the bond breaker tape can be removed. This weatherstripping method appears to be successful for all types of metal windows with varying degrees of air infiltration.

Since the several types of weatherstripping are appropriate for different circumstances, it may be necessary to use more than one type on any given building. Successful weatherstripping depends upon using the thinnest material adequate to fill the space through which air enters. Weatherstripping that is too thick can spring the hinges, thereby resulting in more gaps.

¹One measure of energy efficiency is the U-value (the number of BTU per hour transferred through a square foot of material). The lower the U-value, the better the performance. According to ASHRAE HANDBOOK-87 Fundamentals, the U-value of historic rolled steel sash with single glazing is 1.3. Adding storm windows to the existing units or replacing with 5/8” insulating glass produces a U-value of .69. These methods of weatherizing historic steel windows compare favorably with rolled steel replacement alternatives, with factory installed 3/4” insulating glass (.37 U-value) with added thermal-break construction and factory finished coatings (.28 U-value).

Fig. 8 APPROPRIATE TYPES OF WEATHERSTRIPPING FOR METAL WINDOWS. Weatherstripping is an important part of upgrading the thermal efficiency of historic steel windows. The chart above shows the jamb section of the window with the weatherstripping in place. Drawings: Sharon C. Park, AIA.
Thermal Glazing

The third weatherization treatment is to install an additional layer of glazing to improve the thermal efficiency of the existing window. The decision to pursue this treatment should proceed from careful analysis. Each of the most common techniques for adding a layer of glazing will affect approximately the same energy savings (approximately double the original insulating value of the window); therefore, cost and aesthetic considerations usually determine the choice of method. Methods of adding a layer of glazing to improve thermal efficiency include adding a new layer of transparent material to the window; adding a separate storm window; and replacing the single layer of glass in the window with thermal glass.

The least expensive of these options is to install a clear material (usually rigid sheets of acrylic or glass) over the original window. The choice between acrylic and glass is generally based on cost, ability of the window to support the material, and long-term maintenance outlook. If the material is placed over the entire window and secured to the frame, the sash will be inoperable. If the continued use of the window is important (for ventilation or for fire exits), separate panels should be affixed to the sash without obstructing operability (see fig. 9). Glass or acrylic panels set in frames can be attached using magnetized gaskets, interlocking material strips, screws or adhesives. Acrylic panels can be screwed directly to the metal window, but the holes in the acrylic panels should allow for the expansion and contraction of this material. A compressible gasket between the prime sash and the storm panel can be very effective in establishing a thermal cavity between glazing layers. To avoid condensation, 1/8" cuts in a top corner and diagonally opposite bottom corner of the gasket will provide a vapor bleed, through which moisture can evaporate. (Such cuts, however, reduce thermal performance slightly.) If condensation does occur, however, the panels should be easily removable in order to wipe away moisture before it causes corrosion.

The second method of adding a layer of glazing is to have independent storm windows fabricated. (Pivot and austral windows, however, which project on either side of the window frame when open, cannot easily be fitted with storm windows and remain operational.) The storm window should be compatible with the original sash configuration. For example, in paired casement windows, either specially fabricated storm casement windows or sliding units in which the vertical meeting rail of the slider reflects the configuration of the original window should be installed. The decision to place storm windows on the inside or outside of the window depends on whether the historic window opens in or out, and on the visual impact the addition of storm windows will have on the building. Exterior storm windows, however, can serve another purpose besides saving energy: they add a layer of protection against air pollutants and vandals, although they will partially obscure the prime window. For highly ornamental windows this protection can determine the choice of exterior rather than interior storm windows.

The third method of installing an added layer of glazing is to replace the original single glazing with thermal glass. Except in rare instances in which the original glass is of special interest (as with stained or figured glass), the glass can be replaced if the hinges can tolerate the weight of the additional glass. The rolled metal sections for steel windows are generally from 1 1/2" thick. Sash of this thickness can normally tolerate thermal glass, which ranges from 3/8" - 5/8". (Metal glazing beads, readily available, are used to reinforce the muntins, which hold the glass.) This treatment leaves the window fully operational while preserving the historic appearance. It is, however, the most expensive of the treatments discussed here. (See fig. 6f.

![Fig. 9 Two examples of adding a second layer of glazing in order to improve the thermal performance of historic steel windows. Scheme A (showing jamb detail) is of a ¾" acrylic panel with a clear cell foam gasket attached with self-tapping stainless steel screws directly to the exterior of the outwardly opening sash. Scheme B (showing jamb detail) is of a glass panel in a magnetized frame affixed directly to the interior of the historic steel sash. The choice of using glass or acrylic mounted on the inside or outside will depend on the ability of the window to tolerate additional weight, the location and size of the window, the cost, and the long-term maintenance outlook. Drawing: Sharon C. Park, AIA.

WINDOW REPLACEMENT

Repair of historic windows is always preferred within a rehabilitation project. Replacement should be considered only as a last resort. However, when the extent of deterioration or the unavailability of replacement sections renders repair impossible, replacement of the entire window may be justified. In the case of significant windows, replacement in kind is essential in order to maintain the historic character of the building. However, for less significant windows, replacement with compatible new windows may be acceptable. In selecting compatible replacement windows, the material, configuration, color, operability, number and size of panes, profile and proportion of metal sections, and reflective quality of the original glass should be duplicated as closely as possible. A number of metal window manufacturing companies produce rolled steel windows. While stock modern window designs do not share the multi-pane configuration of
historic windows, most of these manufacturers can reproduce the historic configuration if requested, and the cost is not excessive for large orders (see figs. 10a and 10b). Some manufacturers still carry the standard pre-World War II multi-light windows using the traditional 12" x 18" or 14" x 20" glass sizes in industrial, commercial, security, and residential configurations. In addition, many of the modern steel windows have integral weatherstripping, thermal break construction, durable vinyl coatings, insulating glass, and other desirable features.

For product information on replacement windows, the owner, architect, or contractor should consult manufacturers’ catalogues, building trade journals, or the Steel Window Institute, 1230 Keith Building, Cleveland, Ohio 44115.

SUMMARY

The National Park Service recommends the retention of significant historic metal windows whenever possible. Such windows, which can be a character-defining feature of a historic building, are too often replaced with inappropriate units that impair rather than complement the overall historic appearance. The repair and thermal upgrading of historic steel windows is more practicable than most people realize. Repaired and properly maintained metal windows have greatly extended service lives.

They can be made energy efficient while maintaining their contribution to the historic character of the building.

BIBLIOGRAPHY


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This publication has been prepared pursuant to the Economic Recovery Tax Act of 1981, which directs the Secretary of the Interior to certify rehabilitations of historic buildings that are consistent with their historic character; the guidance provided in this brief will assist property owners in complying with the requirements of this law.

Preservation Briefs: 12 has been developed under the technical editorship of Lee H. Nelson, AIA, Chief, Preservation Assistance Division, National Park Service, U.S. Department of the Interior, Washington, D.C. 20240. Comments on the usefulness of this information are welcomed and can be sent to Mr. Nelson at the above address.
Appendix B

Durability of Timber (in years)

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<th>Species</th>
<th>Always dry</th>
<th>Sheltered outside</th>
<th>Unsheltered outside</th>
<th>In contact with earth</th>
<th>Underwater</th>
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<td>15-60</td>
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<td>Less than 20</td>
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<td>-</td>
<td>Low</td>
<td>-</td>
<td>Low</td>
<td>High</td>
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Source: Berg, 34.
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