

The Effect of Green Insulation Standards on Moisture Accumulation within Framing of Residential Structures

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ABSTRACT

Green building standards recommend use of a variety of new thermal insulation products. However, durability of wooden framing used in conjunction with new insulation materials has not been thoroughly examined, specifically in reference to interstitial condensation. This research used a single-sided hot-box design to measure moisture content of wood framing during a 60-day period. The resulting moisture content of the wood framing was compared as tested with spray-applied cellulose and polyurethane versus fiberglass batt insulation. The average moisture content of framing insulated with cellulose and polyurethane was greater than framing insulated with fiberglass. Based on the results from this research, the use of spray-applied cellulose and polyurethane insulation materials may increase the risk of structural durability.

Green building standards, such as LEED for Homes or the National Green Building Standard, emphasize creating energy efficient structures to limit negative impact on the environment. Green building practices employed to increase energy efficiency of the building enclosure may overlook possible adverse effects that these practices may have on structural durability. Because spray-applied cellulose and polyurethane insulation increase moisture content of wooden framework within building enclosures, it can be deduced that energy efficient insulation may increase risk of moisture-related biodeterioration of the building enclosure. After review of points awarded for insulation materials within LEED for Homes and the National Green Building Standard, results from this study imply that the National Green Building Standard does not emphasize durability of wooden structures in their guidelines at the present time.

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PREFACE

This thesis contains six main chapters. Chapter 1 introduces the subject, while Chapter 2 provides a set of hypothesis, goals and objectives, and Chapter 3 elicits a review of literature. Chapters 4 and 5 are manuscripts intended for publication containing the study results & discussion based on the stated hypotheses listed within Chapter 2. Chapter 4 includes the methodological approaches this study incorporated to research. Chapter 6 summarizes and concludes the overall thesis objectives and discusses general findings and limitations of the research. Due to the autonomous nature of the manuscripts that compose Chapters 4 and 5, some duplication of information was unavoidable.

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1 GENERAL INTRODUCTION

1.1 INTRODUCTION

Green building certification systems provide guidelines for green building construction, such as the Leadership in Energy and Environmental Design (LEED) for Homes program (U.S. Green Building Council 2008a) or the National Green Building Standard (NGBS, National Association of Home Builders 2009a), developed by the United States Green Building Council (USGBC) and National Association of Home Builders (NAHB). A green building is commonly understood to be an environmentally friendly structure that has improved efficiencies compared to a standard building. Separate organizations around the world have created individual green building standards, and materials within these standards have been chosen based upon short-term life cycle analysis or perceptions due to lack of information on the long-term effects of these materials (Cole et al. 2000).

This lack of information on long-term material analysis is especially significant when considering the durability of wood-based building materials. Anecdotal reports of moisture accumulation in the interstitial wall cavity have been reported, but little has been done to determine what this truly means for longevity of our building enclosures. Wood-based building materials are susceptible to moisture-related biodeterioration such as rot, fungus, and mold. If new building materials allow for moisture accumulation within the building enclosure, it introduces a risk of structural degradation as well as introduction of toxic microorganisms into the indoor environment.

The goal of this study is to determine if insulation materials encouraged by green building standards increase risk of biodeterioration of a buildings' wooden framework. In particular, the occurrence and effects of condensation within wooden framework of wall

assemblies manufactured to meet the insulation requirements of the LEED for Homes and National Green Building Standard were investigated, thereby gaining insights into the influence of moisture on long-term durability of wooden framework.

The two main objectives that have been defined for this research are:

1. Determine the state-of-the-art knowledge of moisture occurring within insulated wooden structures and the influence moisture has on structure longevity. Also, identify wall assembly sections that meet the current green building standards. This goal will determine the effect of common insulation materials on moisture accumulation within wooden framework. Insulation materials that retain moisture introduce potential biodeterioration of the wooden framework.
2. Practical research and data collection by building and testing residential wall segments. Moisture content results of framing insulated with spray-applied cellulose and polyurethane will be compared against the moisture content of framing insulated with traditional fiberglass batts.

2 HYPOTHESIS

2.1 OVERVIEW

Green building systems, such as the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) for Homes program (U.S. Green Building Council 2008a) or the National Green Building Standard (NGBS, National Association of Home Builders 2009a), provide guidelines for green building construction. Green building encompasses building methods using environmentally friendly practices to create a structure with improved energy and resource efficiencies compared to a traditional building. Several independent groups with green building interests have created individual green building standards to meet their expectations of what requirements encompass the concept of a green building. Due to different groups creating individual green building standards, there is a lack of uniformity as to what can be categorized as a green building. Some, if not most, green building standards have been developed with an emphasis on the use of materials chosen to be "green" or sustainable based upon short-term life cycle analysis or perception (Cole et al. 2000). With little information on the long-term effects of these materials being considered, it is possible that new green materials may actually become a detriment to the building structure due to durability concerns.

Green building practices emphasize using an energy efficient building enclosure, or wall system. Typically, energy efficient building enclosures use insulation that meets a required thermal resistance while also allowing moisture to pass through the building enclosure with no condensation. To meet thermal resistance requirements, new insulation materials and application methods have been put in use. However moisture movement and long-term performance of these building materials is unknown. Without any knowledge of long-term

performance, these new forms of insulation may increase the risk of biodeterioration, which is degradation of materials by organisms, within the building enclosure.

Control of moisture within the building enclosure prevents moisture related issues such as mold, decay, and decreased thermal performance. Biodeterioration occurs most rapidly at temperatures in the range of 69-90 degrees Fahrenheit, and are generally inhibited at temperatures below 32 degrees Fahrenheit and above 100 degrees Fahrenheit (Bowyer et al 2003). Moisture related issues in wood are possible even with low moisture content, but become prominent at moisture content greater than 20 percent (Bowyer et al 2003). The presence of mold and decay reduces the structural durability by reducing the strength of structural components of wood (Bowyer et al. 2003). Besides decreased durability of the wood structure, mold can also cause health problems for the occupants of a building. Another moisture related issue is decreased thermal performance due to the presence of condensation within the insulation. Water within insulation increases the rate of heat transfer, thereby dramatically reducing the energy-efficiency of insulation.

The purpose of this study was to examine if the insulation requirements of the LEED for Homes (U.S. Green Building Council 2008a) and NGBS (National Association of Home Builders 2009a) standards cause increased moisture content of wooden framework, thereby increasing the susceptibility of biodeterioration of wooden framework. The primary concern of moisture and condensation accumulation in this research will focus around the wooden components of the building enclosure. During this study, environmental conditions and moisture content of wooden framework within a building enclosure will be monitored. The wooden framework will be analyzed for differences in moisture content that occur when traditional wood framing is used in conjunction with three different forms of insulation: fiberglass batts, spray-applied cellulose, and spray-applied polyurethane foam. Wood moisture content will be continuously monitored

using wireless sensors during testing, and the oven-dry method will be for calibration of moisture content at the completion of testing.

To measure the change in moisture content of the framework, measurements will be taken before and after the building enclosure has been conditioned between two separate environments to create a heat and vapor differential through the materials within the building enclosure. The use of a conditioned indoor environment will simulate the typical indoor environment of a residential building and an environmental chamber will simulate winter conditions at the building enclosure's exterior.

Study results will demonstrate if the spray-applied polyurethane foam and spray-applied cellulose forms of insulation cause differences in moisture movement through the building enclosure when compared to traditional fiberglass insulation. If either the polyurethane or cellulose insulation does cause a difference in moisture movement through the building enclosure, these insulation materials may adversely affect the wooden building structures, ultimately decreasing the long-term durability of wooden structures.

2.2 RESEARCH HYPOTHESIS

2.2.1 INSULATION PERFORMANCE REGARDING MOISTURE CONTENT

H₀: Green building insulation methods researched in this study do not cause the wooden framework to gain a larger moisture content percentage within the building enclosure system as compared to the moisture content of wooden framework found within a building enclosure using traditional insulation methods.

H_a: Green building insulation methods researched in this study cause the wooden framework to gain a larger moisture content percentage within the building enclosure

system as compared to the moisture content of wooden framework found within a building enclosure using traditional insulation methods.

2.2.2 INSULATION PERFORMANCE REGARDING NAHB'S NATIONAL GREEN BUILDING STANDARD

H₀: The National Green Building Standard's insulation requirements do not cause an increase in moisture content percentage of wooden framework as compared to the moisture content percentage of traditionally insulated wooden framework.

H_a: The National Green Building Standard's insulation requirements cause an increase in moisture content percentage of wooden framework as compared to the moisture content percentage of traditionally insulated wooden framework.

2.2.3 INSULATION PERFORMANCE REGARDING U.S. GREEN BUILDING COUNCIL'S LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN

H₀: LEED for Homes' insulation requirements do not cause an increase in moisture content percentage of wooden framework as compared to the moisture content percentage of traditionally insulated wooden framework.

H_a: LEED for Homes' insulation requirements cause an increase in moisture content percentage of wooden framework as compared to the moisture content percentage of traditionally insulated wooden framework.

3 LITERATURE REVIEW

This research used a single-sided hot box design to determine differences in moisture content of wooden studs within residential wall sections utilizing different forms of insulation. The goal was to determine if the moisture content of wooden framework changes when insulated with spray-applied cellulose or spray-applied polyurethane foam as compared to framework insulated with traditional fiberglass insulation. Determining those differences, if any, allowed the assessment of the impact of green building certification systems on the risk to moisture-related durability issues. The following literature review summarizes the literature pertaining to wooden residential structures, insulation methods and materials, and green building certification standards.

3.1 INTRODUCTION

3.1.1 OVERVIEW OF THE U.S. CONSTRUCTION INDUSTRY

The U.S. construction industry is a large contributor to the United States economy. In 2009, direct construction spending in the United States was \$907.8 billion, or 6.9 percent of the nation's Gross Domestic Product (GDP, U.S. Census Bureau 2010). In 2009, the residential housing construction industry, including single and multifamily construction, accounted for \$253.6 billion, or about 42.8 percent of the total private construction industry sector, and 27.9 percent of the entire U.S. construction industry (U.S. Census Bureau 2009a). The majority of residential construction is dedicated to building new single-family homes, which creates approximately 2.6 times more value than the new multi-family home industry (U.S. Census Bureau 2009b).

3.1.2 CONSTRUCTION INDUSTRY SUFFERS RECESSION

Starting in 2006, the residential construction industry has suffered a deep downturn, when housing prices began to decline (Gjerstad and Smith 2009). Housing starts in March 2009 were 48.4 percent below the rate of March 2008 (U.S. Census Bureau 2009c). A main cause behind the downturn, that ultimately engulfed the entire global economy, was the collapse of mortgage lenders who financed the housing boom that started in 2002. In 2006, a wave of delinquencies and defaults on these subprime loans placed severe strains on financial institutions causing the near-collapse of the financial system (Gjerstad and Smith 2009).

Despite the current sluggishness of the residential construction market, the green building market is a growing niche. Findings released by National Association of Home Builders (NAHB) and McGraw-Hill Construction showed that 40 percent of builders in the current down economy had an easier time marketing homes built to green building specifications, even if these houses cost more than properties using conventional techniques (U.S. Green Building Council 2008b). The following chapter details the transition of the traditional U.S. residential construction industry to green building construction.

3.1.3 THE TRANSITION TO GREEN BUILDING CONSTRUCTION

Green building construction is a method that emphasizes resource-efficient design and construction practices through use of ecologically based design principles (Kibert 2005). Some of these principles include reducing resource consumption, reusing resources, using recyclable resources, protecting nature, eliminating toxic materials, applying life cycle costing, and focusing on quality (Kibert 2005). The green building market has increased in popularity since resource sustainability became a concern in the 1970's, which at this time, was also fueled by the U.S. dependence on fossil fuels (Kibert 2005). Fossil fuels currently provide more than 85 percent of all energy consumed in the U.S. (U.S. Department of Energy 2009a) and have been recognized

to contribute to global warming and air pollution. The government actively promotes initiatives to reduce reliance on fossil fuels through funding at the national, the state, and local levels, with green building initiatives being among the initiatives supported (U.S. Environmental Protection Agency 2009).

With the rise in popularity of green building principles, numerous green building certification systems were formed to certify and assure that the green construction systems employed are environmentally preferable compared to traditional construction practices. Thus, several green building certification systems have been developed to evaluate the environmental performance of construction systems and practices. Methods to increase environmental quality include, for example, building practices that use little or no off-site energy, using recyclable and biodegradable materials, or using paints, stains and adhesives with low or no volatile organic compound (VOC) emissions and pollutants. Examples of green building rating systems include the U.S. Green Building Council's Leadership in Energy and Environmental Design for Homes (LEED for Homes, U.S. Green Building Council 2008a) and the National Association of Home Builders' (NAHB) National Green Building Standard (National Association of Home Builders 2009a), among others.

The green building industry is predicted to flourish and the green building market for both non-residential and residential construction is predicted to double from its 2009 value of \$36-49 billion to \$96-140 billion by 2013 (U.S. Green Building Council 2009a), which would equal 38.6 to 56.2 percent of the total value of the 2009 residential construction market. Despite the current economic downturn, the green building industry provides a promising outlook to the residential construction industry due to a growing collection of evidence that green buildings are more comfortable, cost less to operate, last longer, and keep occupants healthier than traditionally built homes (Green Home 2010).

3.2 GREEN BUILDING

Man-made structures have a profound effect on the surrounding environment and the world atmosphere. In the United States, the built environment is the largest producer of greenhouse gas emissions associated with global warming, surpassing even the transportation sector (U.S. Green Building Council 2007). Green building construction is a new approach to construct buildings with lower negative impacts on the environment. This method has lately attracted considerable attention from the public, the industry, and the government. The following sections detail the green building evolution and resulting benefits for the environment and homeowners.

3.2.1 GREEN BUILDING PRACTICES IN THE U.S. – HISTORY

Green building practices were developed in tandem with the evolution of the environmental movement in the United States (Kibert 2005). In 1972, sustainable development became an international concern as the United Nations Conference on the Human Environment in Stockholm raised concerns about the fact that humanity is stretching the carrying capacity of the earth (Friedman 2007). Despite notable achievements in green building focused on increased energy efficiency due to climbing fossil fuel prices in the 1970s, the green building movement did not fully mature until the late twentieth century due to the wane in the interest of energy conservation as energy prices began to decline in the early 1980s (Kibert 2005).

3.2.1.1 MATURATION OF GREEN BUILDING MOVEMENT

In the late eighties and early nineties, the green building movement started to develop and become accepted within the mainstream building industry. Three events in the late eighties and early nineties helped focus attention on problems associated with our environmental impact on the globe (Kibert 2005). In 1987, "*Our Common Future*" was published, which was commonly referred to as the Brundtland Report (Kibert 2005, United Nations 1987). The

Brundtland Report targeted environmental concerns and sought to initiate the search for sustainable development. The report defined sustainable development as “...*meeting the needs of the present without compromising the ability of future generations to meet their needs.*” In 1989, the American Institute of Architects (AIA) established its Committee on the Environment (COTE), which promoted design practices integrating built and natural systems as well as enhanced the design quality and environmental performance of the built environment (American Institute of Architects 2010). A third event, the United Nations Conference on Sustainable Development, drew global attention and support in 1992. The United Nations Conference on Sustainable Development was the first summit to discuss global warming related issues on an international level (Kibert 2005) and will be detailed in the following subchapter.

3.2.1.2 THE UNITED NATIONS CONFERENCE ON SUSTAINABLE DEVELOPMENT

In 1992, the United Nations’ Conference on Sustainable Development, often referred to as the Rio Conference or the Earth Summit (Kibert 2005), drew delegates from 172 governments and 2400 representatives of nongovernmental organizations to Rio de Janeiro (U.S. Department of Energy 2003). This conference passed Agenda 21, a blueprint for achieving global sustainability (Vallero and Brasier 2008). The implementation of Agenda 21 was intended to involve actions of international, national, regional, and local activists (United Nations Environment Programme 2010). The Agenda 21 program is run by the United Nations and includes 40 chapters of comprehensive blueprints of actions to be taken to achieve global sustainability. The 40 chapters are divided into four main sections: social and economic dimensions, conservation and management of resources for development, strengthening the role of major groups, and means of implementation (United Nations Environment Programme 2010). The implementation of Agenda 21 united several nations across the globe by creating a common agenda for achieving global sustainability (Kibert 2005).

3.2.1.3 GREEN BUILDING ORGANIZATIONS – BEGINNINGS

Numerous green building organizations started in the 1980s and 1990s driven by the emerging need for more sustainable building construction practices. In 1982, the Rocky Mountain Institute began as a small group of business colleagues who fostered efficient resource use and policy development (Rocky Mountain Institute 2010). Today, the Rocky Mountain Institute has grown into a broad-based institution dedicated to researching, publishing, consulting, and lecturing in the general field of sustainability (Rocky Mountain Institute 2010). In 1991, the National Association of Home Builders (NAHB) began an initiative in green building systems (English 2008) by implementing green building programs in local homebuilding associations (Kibert 2005). In 1992, a green building rating system called Building Research Establishment Environmental Assessment Method (BREEAM) was created in Britain (Kibert 2005). Today, BREEAM is the leading environmental assessment method for buildings around the world (Building Research Establishment Environmental Assessment Method 2009). In 1993, the U.S. Green Building Council (USGBC) was formed and published its own green building guidelines, the Leadership in Energy and Environmental Design (LEED) guidelines. Version 1.0 of this green accreditation system was released in 1998 (Kibert 2005).

3.2.2 GREEN BUILDING BENEFITS

The intention of green buildings is to create benefits that justify the implementation of building practices that are considered to improve environmental quality. The range of benefits that green buildings create can be divided into three categories: Environmental, Health and Safety, and Economic. Examples of benefits that can be found within each of the mentioned categories will be discussed in the following subsections.

3.2.2.1 ENVIRONMENTAL BENEFITS

The benefits of green and sustainable building practices can be measured in monetary value, but the environmental impact of the built environment is often considered the ultimate measure. In the United States, buildings account for 72 percent of electricity consumption, 39 percent of total energy use, 38 percent of all carbon dioxide (CO₂) emissions, 40 percent of all raw materials used, 30 percent of total waste output, and 14 percent of potable water consumption (U.S. Green Building Council 2009a). These numbers suggest that traditional building practices must be improved to create more resource-efficient structures.

Given the excessive consumption of resources by traditional buildings, green building methods are designed to decrease the impact that humans have on the environment by limiting the use of the above-mentioned, exhaustible resources. For example, the primary source of carbon dioxide emissions ascribed to human activity is the combustion of fossil fuels to produce electricity and heat for buildings (Massachusetts Technology Collaborative 2009). Reducing fossil fuel consumption through energy efficient and clean energy technologies lessens the environmental impact (Massachusetts Technology Collaborative 2009). According to the U.S. Environmental Protection Agency (2009), environmental benefits of green buildings can include enhancing and protecting biodiversity and ecosystems, improving air and water quality, reducing waste streams, and conserving and restoring natural resources.

Timber waste reduction is another key element of green building practices, since most new homes in North America are constructed with wood (Massachusetts Technology Collaborative 2009). In the U.S., new homes consume, on average, approximately three-quarters of an acre of forest per home (Massachusetts Technology Collaborative 2009). Green building incorporates practices that reduce construction waste by using pre-cut material sizes, basing dimensions on standard material sizes, and incorporating recycled materials

(Massachusetts Technology Collaborative 2009). Optimum Value Engineering, an advanced framing technique that uses engineering principles to minimize material usage, can reduce framing wood costs and reduce wood consumption for framing by 11 to 19 percent (Natural Resource Defense Council 1998). Sustainable forest products, such as those recognized by the Forest Stewardship Council (FSC), can also be used to reduce the impact of buildings on forest ecosystems (Massachusetts Technology Collaborative 2009). Environmentally certified and reclaimed wood can be substituted directly for standard dimensional lumber, and gains a “green” marketing advantage as people prefer green products over their traditional counterparts (Natural Resources Defense Council 1998).

3.2.2.2 HEALTH AND SAFETY BENEFITS

In addition to improvements in resource consumption and environmental impact, green and sustainable building practices can also have favorable social benefits, such as to human health, safety, and heightened aesthetic qualities (U.S. Environmental Protection Agency 2009). Improvements in indoor air quality are of main concern to the U.S. population. On average, Americans spend about 90 percent or more of their time indoors (U.S. Environmental Protection Agency 1989). A 1983 World Health Organization report suggested that as much as 30 percent of new and remodeled buildings worldwide generate excessive complaints related to indoor air quality (World Health Organization 1983). Buildings with good overall environmental quality can reduce the rate of respiratory disease, allergy, asthma, or sick building symptoms, and can enhance worker performance (Fisk and Rosenfeld 1998). In traditional buildings, indoor levels of pollutants may be two to five times higher, and occasionally more than 100 times higher, than outdoor pollutant levels (U.S. Environmental Protection Agency 1989). The U.S. Environmental Protection Agency estimates that nearly one out of every 15 homes did not allow for proper mitigation of indoor air contaminants and contained radon (an odorless, colorless, and

poisonous gas) concentrations above the Environmental Protection Agency recommended action level (U.S. Environmental Protection Agency 2011).

A study by the National Research Council (2006) concluded that there is a relationship between moisture problems in buildings and adverse health effects upon children and adults. The same study also concluded that absenteeism may be affected by indoor air quality (National Research Council 2006). The reduction of pollutant loads has also been shown to improve the health and comfort of building occupants (National Research Council 2006). Green buildings aim to improve indoor air quality through the use of non-toxic building materials and the mitigation of indoor air contaminants (Kibert 2005). Since Americans spend a considerable amount of time indoors, green building methods can improve the health and safety of a majority of the U.S. population.

Green buildings pursue several approaches that promote occupant health. Ductwork must be protected during construction to avoid contamination. Finishes with low to zero volatile organic components (VOCs) are specified to prevent chemical off gassing. More precise sizing of heating and cooling components promotes dehumidification, thereby reducing mold, as does the use of ultraviolet radiation and flushing of these systems to kill mold and bacteria and remove particulates in ventilation systems (Kibert 2005, Lung Association of Saskatchewan 2004). Green building methods use various methods to increase health and safety of the building occupants as well as reduce future building maintenance and health costs.

3.2.2.3 ECONOMIC BENEFITS

Green building creates substantial economic benefits for the owners, workers, and occupants of a building. Productivity gains and reports of workers' overall positive feeling about the environment increased by 60 percent when a green or sustainable working environment was introduced (Heerwagen 2001). Romm and Browning (1998) showed an improvement of up to

16 percent in productivity by employees in new facilities designed according to green building principles compared to the productivity of existing facilities. Other studies have also shown significant productivity increases in commercial and educational areas (Kats 2003). Also, providing a temperature control of +/- 3 degrees Celsius (5.4 degrees Fahrenheit) to workers within an approximate 23 to 32 degrees Celsius (73.4-89.6 degrees Fahrenheit) environment increases work performance by 3 to 7 percent compared to workers without temperature control of their environment (Wyon 1996). Estimated productivity gains from improvements in indoor environments in U.S. office workers range from \$20-160 billion annually nationwide, accounting for reductions in health issues and increased performance (Fisk 2002). According to Zabarsky (2002), direct and indirect costs of building-related illnesses in corporate America, including lost worker productivity, were estimated to exceed \$150 billion per year in 2001.

Energy and operational costs have been shown to decrease when using green building methods. Green buildings almost always lower expenses on a life cycle cost basis (Kibert 2005). Though upfront costs may be greater for green buildings, most green building systems recoup the original investment within a relatively short time, typically estimated between 5 and 10 years (Kibert 2005). Increasing upfront costs by approximately 2 percent can increase life cycle cost savings by 20 percent (Kats 2003). For example, Kats (2003) estimated that a \$100,000 investment into green building features for a \$5 million project produced expected savings of \$1 million (2003 dollars) over a 20-year period. LEED buildings, on average, have proven to be 25 to 30 percent more energy efficient than standard housing (Kats 2003), translating into considerable cost savings over the lifetime of a building.

3.3 GREEN BUILDING ORGANIZATIONS

With the increased support of green building practices and awareness of environmental sustainability, numerous green building organizations have been formed in the U.S. to support

the green building movement. Some prominent organizations that endorse specific green building guidelines include the U.S. Green Building Council and the National Association of Home Builders (NAHB).

3.3.1 U.S. GREEN BUILDING COUNCIL

Located in Washington, D.C., the U.S. Green Building Council (USGBC) is a non-profit organization founded in 1993 (Kibert 2005) that is committed to a prosperous and sustainable future through cost-efficient and energy-saving green buildings (U.S. Green Building Council 2009a). Currently, the USGBC is comprised of 78 local affiliates and over 20,000 member companies and organizations (U.S. Green Building Council 2009a). In 1998, the USGBC created a first version of their green accreditation system entitled Leadership in Environmental and Energy Design (LEED). LEED Version 1.0 was the result of an accreditation system development process that occurred between 1994 and 1998. The LEED accreditation system evolved into a second version, released in 2000 (U.S. Green Building Council 2008a), and most recently a third version, known as LEED 2009, released in April 2009 (U.S. Green Building Council 2009a). LEED 2009 consists of a suite of rating systems including:

- LEED for New Construction
- LEED for Existing Buildings: Operations and Maintenance
- LEED for Commercial Interiors
- LEED for Core and Shell
- LEED for Schools
- LEED for Retail
- LEED for Healthcare
- LEED for Homes
- LEED for Neighborhood Development

LEED is the most prominent green building standard in the U.S. and has been wholly or partially adopted in Canada, Brazil, Mexico, and India (Kibert 2005, U.S. Green Building Council 2008a). Currently, there are LEED projects that have been registered or completed in all 50 states in the U.S. and in 91 different countries (U.S. Green Building Council 2009b). The LEED

program has achieved widespread recognition, and applications for certification have doubled each year from 1998 through 2004 (Kibert 2005). In January 2008, the number of LEED certified buildings had more than doubled in the past two years alone, a trend that is considered to continue as awareness of the standard is increased (Greener Buildings 2008).

3.3.1.1 LEED ASSESSMENT SYSTEM: LEED FOR HOMES

LEED for Homes is the focus of the discussion in this sub-chapter. The current LEED for Homes scheme employs a point system to award a platinum, gold, silver, or certified rating to a given home construction project based on specific, predetermined criteria in several categories that the building addresses (Kibert 2005). A set of prerequisites must be met and then the following points must be earned corresponding to the level of certification. The required points for each LEED for Homes certification level are shown in Table 3-1.

**Table 3-1: LEED for Homes Certification Levels
(U.S. Green Building Council 2008a)**

	REQUIRED POINTS
Certified	45-59
Silver	60-74
Gold	75-89
Platinum	90-136
Total available points	136

3.3.1.1.1 LEED FOR HOMES: PREREQUISITES

All levels of LEED for Homes certification are based on 18 prerequisites that must be fulfilled before any credits can be earned (U.S. Green Building Council 2008a). The prerequisites are considered basic performance standards, and therefore have no points awarded. To achieve certification, builders must earn points by exceeding these minimum standards. In total, there are 136 credit points available within eight credit categories (U.S. Green Building Council 2008a). In the following subchapters eight LEED credit categories are briefly described:

1. Sustainable Sites
2. Water Efficiency
3. Energy & Atmosphere
4. Materials & Resources
5. Indoor Environmental Quality
6. Location and Linkages
7. Awareness & Education
8. Innovation and design

3.3.1.1.2 LEED FOR HOMES: SUSTAINABLE SITES

The design of the site and its natural elements (i.e. - natural land slopes and features) can have a significant environmental impact on the construction process and the structure (U.S. Green Building Council 2008a). The sustainable site category refers to choosing a building site and managing that site during construction. The category discourages development on previously undeveloped land; minimizes a building's impact on ecosystems and waterways; encourages regionally appropriate landscaping; rewards smart transportation choices; controls storm water runoff; and promotes the reduction of erosion, light pollution, heat island effects (i.e. – densely developed areas are warmer than nearby rural areas) and construction-related pollution (U.S. Green Building Council 2009a).

3.3.1.1.3 LEED FOR HOMES: WATER EFFICIENCY

Buildings are large consumers of potable water, and approximately 340 billion gallons of fresh water is withdrawn every day from rivers and reservoirs (U.S. Green Building Council 2009b) for use within buildings. The goal of the water efficiency category is to encourage more efficient use of water, both inside and outside the home. Efficient water consumption can be achieved through more efficient appliances, fixtures, and fittings inside and water-wise landscaping outside (U.S. Green Building Council 2008a).

3.3.1.1.4 LEED FOR HOMES: ENERGY AND ATMOSPHERE

The energy and atmosphere category encourages a wide variety of strategies that encourage energy efficiency including commissioning; energy use monitoring; efficient design

and construction; efficient appliances, systems and lighting; the use of renewable and clean sources of energy, generated on-site or off site; and other innovative strategies (U.S. Green Building Council 2008a). There are two separate pathways that can be taken for this section depending on the use of energy modeling. One path requires the use of an approved energy analysis software program, such as Energy-10 (National Institute of Building Sciences 2010) or RESNET (Residential Energy Services Network 2010), to demonstrate the overall energy performance of the home's design. The other path enables a project to achieve LEED points by fulfilling prescriptive requirements without the need for energy modeling (U.S. Green Building Council 2008a).

3.3.1.1.5 LEED FOR HOMES: MATERIALS AND RESOURCES

The materials and resources category encourages the selection of sustainably grown, harvested, produced, and transported products and materials. This section also promotes the reduction of waste as well as the reuse or recycling of materials. Reduction of waste at a product or material's source is also accounted for in this category (U.S. Green Building Council 2008a).

3.3.1.1.6 LEED FOR HOMES: INDOOR ENVIRONMENTAL QUALITY

The indoor environmental quality category promotes strategies that improve indoor air quality, provide access to natural daylight and views, and improve a building's acoustics (U.S. Green Building Council 2008a). There are two pathways for this section. One pathway includes projects that participate in the U.S. Environmental Protection Agency's ENERGY STAR with Indoor Air Package (IAP). ENERGY STAR's IAP includes over 70 additional home design and construction features that protect qualified homes from moisture and mold, pests, combustion gasses, and other airborne pollutants (ENERGY STAR 2011). Projects that do not participate in the ENERGY STAR IAP can receive points distributed throughout the Indoor Environmental

Quality (IEQ) section of the LEED for Homes Reference Guide (U.S. Green Building Council 2008a).

3.3.1.1.7 LEED FOR HOMES: LOCATIONS AND LINKAGES

The locations and linkages category encourage homes not to be built near environmentally sensitive sites, but rather on infill sites, previously developed, and other preferable sites (U.S. Green Building Council 2008b). This section rewards homes built near existing infrastructure, community resources and transit, and encourages access to open space for walking, physical activity, and time spent outdoors (U.S. Green Building Council 2008b). There are two pathways that can be taken to obtain credit for this section: one pathway is for a house that is built on a site that has been deemed a LEED for Neighborhood Development site, which already satisfies the locations and linkages requirements. The other pathway is for a house that is not built within a LEED for Neighborhood Development site, which must meet the location and linkages requirements independently (U.S. Green Building Council 2008b).

3.3.1.1.8 LEED FOR HOMES: AWARENESS AND EDUCATION

The awareness and education category encourages home builders and real estate professionals to provide homeowners, tenants, and building managers with the education and tools they need to understand what makes their homes green and how to use these features (U.S. Green Building Council 2008b). Some homeowners may know very little about green home construction, and are unaware of or unfamiliar with how to use and maintain green features in the home. Since most new homes are expected to last 50 to 100 years, the occupants play a substantial role in the resource use of a home over its lifetime. Without adequate training, the full benefits of green features will likely not be achieved. The awareness and education section includes basic operations training and education for the occupants or building manger (U.S. Green Building Council 2008b).

3.3.1.1.9 LEED FOR HOMES: INNOVATION AND DESIGN

Since sustainable design strategies are constantly evolving and improving, occasionally a strategy results in an increase in building performance that greatly exceeds what LEED requires (U.S. Green Building Council 2008b). The innovation and design category encourages opportunities for the application of integrated, cost-effective adoption of newly developed green design construction strategies. Also promoted in the innovation and design category is the use of durable and high performance components. Incorporation of additional green designs and construction measures according to specific regional requirements are also promoted within this category (U.S. Green Building Council 2008b).

3.3.2 NATIONAL ASSOCIATION OF HOME BUILDERS

Much like the U.S. Green Building Council and their LEED for Homes standard, the National Association of Home Builders created the National Green Building Standard. Both standards focus on increased occupant health and safety and decreased impact on the environment. The following chapter describes the National Association of Home Builders (NAHB) and summarizes their National Green Building Standard.

The National Association of Home Builders (NAHB), based in Washington, D.C., is one of the most influential building groups in the U.S. Founded in 1942, the NAHB is a federation of more than 800 state and local associations whose mission is to enhance residential housing (National Association of Home Builders 2009b). About one-third of NAHB's more than 200,000 members are homebuilders and/or remodelers. The NAHB claims that members construct approximately 80 percent of all the new homes built each year in the United States. The NAHB is affiliated with the NAHB Research Center, which develops, tests, and evaluates new building materials, methods, standards, and equipment. The NAHB also works with federal agencies on

regulations affecting the housing industry in areas such as mortgage, finance, codes, energy, and the environment (National Association of Home Builders 2009b).

3.3.2.1 NATIONAL GREEN BUILDING STANDARD

In 2004, NAHB began to develop the NAHB Model Green Home Building Guidelines, which was a continuation of green building efforts initiated by the association in 1998 (National Association of Home Builders 2009a). The Model Green Home Building Guidelines were first published in 2005 and served as a basis for numerous localized green building programs across North America. In 2007, the NAHB partnered with the International Code Council (ICC) to create and establish a nationally recognized green building standard in compliance with the requirements of the American National Standards Institute (ANSI). The resulting American National Standards Institute (ANSI) approved ICC-700-2008 National Green Building Standard (NGBS), is the first ANSI consensus standard on sustainable green building for residential construction in the U.S. (National Association of Home Builders 2009a). The NGBS defines green building for single and multifamily homes, residential remodeling projects, and site development projects (National Association of Home Builders 2009c). The NGBS assessment system employs a point system to award an emerald, gold, silver, or bronze rating based on how many specific, predetermined criteria in several categories the building successfully addresses (National Association of Home Builders 2009c). The NGBS consists of seven chapters that detail the criteria considered as green building practices. These seven chapters are shown in Table 3-2, along with the points required per section to gain specific levels of certification within the NGBS (National Association of Home Builders 2009a). Unlike LEED, which has a separate category for innovation and design, the NGBS includes innovation and design within each chapter. A brief description of each chapter of the National Green Building Standard is given below.

Table 3-2: Performance level points required in each category of the National Green Building Standard (National Association of Home Builders 2009a)

GREEN BUILDING CATEGORY ¹	PERFORMANCE LEVEL POINTS ¹²			
	BRONZE	SILVER	GOLD	EMERALD
Lot Design Preparation and Development	39	66	93	119
Resource Efficiency	45	79	113	146
Energy Efficiency	30	60	100	120
Water Efficiency	14	26	41	60
Indoor Environmental Quality	36	65	100	140
Operation, Maintenance, and Building Owner Education	8	10	11	12
Additional points from any category	50	100	100	100
Total Points:	222	406	558	697

¹ In addition to the threshold number of points in each category, all mandatory provisions of each category shall be implemented.

² For dwelling units greater than 4,000 square feet (372 m²), the number of additional points shall be increased in accordance. The same number of points shall increase in the "Total Points" row.

3.3.2.1.1 LOT DESIGN, PREPARATION, AND DEVELOPMENT

The lot design, preparation, and development subchapter describes how points can be awarded for specified methods of lot development for the construction of residential buildings, multi-unit buildings, or additions containing dwelling units (National Association of Home Builders 2009a). Points are awarded for low environmental impact lot selection, having a knowledgeable project team, construction practices that emphasize natural resource conservation, and construction practices that create low impact on the surrounding environment (National Association of Home Builders 2009a).

3.3.2.1.2 RESOURCE EFFICIENCY

The resource efficiency chapter describes how points are awarded for quality of construction materials, reduced quantity of material waste, enhanced durability and reduced maintenance requirements, use of reused or salvaged materials, recycled-content building

materials, recycled construction waste, renewable materials, resource-efficient materials, indigenous materials, life-cycle analysis, and innovative practices (National Association of Home Builders 2009a).

3.3.2.1.3 ENERGY EFFICIENCY

The energy efficiency chapter describes minimum efficiency requirements including a performance-based path to gain energy efficiency points, a prescriptive-based path to gain energy efficiency points, additional methods, and innovative practices to achieve increased energy efficiency. The minimum efficiency section details mandatory prerequisite practices required to obtain points within the energy efficiency subchapter. The performance path for energy efficiency requires computer energy modeling to show that the energy cost performance of a building exceeds the ICC IECC guidelines by a given percentage. The prescriptive path for energy efficiency gives points for specific energy efficient features such as achieving a specific thermal enclosure heat resistance, HVAC requirements, lighting, and appliances. For innovative practices, points are awarded for energy consumption control such as using a programmable communicating thermostat or energy-monitoring device. Points are also awarded for the selection of a renewable energy service plan provided by the local electrical utility (National Association of Home Builders 2009a).

3.3.2.1.4 WATER EFFICIENCY

The water efficiency chapter includes sections on indoor and outdoor use and innovative practices to improve water efficiency (National Association of Home Builders 2009a). The indoor and outdoor use sections awards points for reducing water usage, reducing indoor hot water usage, water-conserving appliances, food waste disposers, showerheads, faucets, water closets and urinals, irrigation systems, and rainwater collection and distribution. The innovative practices section awards points for reusing gray water, composting or waterless toilets and/or

urinals, and the use of automatic water shutoff devices (National Association of Home Builders 2009a).

3.3.2.1.5 INDOOR ENVIRONMENTAL QUALITY

The indoor environmental quality chapter awards points for pollutant source control, pollutant control, moisture management, and innovative practices (National Association of Home Builders 2009a). Points are also awarded for the use of efficient heating equipment, heating, ventilation, and air conditioning (HVAC) system protection from pollutants, using construction methods that control moisture and moisture effects, and practices such as a humidity monitoring system or using a kitchen exhaust (National Association of Home Builders 2009a).

3.3.2.1.6 OPERATION, MAINTENANCE, AND BUILDING OWNER EDUCATION

The operations, maintenance, and building owner education chapter includes sections on the use of a building owner's manual, training of the building owners on operation and maintenance, and the use of construction, operation, and maintenance manuals and appropriate training. This chapter awards points for providing manuals, and for the appropriate training of building owners so that operators understand how and why to best use the green features installed (National Association of Home Builders 2009a).

3.4 TRADITIONAL VERSUS GREEN CONSTRUCTION

The most basic function that a building provides is a sound structural system (Germer 2006). Traditionally buildings have been constructed with little thought to the surrounding environment, and many inefficient products such as inefficient mechanical systems and wasteful water fixtures have been included (Friedman 2007). With the world population growing and natural resources becoming scarcer, building practices are evolving to conserve and/or regenerate available resources (Friedman 2007). It is important to note that green and

sustainable construction, no matter how progressively designed and energy-efficient, still must comply with all existing and applicable building codes that have been established. However, typically, green and sustainable construction standards surpass the building code standards (Germer 2006).

3.4.1 BUILDING CODES

In most jurisdictions, the builder has a legal obligation to obtain a building permit for construction (Germer 2006). Building codes emphasize the construction requirements of an entire building and place restrictions on hazardous materials or appliances and other equipment that can be used within a building (Macasai et al. 1982). Building codes ensure the public health, safety, and welfare of all users of a building (Macasai et al. 1982). When building homes on-site, the building codes that apply depend on the location of the project, the project size, and the project type (Germer 2006). Commonly addressed issues in residential home buildings codes include structural, mechanical, electrical, plumbing, life safety, fire safety, natural light and air, accessibility and egress standards, and energy conservation issues (Macasai et al. 1982).

3.4.1.1.1 ENERGY CONSERVATION

To encourage the conservation of energy during building use, federal, state, and local governments have developed standards that work closely with various energy codes (Germer 2006). Building codes now include energy conservation regulations that limit, for instance, the maximum heat loss through the building enclosure when the building is in operation (Macasai et al. 1982). Other regulations related to energy conservation include glass areas, such as windows and doors, which must be minimized and dual glazed, and solid walls and roofs with adequate quantities of thermal insulation (Macasai et al. 1982).

3.4.1.2 INTERNATIONAL RESIDENTIAL CODE

All codes recognize the differences between buildings based on occupancy and use (Macasai et al. 1982). The International Residential Code (IRC) addresses specific issues related to home design and construction (Germer 2006). The IRC is a consensus-based code that is open to public comment and revised on a three-year rotation. The IRC includes all one- and two-family detached dwellings and apartment buildings up to three stories (International Code Council 2009). The IRC creates minimum regulations for residential buildings and contains standards on foundations, framing, plumbing, electrical, mechanical systems, and energy usage (International Code Council 2009). The IRC also contains detailed requirements for emerging techniques such as steel stud construction, frost-protected shallow foundations and insulated concrete forms (International Code Council 2009). The IRC addresses regional variations such as frost depths, snow loads, and termite threat potential, but also incorporates residential structures built in areas prone to flooding, high winds, and seismic activity (International Code Council 2009).

3.4.1.3 INTERNATIONAL ENERGY CONSERVATION CODE

The IRC is the comprehensive standard for all building aspects (structure, plumbing, mechanical systems, etc.) of residential construction. The International Energy Conservation Code (IECC) is published by the ICC and encourages energy conservation through efficiency in enclosure design, mechanical systems, lighting systems, and the use of new materials and techniques (ENERGY STAR 2009). Though similar to the energy related components of the IRC, and even referenced within the IRC, the two codes are not always identical (ENERGY STAR 2009). The IECC is a consensus-based code and remains current by being regularly revised by code enforcement officials, industry representatives, design professionals, and any other interested parties (International Code Council 2009a).

The IECC is a model code that regulates minimum energy conservation requirements for new buildings, and addresses requirements for all aspects of both commercial and residential construction (International Code Council 2009a). The 2009 IECC is arranged and organized to follow sequential steps that generally occur during a construction plan review or inspection. The IECC is divided into five different parts: administration and definitions, climate zones and general materials requirements, energy efficiency for residential buildings, energy efficiency for commercial buildings, and referenced standards (International Code Council 2009a).

3.4.2 COMPONENTS OF RESIDENTIAL FRAMING

The framing of a house can consist of many different materials and systems (Germer 2006). Most residential homes are built using lightweight structural systems, with other systems available (Germer 2006). The selection of framing used in a building should result in the most economical structure within the bounds of the building function (Macasai et al. 1982). Another important aspect of the framing choice is the serviceability of the structure. Serviceability is a human perception that refers to the deflection of floors and vibrations, architectural elements interfacing with structural elements, building drift, and adverse human response to building movement. Once the building structure has satisfied the required strength and serviceability requirements, additional structural elements add only to cost, not to structural quality (Macasai et al. 1982). Wooden framework has been the predominant framing material of choice in the United States as wood frame buildings are economical to build and provide a comfortable shelter for occupants (American Wood Council 2001). Stud framing, the most commonly used framing within residential construction, will be briefly described in the following subchapter.

3.4.2.1 STUD WALL AND PLATFORM FRAMING

Stud wall framing became a popular method of building after the advent of wire nails and improved sawmill technology in the first half of the nineteenth century, and has revolutionized

housing construction (Germer 2006). The advantage of stud wall framing lies in the joints, which do not require skilled craftsmen to construct. The stud wall framing system allowed the roofs of single-story houses to bear directly on the top plate supported by regularly spaced studs in a wall (Germer 2006).

Once two story houses began to be constructed, a method of stud wall construction called “balloon framing” was created (Germer 2006). Balloon framing, as shown in Figure 3-1, consisted of studs that extended from the foundation to where the wall met the roof. The first floor joists bear on the mudsill, while the second floor joists bear on a ledger board set in notches in the studs. Disadvantages of this method of framing are that fire can easily travel from floor to floor, that there is a lack of working platforms for upper floor construction, and the requirement for long framing members. Balloon framing requires additional fire blocking to be installed to prevent a chimney effect from occurring within the wall cavities. Balloon framing also makes tall walls for 2 and 3 story structures challenging, as it requires long or spliced lumber. The disadvantages of this framing system caused the introduction of a simpler framing system called platform framing (Germer 2006).

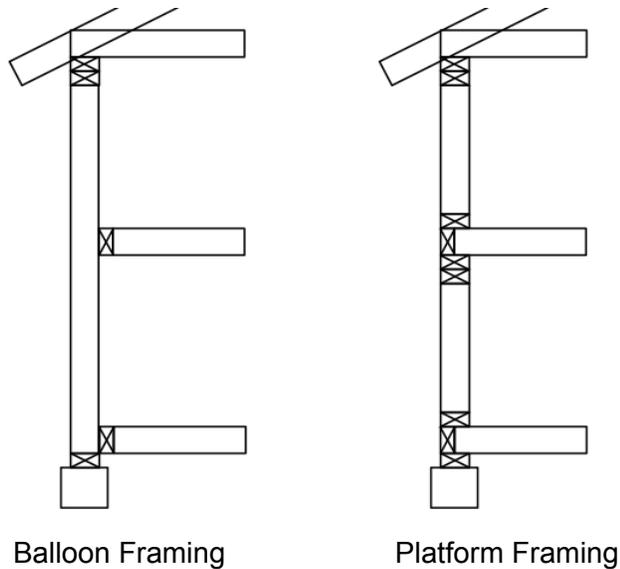


Figure 3-1: Diagrams of balloon and platform framing methods of stud wall construction.

Platform framing consists of studs in platform-framed walls that span between the floors or platforms (Figure 3-1, Germer 2006). In platform framing, the first floor studs bear on a top plate, and extend to the bottom of the band joist of the second floor. Second floor joists extend from the band joist of the second floor to the roof plate (for a two-story building). Platform framing typically requires more lumber and fasteners, and therefore can be more expensive to construct. Because platform framing is simpler and therefore quicker, easier, and safer for workers to construct, platform framing is today’s method of choice for the construction of most modern residential housing (Germer 2006).

3.4.2.2 PANEL WALL SYSTEMS

Panel wall systems are wall sections that are produced in a factory, which can be shipped and assembled on the construction site (Friedman 2007). Panel wall systems are assembled with the platform framing method. Prefabrication methods offer many advantages over conventional construction methods including quick assembly; prevention of damage to building materials due to weathering, storage, and vandalism; shorter assembly time; and reduced material costs due to reduced on-site waste. Numerous types of prefabricated

systems, subsystems, and components can be combined at various levels to provide a complete framing package. Several types of panel systems are applicable to residential wood-frame construction. These panel wall systems can be divided into three categories: open-sheathed panels (OSPs), structural sandwich panels (SSPs), and unsheathed structural panels (USPs) (Friedman 2007).

3.4.2.3 GREEN FRAMING

To create a green framing technique, the life cycle of a building must be considered (Friedman 2007). A life cycle analysis examines a product from “cradle-to-grave”, and accounts for the environmental impacts of a product (Friedman 2007). During a life cycle analysis, parameters of a product are examined including energy efficiency, waste generation, natural resource pollution, recycled content or ability to be recycled, sustainability, and costs during acquisition (Friedman 2007).

Good design decisions in the framing of homes with a focus on proper and efficient material usage can significantly reduce the demand for framing materials as well as reduce the amount of waste created (U.S. Green Building Council 2008b). Construction waste can, for example, be reduced by using precut framing packages, off-site fabrication of building components, structural insulated panels or open-web trusses, or increasing joist and rafter spacing. Also, construction waste management planning can divert waste from landfills for reuse or recycling (U.S. Green Building Council 2008b).

Another method of greening the framing process relies on using environmentally preferable materials (U.S. Green Building Council 2008b). Environmentally preferable products can consist of building components extracted, processed, and manufactured within the surrounding region. An environmentally preferable product may also be considered if a product contains materials that are recycled, reclaimed, or certified as being sustainable. Building

materials with low emission specifications can also be classified as environmentally preferable (U.S. Green Building Council 2008b).

A critical aspect of green framing is the enhanced ability to reduce the movement of temperature and moisture between the indoor and outdoor environment as compared to traditional framing. Properly constraining the temperature and moisture movement through the structure of a building reduces the need for conditioning of the indoor air and increases the overall energy efficiency and durability of the structure. The choice of insulation material and methods of installation are important to the behavior of wall sections.

3.5 INSULATION

The use of insulation is fundamental to an energy efficient building enclosure. An energy-conserving enclosure is a building enclosure in which walls and roof reduce heat transfer in the hot season and retain heat in the cold seasons, therefore reducing the consumption of energy needed to condition the indoor environment (Germer 2006). The method of insulating a building depends on the geographic location of the building site as the particular climate dictates the method and amount of insulation that is necessary to control heat gain and loss (Germer 2006).

3.5.1.1 R-VALUE

The standard index for rating insulation is called R-value (Nisson and Wilson 2008). The R-value is an index of the ability of material to resist heat flow by conduction, and the unit of the R-value in US units is given in $\text{ft}^2 \cdot \text{°F} \cdot \text{h} / \text{Btu}$, while the internationally accepted SI-unit is $\text{m}^2 \cdot \text{K} / \text{W}$ (Germer 2006). The greater a material's R-value, the more the material resists the flow of heat. With a temperature difference of 1 degree Fahrenheit, insulation with an R of 1.0 allows 1.0 Btu per hour heat flow per square foot of surface area (Nisson and Wilson 2008). For conduction, the heat flow is determined as follows:

$$\text{Heat Flow (Btu/hr/ft}^2\text{)} = \text{Temperature Difference (}^\circ\text{F)} \times \text{R-value}$$

Manufacturers usually list the R-value of an insulation material in terms of R per inch thickness (Nisson and Wilson 2008). Different geographical locations require different R-values to properly insulate a home depending on the climate (Germer 2006). The U.S. Department of Energy provides a set of guidelines for insulation recommendations for each climate zone across the United States. Figure 3-2 is a map of the insulation requirement zones while the recommended insulation requirements in each zone are shown in Table 3-3 (North American Insulation Manufacturers Association 2005). Choosing the best insulation from the options available requires matching the insulation to the application, balancing R-values with costs and benefits, and considering the ease of installation (Germer 2006).

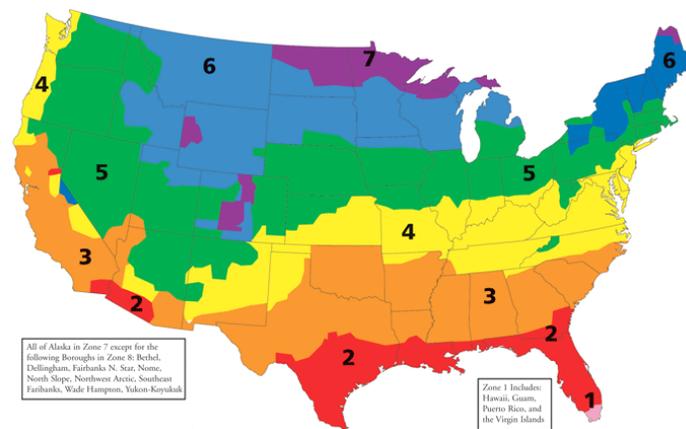


Figure 3-2: U.S. Department of Energy's recommended insulation levels. Permission to reproduce this image has been granted by the North American Insulation Manufacturers Association (Appendix A, North American Insulation Manufacturers Association 2005).

Table 3-3: Insulation zones for new wood-framed houses shown in Figure 3-2. (North American Insulation Manufacturers Association 2005).

ZONE	HEATING SYSTEM	ATTIC	CATHEDRAL CEILING	WALL		FLOOR
				Cavity	Insulation Sheathing	
1	All	R30 to R49	R22 to R15	R13 to R15	None	R13
2	Gas, oil, heat pump	R30 to R60	R22 to R38	R13 to R15	None	R13
	Electric furnace					R19 to R-25
3	Gas, oil, heat pump	R30 to R60	R22 to R38	R13 to R15	None	R25
	Electric furnace				R2.5 to R5	
4	Gas, oil, heat pump	R38 to R60	R30 to R38	R13 to R15	R2.5 to R6	R25 to R30
	Electric furnace				R5 to R6	
5	Gas, oil, heat pump	R38 to R60	R30 to R38	R13 to R15	R2.5 to R6	R25 to R30
	Electric furnace		R30 to R60	R13 to R21	R5 to R6	
6	All	R49 to R60	R30 to R60	R13 to R21	R5 to R6	R25 to R30
7	All	R49 to R60	R30 to R60	R13 to R21	R5 to R6	R25 to R30
8	All	R49 to R60	R30 to R60	R13 to R21	R5 to R6	R25 to R30

3.5.2 CATEGORIES OF INSULATION

The type of insulation used for a particular project is subject to its placement in the building, the thermal properties required, and the price. This section discusses the most commonly used insulation methods in residential light frame construction, including batts, loose fill, rigid foam and spray applied insulation. The approximate ranges of R-values for each insulation method are shown in Table 3-4. Details about each method are summarized in the following sections.

Table 3-4: Approximate R-value per inch ranges for different insulation materials (Nisson and Wilson 2008).

INSULATION METHOD	R-VALUE/INCH
BATT	3.1 – 3.8
LOOSE FILL	2.3 – 3.7
RIGID FOAM	4.5 – 8.7
SPRAY APPLIED	3.6 – 8.0

3.5.2.1 BATTES AND BLANKETS: FIBERGLASS AND MINERAL WOOL

Fiberglass is the most commonly used insulation material, accounting for roughly 90 percent of new home use (Nisson and Wilson 2008). Mineral wool, also called rock wool, is the second most common insulation material and is slightly more expensive than fiberglass (Germer 2006). Mineral wool is similar to fiberglass, but has a higher density, better acoustic insulation, does not change R-value when wet, and has better resistance to fire. However, mineral wool is known to be an even greater irritant to the skin, eyes, and nasal passages than fiberglass (Germer 2006). Protective clothing, goggles, and an appropriate dust mask are recommended for installation of both products (Nisson and Wilson 2008).

Fiberglass and mineral wool are typically available in blanket or batt form, with thickness between 3 to 12 inches (Germer 2006). The various thicknesses of fiberglass batts available are shown in Table 3-5 along with their respective R-values (Nisson and Wilson 2008). The widths of the blankets or batts are sized to fit between framing members spaced 16 or 24 inches on center. Batts are typically cut and packed into bundles containing eight-foot long rolls (Germer 2006). Unlike batts, blankets are longer uncut rolls of material designed to be cut to desired lengths while on site (Nisson and Wilson 2008).

Table 3-5: Available fiberglass batt thicknesses and R-values (Nisson and Wilson 2008).

THICKNESS	R-VALUE
3-1/2"	R-11
3-1/2"	R-13
3-1/2"	R-15
6-1/4"	R-19
5-1/2"	R-21
8-1/2"	R-30
12"	R-38

Fiberglass blankets/batt insulation consists of glass fibers pressed together with a binding substance (Germer 2006). Fiberglass batts are available with or without paper or foil facing on one side (Nisson and Wilson 2008). When faced with Kraft paper or foil, facing flanges allow the batt to be stapled to the framing (Nisson and Wilson 2008, Germer 2006). Unfaced batts are typically slightly wider than faced batts in order to “friction fit” them into stud wall cavities with the aid of support wires to prevent sagging (Nisson and Wilson 2008). The kraft paper or foil facing can serve as a vapor barrier if the edges are thoroughly sealed with tape or caulk (Germer 2006). However, kraft paper facing is considered a marginal vapor barrier (Germer 2006).

3.5.2.2 LOOSE FILL INSULATION

Loose-fill insulation consists of granular or fluffy materials that can be blown into hollow cavities or open attics (Nisson and Wilson 2008). The main advantage of loose-fill insulation is the ability to completely fill the space without any cutting and fitting of the insulation (Nisson and Wilson 2008). Due to the ease of installation in obstructed spaces, loose-fill is usually used for remodeling purposes to insulate nooks and crannies that are difficult to fill (Nisson and Wilson 2008, Germer 2006). Cellulose, Perlite, Vermiculite, fiberglass, and mineral wool are available in bags of loose fiber or pellet form. The bags of fibers or pellets can be poured by hand or be blown into the cavity (Germer 2006). Loose fill cellulose insulation traditionally has an R-value

that is higher than loose fill fiberglass or mineral wool, as shown in Table 3-6, and is also slightly denser making the cellulose insulation less susceptible to movement from wind gusts in the attic (Germer 2006). The main drawback of loose fill is the tendency to attract and hold moisture, which usually can be prevented by an appropriate vapor barrier. Settling of the fill material is another drawback as gaps in insulation occur over time (Germer 2006).

Table 3-6: R-values of loose-fill insulation materials (Germer 2006).

MATERIAL	R-VALUE PER INCH
Cellulose Fiber	R-3.7
Fiberglass	R-2.3 to R-2.8
Mineral Wool	R-3.2
Vermiculite	R-2.4

3.5.2.3 RIGID FOAM INSULATION

Various plastics, such as polyurethane and polyisocyanurate, are formed into foam sheets of insulation two or four feet wide, eight feet long, and between one-half and four inches thick (Germer 2006). Higher R-values of rigid foam insulation can offset higher cost over batt/blanket insulation per inch thickness. The main uses of rigid insulation are the outside of foundations and the undersides of concrete slabs (Germer 2006). The R-value of rigid foam insulation can vary, depending on the type of foam used. The typical R-value per inch of rigid foam ranges from R-4.0 to R-8.7 per inch as shown in Table 3-7 (Nisson and Wilson 2008). Rigid foam sheets provide an increased R-value for an existing wall or ceiling (Germer 2006).

The foil facing of some foam sheets serve as a vapor barrier if the joints are taped (Germer 2006). Foam sheets can easily be cut with a sharp knife, and secured by nails, screws, or adhesives (Germer 2006). Almost all rigid foam insulation boards are flammable and must be protected by a fire-rated covering if installed in a living space or basement (Nisson and Wilson 2008).

Table 3-7: Example R-values of rigid foam insulation.

MATERIAL	R-VALUE PER INCH
Extruded Polystyrene	R-5.0
Expanded Molded Bead Polystyrene	R-4.5
Polyisocyanurate	R-7.2 to R-8.7

3.5.2.1 SPRAY APPLIED PRODUCTS

A majority of heat loss through the building enclosure results from air infiltration and exfiltration, which often is reduced by the application of a spray applied insulation (Germer 2006, Nisson and Wilson 2008). Various polymers, typically derived from oil-based polymers or cellulose, are commonly used for spray-applied insulation. Spray-applied insulation offers increased resistance to air and moisture passage by filling the voids in the building enclosure (U.S. Department of Energy 2009b). The following sections discuss specific spray-applied insulation types and the use of air and vapor barriers in insulation.

3.5.2.1.1 SPRAY APPLIED SYNTHETIC POLYMER PRODUCTS

Polyurethane and polyisocyanurate are two polymers commonly used as spray applied insulation. These polymers are applied to wall stud cavities in liquid form with special equipment and then allowed to foam, filling all voids between studs. Two types of plastic spray-foam commonly used are closed-cell and open-cell foam, with the main difference being the gas used as a foaming agent to fill the cells formed within the polymer (U.S. Department of Energy 2009b). Closed-cell foam is produced with a low-conductivity gas, commonly hydrochlorofluorocarbons (HCFCs), while open-cell foam commonly uses carbon dioxide (CO₂). HCFCs act in the upper atmosphere to destroy the ozone layer above the earth that helps to protect the earth's surface from harmful ultraviolet radiation, ultimately contributing to global warming. While the low-conductivity gases have lower thermal conductance, they do off-gas, or slowly release hazardous volatile organic compounds (VOCs) into the surrounding environments (U.S. Department of Energy 2009b).

Polyurethane can be applied as closed-cell or open-cell foam, and is most commonly applied as open-cell foam in residential applications due to its flexibility and lack of off gassing (U.S. Department of Energy 2009b). Closed-cell polyurethane foam has an R-value of approximately 6.5 per inch of thickness and open-cell polyurethane has an R-value of approximately 3.6 per inch of thickness (U.S. Department of Energy 2009b). Polyisocyanurate is offered only as closed-cell foam. Depending on the gas used as a foaming agent, R-values range from 5.6 to 8.0 per inch of thickness (U.S. Department of Energy 2009c). Over time, the R-value of polyisocyanurate insulation can drop due to loss of the low-conductivity gas, but typically remains constant once they polyisocyanurate finished off gassing, which is about two years after application unless damaged (U.S. Department of Energy 2009c).

3.5.2.1.2 CELLULOSE

Cellulose insulation is made from recycled newspaper treated with fire and pest retardant chemicals, typically a borate solution (Cellulose Insulation Manufacturers Association 2010). Sprayed cellulose is typically applied dry into horizontal areas such as floors and attics, but is mixed with water and adhesives (referred to as damp-spray cellulose) when sprayed into vertical wall cavities (Cellulose Insulation Manufacturers Association 2010). Damp-spray cellulose forms a denser layer of insulation, which creates better insulation and lower air infiltration compared to the dry application (Fisette 2005). Depending on the application method, damp or dry, cellulose insulation has an R-value ranging from 3.6 to 4.0 per inch of thickness (Cellulose Insulation Manufacturers Association 2010).

3.5.3 AIR BARRIERS

The sheathing used to enclose a structure rarely fits together perfectly, requiring an air barrier to control the movement of air through the building enclosure. Gaps in the insulation may also allow air to infiltrate and penetrate the enclosure causing changes in temperature and

introduction of outside air (U.S. Department of Energy 2002). These gaps are attributed to approximately one-third of the total heat loss of an average home (Fisette 2005). An air barrier is used to wrap the enclosure of a house to reduce air infiltration. Air barriers are required in all houses by the International Residential Code (International Conservation Code 2009a).

Building codes typically determine if a structure has proper air sealing by means of a compliance testing option or visual inspection of the building enclosure (International Conservation Code 2009b). An air barrier is typically placed under the exterior cladding (International Conservation Code 2009b) and is commonly referred to as a “house wrap.” The air barrier allows water vapor to transfer through the building enclosure, while air movement and liquid water are prevented from transferring through the building enclosure. Additionally, the joints of the sheathing or the air barrier should be taped to prevent air infiltration (International Conservation Code 2009b). For a more specific and comprehensive list of where an air barrier should be used, refer to Chapter 402.4.1 of the 2009 IECC (International Conservation Code 2009b).

3.5.4 VAPOR BARRIERS

Water vapor diffuses from high pressure to lower pressure areas until equilibrium is reached (U.S. Department of Energy 2002). In this process, vapor condenses on materials or in locations with temperatures at or below the dew point temperature (Germer 2006). Moisture condensation in the wall or roof can cause insulation to lose efficiency, wood framing and sheathing to decay, and outside paint to peel. To avoid moisture related issues, the application of a vapor barrier to the building enclosure can reduce moisture movement, therefore preventing moisture from diffusing through the building enclosure and becoming trapped (Germer 2006).

3.5.5 RISKS OF AIR AND VAPOR BARRIERS

Sealing a house with an air or vapor barrier risks the creation of a “tight” house, which can prevent fresh air from circulating into the house for occupants' comfort and to replace air (oxygen) from fuel burning appliances (Germer 2006). No house should be completely sealed without providing a compensating air supply or indoor air quality problems will result (Sherman 2004). The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) published the ASHRAE 62.2-2003 code, which requires “*0.35 changes per hour, but no less than 15 cubic feet per minute per person*” (Sherman 2004). Methods used to ensure adequate air supplies include heat recovery air-to-air heat exchangers, commonly referred to as an energy recovery ventilator or heat recovery ventilator (ERV/HRV), as well as other simpler forms of ventilation including conventional fans (Germer 2006).

3.6 INSULATION REQUIREMENTS FOR BUILDING ENCLOSURES

Green building certification systems prescribe specific requirements for construction to achieve reduced impact on the environment. Such green building certification systems share a common emphasis on energy efficiency through using good insulation materials and methods, among other things. The following section describes the insulation requirements of the LEED for Homes and the National Green Building Standard systems.

3.6.1 LEED FOR HOMES INSULATION RATING REQUIREMENTS

LEED for Homes has a mandatory prerequisite that must be fulfilled to achieve the maximum two-point rating for insulation (U.S. Green Building Council 2008a). Prerequisite EA 2.1 prerequisite requires the insulation to meet the R-values listed in Chapter 4 of the 2004 International Energy Conservation Code (International Code Council 2004). According to the 2004 IECC, all cavity insulation must meet or exceed R-15 insulation and conform to a Grade II installation specification as set by the National Home Energy Rating Standards (HERS; U.S.

Green Building Council 2008a). The HERS insulation grades are shown in Table 3-8. Grade II insulation installation requires ten percent or less square footage of air gaps in the insulation. To achieve the highest grade, Grade I, no more than two percent of the square footage of insulation installation can contain air gaps. The installation must be verified by a certified Energy Rater or certified Green Rater conducting a pre-drywall thermal bypass inspection as summarized in the LEED for Homes Reference Guide (U.S. Green Building Council 2008a). An energy rater is qualified to conduct HERS ratings, while a Green Rater is certified to work with LEED for Homes projects.

Table 3-8: HERS Installation Grades (National Association of Home Builders 2009a)

GRADE	DESCRIPTION
I	Meet the requirements of Grade II (below), but allow only very small gaps, and compression or incomplete fill amounts to 2 percent or less.
II	Moderate to frequent installation defects, gaps around wiring, electric outlets, etc. and incomplete fill amounts to 10 percent or less. Gaps running clear through the insulation amount to no more than 2 percent of the total surface area covered by the insulation. Wall insulation is enclosed on all six sides and in substantial contact with the sheathing material on at least one side (interior or exterior) of the cavity.

After the prerequisite EA 2.1 is met, Credit EA 2.2 provides two points for the insulation category. One point is given if the insulation exceeds the R-value requirements listed in Chapter 4 of the International Energy Conservation Code by at least 5 percent (U.S. Green Building Council 2008a). The other point is given if the insulation meets the Grade I specifications set by the National Home Energy Rating Standards (refer to Table 3-8), and is verified by an energy rater or Green Rater conducting a pre-drywall thermal bypass inspection as summarized in the ENERGY STAR Thermal Bypass Inspection Checklist (U.S. Green Building Council 2008a). In LEED for Homes, the two points achievable in the insulation category represent 20 percent of the ten total points available for the Energy & Atmosphere category, and represent 1.5 percent of the total 136 possible LEED for Homes points.

3.6.2 NATIONAL GREEN BUILDING STANDARD INSULATION RATING REQUIREMENTS

Within its Energy Efficiency chapter, the National Green Building Standard (NGBS) includes a performance and prescriptive path, but points can only be attained through one path (National Association of Home Builders 2009a). Independent from which path is chosen, insulation must be installed in accordance to manufacturers' instructions or local codes. Another option, besides attaining points, allows the building to qualify up to a bronze rating by an ENERGY STAR Qualified Home or equivalent certification. Within the Energy Efficiency chapter of the NAHB, possible points that can be awarded for insulation rating requirements are shown in Figure 3-3.

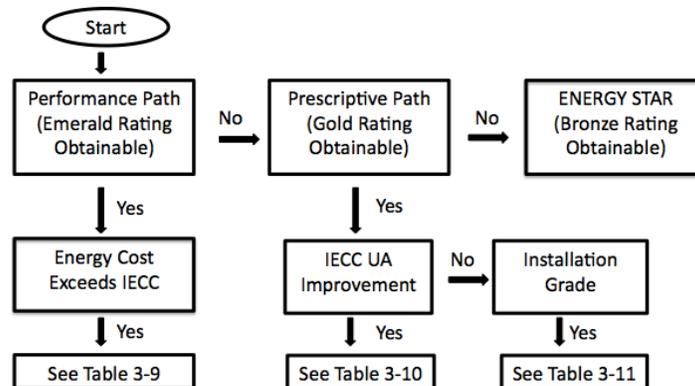


Figure 3-3: Diagram of possible energy efficiency points using the NGBS (National Association of Home Builders 2009a).

The Energy Efficiency chapter of the National Green Building Standard (NGBS, National Association of Home Builders 2009a), allows insulation methods to achieve up to a total of 120 points, which is 17.2 percent of the points required to receive an Emerald rating (e.g., the highest rating possible). To gain the Emerald rating, the performance path must be used (Credit 702.2 of the NGBS), which awards points when the energy cost performance of the International Energy Conservation Code (International Code Council 2009) is exceeded by a given

percentage. The performance path points are dependent on the percentage improvement of energy cost performance as compared to the IECC and are shown in Table 3-9 (National Association of Home Builders 2009a). For insulation to gain the maximum 120 points, the building enclosure must provide energy efficiency that achieves an energy cost performance exceeding the IECC guidelines (International Code Council 2009) by at least 60 percent.

Table 3-9: Performance path points awarded as described by NGBS Credit 702.2 (National Association of Home Builders 2009a)

ENERGY COST PERFORMANCE EXCEEDS THE ICC BY:	POINTS
15 percent	30
30 percent	60
50 percent	100
60 percent	120

If the building's thermal enclosure does not conform to the IECC (as described in the performance path), the overall building thermal enclosure can still earn points using the prescriptive path (NGBS Credit 703, National Association of Home Builders 2009a). Within the prescriptive path, a total of 36 points (depending on the climate zone in which the building is located) can be earned. These 36 points are 30 percent of the points within the Energy Efficiency chapter, or 6.4 percent of the points required to meet the Gold rating, which is a rating below Emerald. The Emerald rating cannot be achieved using the prescriptive path. Using the prescriptive path, points can be gained by exceeding the IECC cost performance or by meeting an insulation installation grade. However, points earned by exceeding the IECC cost performance cannot be used in conjunction with points earned by meeting an insulation installation grade.

Prescriptive points awarded for exceeding the “UA”, the total U-factor times the area of a given component of a building are shown in Table 3-10. Documentation is performed by RESCheck (U.S. Department Of Energy 2010) or equivalent software based on comparison to the IECC, IRC, or IBC as described in Credit 703.1.1. For residential buildings, UA equals the U-factor (inverse of R-value) of the insulation times the area of insulation used in a building enclosure. A maximum of 36 points, depending on climate zone, can be achieved by exceeding the UA requirements of the IECC.

Table 3-10: Points awarded in section 703.1.1 of the National Green Building Standard for total building thermal enclosure UA (National Association of Home Builders 2009a)

	CLIMATE ZONE				
	2	3	4	5-6	7-8
	Points				
10% UA improvement	10	12	14	16	18
20% UA improvement	20	24	28	32	36

If points are not earned by exceeding the UA (Table 3-10), points can be obtained by meeting an insulation installation grade as shown in Table 3-11 (Credit 703.1.2). Achieving a Grade I insulation installation grade can earn a maximum of 15 points (National Association of Home Builders 2009a). The description of the requirements for each grade is shown in Table 3-8.

Table 3-11: Points available in section 703.1.2 for insulation installation grades (National Association of Home Builders 2009a)

GRADE	POINTS
I	15
II	10

3.7 IMPACTS OF MOISTURE WITHIN BUILDING ENCLOSURES

Previous research has shown that moisture from indoor air interacting with the building enclosure can significantly impact the building’s interior humidity, comfort, and air quality

(Virtanen et al. 2000, Rode et al. 2001, Simonson et al. 2002). Moisture may also be stored in the building enclosure, where it is detrimental to the building enclosure if left uncontrolled (Simonson et al. 2005). The accumulation of moisture within the building enclosure due to heat transfer and diffusion of water vapor from indoor air is an important issue with building enclosure durability, especially in cold climates (American Society of Testing Materials 1994).

Moisture accumulation can decrease the indoor air quality of a building, but can also negatively affect building materials through mold growth, rotting and decay, corrosion, and other physical or aesthetic damage (Simonson et al. 2005). While researching the effect of exfiltration on the hygrothermal performance of residential wall assemblies, Ojanen and Kumaran (1996) found that even low continuous airflow leakage could cause severe moisture accumulation in building enclosures in cold climates and thus create severe damage to a building.

3.7.1 INTERSTITIAL CONDENSATION

Interstitial condensation occurs when the dew point temperature within a building enclosure is surpassed, causing water vapor to precipitate and accumulate. Vapor moves by diffusion, from areas of higher vapor content to areas of lower vapor content. Because of diffusion, vapor transfers through the building enclosure surfaces and enters the insulation cavity where it condenses if the saturation point is exceeded (Lstiburek and Carmody 1994). The resulting increase in moisture content of building materials through interstitial condensation changes the structural material's performance and increases the risk of organic deterioration where applicable. According to a Special Technical Publication titled *Moisture Migration in Buildings* by the American Society for Testing and Materials (American Society of Testing Materials 1982), approximately 90 percent of all building construction problems are associated with moisture (American Society of Testing Materials 1982). Moisture within a building enclosure can cause damage through a number of failure mechanisms, including rot,

freeze/thaw damage, dimensional changes, delamination, corrosion, mold development, staining, degradation of non-moisture resistant materials, efflorescence, and loss of insulating capability (Proskiw 2007). For this research, the affects of moisture on wood durability are a main concern.

3.7.2 BIODETERIORATION OF WOODEN FRAMEWORK

Wood structures, when properly designed, constructed, and maintained, can satisfactorily last for hundreds of years (Bowyer et al. 2003). However, as a naturally produced organic material, wood is subject to biodeterioration including decay and insect infestation, as well as fire and surface weathering. H. J. Hueck (as cited in Allsopp et al. 2004, p. 1) defined biodeterioration as “...*Any undesirable change in the properties of a material caused by the vital activities of organisms.*” Biodeterioration can greatly reduce the useful life of buildings, and therefore needs to be properly addressed. The susceptibility of wood to biodeterioration is significantly increased at moisture contents greater than 20 percent (Bowyer et al. 2003, Lebow and White 2007). Biodeterioration occurs most rapidly at temperatures in the range of 68 to 90 degrees Fahrenheit. Thus, temperatures as they exist within the walls of buildings, depending on the season, can be optimal for biodeterioration to form and progress (Bowyer et al. 2003).

Scheffer (1973) and Morrell (2002) have shown that biodeterioration can occur at moisture contents as low as 20 percent, although most forms of biodeterioration require moisture contents between 40 to 60 percent (Scheffer 1973, Morrell 2002). Many organisms causing biodeterioration have been found to colonize in materials during wet conditions and then adapt to complete their life cycles in dry, low moisture content conditions (Morrell 2002).

3.7.2.1 FUNGI

Fungi deteriorate building materials and can lead to allergic reactions by occupants as well as induce other health problems (Lstiburek and Carmody 1994). Some types of fungi have

been observed to produce mycotoxins, which have been found to be a carcinogenic, teratogenic, immunosuppressive, and oxygenic. The bioaerosols produced by fungi have also been associated with tuberculosis, Legionnaire's disease, humidifier fever, hypersensitivity, pneumonitis, aspergillosis, allergic rhinitis, and viral respiratory infection (Lstiburek and Carmody 1994). Since the fungi kingdom contains a variety of organisms, the most common ways fungi causes biodeterioration within building enclosures is described below.

Fungi are microorganisms that grow on dead organic matter, which constitutes the source of their basic nutrients including nitrogen, sulfur, phosphorus, and potassium (Janinska 2000). Fungi secrete digestive enzymes that break down the substrate that they grow on, allowing the fungi to absorb the nutrients contained in the substrate (University of California Museum of Paleontology 2010). Fungi require hydrogen from a water source as well as oxygen to survive. The basic requirements of fungi are minimal, and researchers have shown that microfungi can develop on completely sterile glass surfaces if traces of organic matter from fingerprints are present (Janinska 2000). Fungi easily contaminate building enclosures since fungal spores are typically prevalent in the atmosphere (Janinska 2000). Mold is an example of a common fungi found in wet building enclosures that grow in the form of multicellular filaments called hyphae (Madigan and Martinko 2005).

3.7.2.2 MOLD

Mold can grow on any organic building material, including paper, adhesives, resins, and wood. In homes, dust alone has been found to provide mold an adequate nutrient source. Mold has been found to thrive at the same temperature range of a typical indoor building environment. Moisture control is the only practical way to control mold growth (Morse and Acker 2009, U.S. Environmental Protection Agency 2008). Water-damaged areas should be dried within 24-48 hours to prevent mold growth (U.S. Environmental Protection Agency 2008).

3.8 PREVIOUS RESEARCH ON MOISTURE WITHIN BUILDING ENCLOSURES

Biodeterioration within building enclosures is of considerable concern to the construction industry. The conditions needed to cause condensation within a building enclosure have been determined as well as where the condensation occurs.

This section reviews past experiments testing heat and moisture transfer through wood frame construction. Previous research has been used to create a unique experiment that examines the impact that insulation has on moisture accumulation within wooden members of a building enclosure. The following sections focus on research designs using environmentally controlled chambers, often referred to as semi-scale hygrothermal design or hot box-cold box design.

3.8.1 SEMI-SCALE HYGROTHERMAL EXPERIMENT METHODOLOGY

Pavlik et al. (2002) designed a measuring system for determination of temperature, moisture, relative humidity, capillary pressure, and salinity profiles in building enclosures. This system can analyze hygrothermal performance of particular materials or the entire building enclosure under specific conditions. The methodology that Pavlik et al. (2002) designed was influenced by the work of several semi-scale experiments that measured temperature and moisture fields, such as the work of Rode et al. (1993), Zheng et al. (1999), Haupl et al. (1999), Ojanen (2000), and Geving and Uvslokk (2000).

3.8.1.1 BASIC DESIGN PRINCIPLES

Pavlik et al. (2002) designed a semi-scale experiment for testing the hygrothermal performance of a building enclosure. The semi-scale experiment uses model of a building enclosure scaled down from the typical size, allowing for experiments to be performed within

laboratory conditions instead of on actual buildings. The temperature and moisture ranges were selected to simulate real conditions while allowing for lower costs compared to testing a real house (Pavlik et al. 2002). Figure 3-4 is a diagram of the basic arrangement of the experiment, which consisted of two climatic chambers imposing conditions of different climates on a sample wall system (Pavlik et al. 2002). The two chambers were connected by a specially developed tunnel that can fit large specimens and simulate two-dimensional flow of temperature and moisture (Pavlik et al. 2002). The construction of the chambers was based on common commercial solutions for controlling temperature and relative humidity conditions. Conditions of the chambers, such as temperature and humidity, were changed to simulate different climates and seasons.

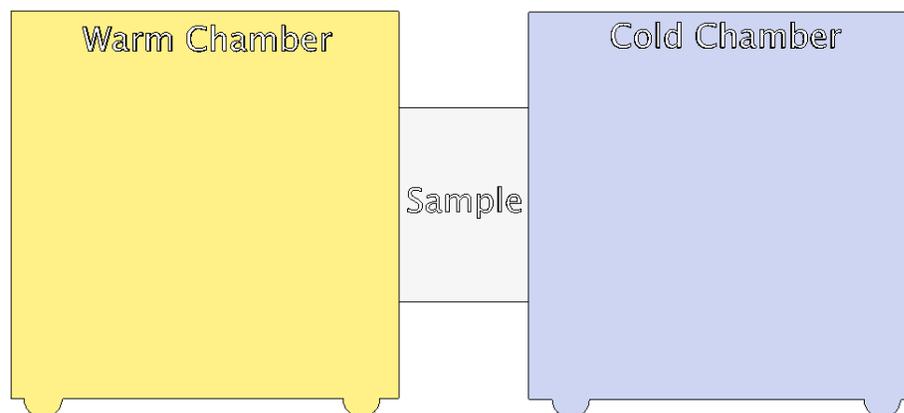


Figure 3-4: Dual climatic chamber set-up allowing two-dimensional flow of temperature and moisture. Both temperature and moisture can be adjusted in each chamber (Pavlik et al. 2002).

3.8.1.2 MOISTURE, RELATIVE HUMIDITY, AND TEMPERATURE MONITORING DEVICES

Pavlik et al. (2002) measured and monitored moisture content, capillary pressure, and temperature. Water content was measured by means of Time-Domain Reflectometry (TDR), a method using electric pulses and measuring them at the input and output. Temperature was measured by means of resistance thermometers and capillary pressure by means of mini-

tensiometers (Pavlik et al. 2002). For measurements of relative humidity and temperature in the porous space, Pavlik et al. (2002) used electronic sensors that logged and saved the data collected. Temperature and humidity sensors provided four channels that can be optionally programmed regarding the following variables: temperature, relative humidity, dew point, partial water vapor pressure or enthalpy. Using the aforementioned measuring devices, Pavlik et al. (2002) was able to plot moisture, relative humidity, and temperature of the chambers and sample materials over a period of time. These moisture, relative humidity, and temperature plots were then used to display the effects of environmental changes on sample materials as variables change.

3.8.2 HOT BOX-COLD BOX DESIGN

A hot box-cold box design was used by Zheng et al. (2004) to investigate corrosion behavior of highly insulated zinc roofing systems. The system used by Zheng et al. (2004) created moisture within a roofing system and a wall section of the building enclosure. The objective of Zheng et al. (2004) was to increase the moisture content of the air within one chamber to cause condensation to form on metal elements that reached the dew point due to the temperature gradient within the building enclosure sample. The hot box-cold box design used the same environmental conditioning methods as the semi-scale hygrothermal design from Pavlik et al. (2002) shown in Figure 3-4.

While Zheng et al. (2004) determined corrosion behavior of nails used in zinc roofing systems, the methodology created moisture accumulation within a building enclosure. Zheng et al. (2004) needed to accumulate moisture within the building enclosure to encourage the corrosion of nails within the zinc roof. Temperature was set at 21 degrees Celsius and relative humidity to 52 percent within the hot box, and 2 degrees Celsius and 88 percent relative humidity in the cold box. The roof sections were exposed to a steady-state environment for 60

or 100 days. At both 60 and 100 days, the moisture content of the timbers were determined and compared between roofing systems with and without an air-vapor retarder. Roofing systems with a perfect air-vapor retarder in place had much lower moisture content than roofing systems without a vapor retarder in place. The vapor retarder kept the moisture content of the system below the critical 20 percent moisture content for biodeterioration to occur. Differences in moisture content between timbers tested for 60 and 100-days were minimal for all tests. The minimal fluctuations resulted from the slight differences in relative humidity within the experimental chambers that was uncontrolled during the testing.

3.8.3 EXPERIMENTAL METHODOLOGY SUMMARY

When measuring heat and moisture transfer through a building enclosure, the most common practice is to place a specimen between two chambers with controlled environments set at specific temperature and humidity values. Controlling the environment on both sides of a building enclosure specimen allows for the calculation of how heat and moisture travels through the enclosure and where moisture will accumulate. Sensors placed within the specimen measure both moisture and temperature at locations desired, thus supplementing the measurement of temperature and moisture movement through the building enclosure.

3.9 MEASUREMENTS AND SENSORS

Experimental methodology to measure the moisture accumulation within a building enclosure was detailed in the last section. This section details common measurements and sensors used during experimentation with heat and moisture transfer through building enclosures. Along with common measurements taken during experiments (i.e. temperature and moisture movement within walls), this chapter will also describe common sensors used to take these measurements. To detect if conditions were susceptible for biodeterioration, sensors need to be placed within the building enclosures tested.

3.9.1 TEMPERATURE MEASUREMENT

Temperature measurements within enclosure systems assessed heat flow, condensation potential, thermal bridging, drying and wetting potentials, and convective loops, among various other potential assessments (Straube et al. 2002). The most common temperature measuring devices are thermocouples, which are rugged and simple, but not accurate and generate low-level signals (micro-volts per degree Celsius; OMEGA 2010a). Platinum resistance temperature detectors (RTDs), or their equivalent microchip-based versions, offer more accurate temperature readings (OMEGA 2010b). RTDs also offer excellent stability and repeatability due to their linear measurement over a wide temperature range (OMEGA 2010b), but are large and have high cost (Straube et al. 2002). In addition, long lead wires add noise to the temperature measurements and the resistance of an RTD may cause slight heating, making short measurement times and thermally heavy sensors preferable (Straube et al. 2002). Thermistors, like RTDs, are resistors that measure the change of their properties with changing temperature to determine temperature (OMEGA 2010c). Thermistors are moderately priced and readily available, but are useable only in a nominal range of 0°C to 100°C (OMEGA 2010c) and induce a small self-heating error due to their high electrical resistance values (Straube et al. 2002).

3.9.2 WATER VAPOR CONTENT

The measurement of water vapor pressure is a fundamental measurement for biodeterioration. However, water vapor is a difficult quantity to measure (Straube et al. 2002). Dew point sensors are typically based on the chilled-mirror approach and allow for the measurement of dew point temperature within $\pm 0.2^\circ\text{C}$ (Straube et al. 2002, Sensors Magazine 2005). Chilled mirror hygrometers operate under a simple principle and have a wide measuring span, high level of precision, and inert construction (Sensors Magazine 2005). The drawback of chilled-mirror dew point sensors is the high cost and the sensors are fragile, easily dirtied, and

difficult to insert into an enclosure without disrupting the natural temperature regime (Straube et al. 2002).

A more practical sensor is a combined relative humidity (RH) and temperature sensor (Straube et al. 2002). Given the RH and temperature, the moisture content and dew point temperature can be easily calculated. Small RH sensors, primarily based on the change of capacitance of a thin film that is directly proportional to the relative humidity of the surrounding environment and accurately measures RH (Sensors Magazine 2001). Small RH sensors require a power supply, produce a high-level linear signal, and are on an order of magnitude less expensive than the chilled mirror devices (Straube et al. 2002). Capacitance based sensors are limited by the distance the sensing element can be located from the signal conditioning circuitry due to capacitive effect of the connecting cable (Sensors Magazine 2001). Due to deterioration of RH sensors induced by water, acidic, or alkaline environments (i.e., concrete and masonry), the long-term accuracy and durability of RH sensors is a concern (Straube et al. 2002).

3.9.3 WOOD MOISTURE CONTENT SENSORS

The moisture content of wood is a fundamental measurement of performance since moisture content indicates the susceptibility to mold and decay (Straube et al. 2002). The moisture content of wood is most commonly measured with electric moisture meters, which are either of the electric conductance (resistance) or the dielectric type (James 1988). Conductance meters use penetrating electrodes while dielectric meters use surface electrodes that do not puncture the wood surface. Resistance meters translate electrical resistance into a moisture content reading while conductance meters translate capacitance or power-loss into a moisture content reading (James 1988).

When using resistance meters, the pins must be installed parallel to the grain in clear wood sections away from knots, splits, resin pockets, visible grain variations, or pockets of

decay (Straube et al. 2002). Furthermore, these meters must be calibrated according to the wood species (Straube et al. 2002; James 1988). Several factors that affect the accuracy of electric moisture meters include specimen characteristics (density, moisture distribution, thickness, and temperature), electrode contact, and chemicals present.

3.9.4 GRAVIMETRIC MOISTURE CONTENT METHODS

One of the most reliable and inexpensive means of measuring moisture content, for wood, or any other porous material, is gravimetric measurement (Straube et al. 2002). The gravimetric method, commonly referred to as the “oven dry method”, consists of calculating the moisture content by means of comparison of the sample’s initial weight versus its oven-dry weight (Bowyer et al. 2003). Thus, moisture content is defined as the weight of the water expressed as a percentage of the moisture-free wood weight (Bowyer et al. 2003). The main challenges in this method are ensuring that the sample is representative of the actual component (Straube et al. 2002). The disadvantage of the gravimetric method is that the specimen must be destroyed or altered from its current state to determine the moisture content. In any case, gravimetric analysis is used as a calibration method for sensors.

3.9.5 MEASUREMENT AND SENSOR SUMMARY

Sensors used for measurement of temperature and moisture commonly use electronic devices that measure the change in resistance or capacitance of a material. A commonality between all sensors in the case of measuring temperature and moisture is that sensor accuracy is highly influenced by the properties of the material measured, which is highly critical when measuring materials with high variability, such as wood. The cost of sensors and their ease of use vary widely, as well. Devices most commonly used are the thermistor for temperature measurement, relative humidity meters for vapor measurement, and a resistance meter for moisture measurement within solid materials.

3.10 LITERATURE REVIEW SUMMARY

Green building construction methods that emphasize resource-efficient design and construction practices are gaining international popularity. Because some green building practices are relatively new, only their short-term effects are known. Without knowledge of long-term effects of green building practices, building methods and materials may be encouraged that cause moisture accumulation within the building enclosure. This potential moisture accumulation within the building enclosure increases risk of decreased structural durability and increased health and safety risks for the buildings' occupants.

Condensation naturally occurs during fluctuating temperatures when water vapor contacts materials whose temperatures are below the vapor saturation point. Wood is a hygroscopic material and thus absorbs moisture from the environment, potentially inducing biodeterioration. Wooden building components are at risk to biodeterioration due to vapor diffusion through the building enclosure causing interstitial condensation within the wall. Vapor diffusion through the building enclosure is dependent on the materials used for the wall structure, as well as the material selected for the insulation. To determine how different types of insulation affects moisture diffusion through the building enclosure, wall sections can be subjected to real environmental conditions simulated by using a combination of two experimental methodologies: semi-scale and hot box-cold box experimental design. The experimental results can be used to determine if insulation materials and methods promoted as being energy efficient and environmentally preferable by green building systems may actually increase wooden building components susceptibility to biodeterioration.

4 RESULTS AND DISCUSSION: IMPACT OF RESIDENTIAL INSULATION ON MOISTURE CONTENT OF WOOD FRAMEWORK

Chapter 4 presents the experimental results from testing stud specimens subjected to winter conditions: a cold exterior and a warm interior environment. Results from these tests will aid in determining if insulation methods encouraged by residential green building standards, such as LEED for Homes (U.S. Green Building Council 2008) and the National Green Building Standard (National Association of Home Builders 2009), cause increased moisture content of the wooden framework within the building enclosure, thereby potentially increasing wooden structures' susceptibility to biodeterioration. Chapter 5 is written in manuscript form to be submitted to the *Journal of Building Physics*.

4.1 ABSTRACT

Green building construction standards recommend the use of a variety of new thermal insulation products. However, the durability of wooden framing used in conjunction with these new insulation materials has not been examined, especially with reference to interstitial condensation. This research compared the moisture content of wood framing with spray-applied polyurethane insulation, cellulose insulation and fiberglass batt insulation to determine if a particular type of insulation caused a greater susceptibility to moisture-related durability of wood wall framing. A single-sided hot-box design that allowed the moisture content of wood framing was measured for 60 days. The average moisture content of framing members surrounded by spray-in polyurethane and spray-in cellulose insulation was greater than was the average moisture content of the framing members surrounded by the fiberglass batts. Spray-in polyurethane insulation can create a vapor barrier that does not allow wooden framing members to dry out. Cellulose insulation absorbs moisture and keeps a moist environment around the

wooden framing member, which decreases the ability of the wooden framing member to dry out. By encouraging the use of spray-applied polyurethane and cellulose insulation materials, the risk of wall-frame durability problems may increase. Spray-applied insulation imperfections were also noted during the experimental phase of this research. These imperfections caused concern that perceived thermal and air-sealing benefits of spray-applied insulation may be overstated.

4.2 INTRODUCTION

Wood-framed structures dominate the U.S. residential construction market due to the availability and favorable economics of wood (American Wood Council 2001). Typically, U.S. residential structures use wooden studs as framing material and wood-based oriented strand-board (OSB) sheathing for strength against vertical and lateral loads. On the interior of the building enclosure, a variety of panel-type materials, such as gypsum, sheetrock, or wood panels are used. These paneling materials are porous materials that allow moisture to migrate through the wall. Insulation is placed in the wall cavity to create a thermal barrier to regulate the building's indoor environment. Thermal insulation limits the transfer of air, moisture, and thermal energy between the interior and exterior environment (Germer 2006). The transfer of thermal energy through the building enclosure by thermal insulation is well documented (Moyers 1971, Hasnain 1998, Zalba et al. 2003). However, the effect of thermal insulation on the movement of moisture through the building enclosure is not as well documented (Treichsel 2001). The effect of thermal insulation and its impact on interstitial condensation is of considerable importance to the durability of a wall's frame as elevated moisture can lead to accelerated decay (Bowyer et al. 2003).

4.2.1 GREEN BUILDING DEFINITION

The U.S. Environmental Protection Agency (U.S. Environmental Protection Agency 2010) defines green building as, “*the practice of creating and using healthier and more resource-efficient models of construction, renovation, operation, maintenance and demolition,*” while Kibert (2005) defines a green building as a building with unique qualities and characteristics emphasizing principles and methodologies of building with a minimal effect upon the ecosystem. The U.S. Green Building Council (2008), in another definition, defines green building practices as those that “*reduce the negative impacts of buildings on occupants and the environment.*” The U.S. Green Building Council (2008) lists the following categories to be addressed in, including sustainable site planning, safeguarding water, energy efficiency and renewable energy, conservation of materials and resources, and indoor environmental quality. Green building, for the purpose of this paper, is defined as construction with reduced impact on the ecosystem throughout a building’s life by means of efficient design.

4.2.2 INSULATION AND BUILDING PHYSICS

Energy efficiency and conservation are important considerations in green building standards and green building guidelines encourage insulation practices to increase the energy efficiency of structures (U.S. Green Building Council 2008, National Association of Home Builders 2009). In a typical residential building, a majority of energy loss occurs when heat transfers through the building enclosure (Germer 2006, National Association of Home Builders 2009, U.S. Green Building Council 2008). The most effective way to minimize heat conduction through a building’s enclosure is by using thermal insulation in the wall cavities that have direct contact with the outside element conditions (Germer 2006, National Association of Home Builders 2009, U.S. Green Building Council 2008). Insulation material creates a thermal barrier between the interior and exterior environment by filling the wall cavity with small, separated air pockets, thereby limiting heat transmission (Germer 2006, Lstiburek and Carmody 1994).

Thermal insulation also has an important impact on air and moisture movement through the building enclosure (Lstiburek and Carmody 1994).

When a moisture differential is present between the indoor and outdoor environments of a structure, water vapor moves through the building enclosure by diffusion, unless prevented by a vapor barrier. The vapor diffusing through a structure can condense and collect on materials that are at or below the dew point, causing interstitial condensation (Lstiburek and Carmody 1994). In the building enclosure, the most common location for interstitial condensation is the interface between the exterior sheathing and the insulation. Liquid condensation at the wall interface is then absorbed by the surrounding wooden framing and insulation materials (Germer 2006, Lstiburek and Carmody 1994). In cold climates, vapor will often condense in the form of frost, which melts when the sheathing temperature rises creating a cyclical process that can cause liquid moisture to be absorbed into building enclosure materials (Lstiburek and Carmody 1994).

When water is absorbed into the insulation material, water replaces the air entrapped within the insulation, reducing the insulation material's thermal resistance characteristics since water has a lower thermal resistance than air (Nisson and Wilson 2008; Lstiburek and Carmody 1994). Wet insulation is heavier than dry insulation, which can also cause the insulation to collapse and settle within the wall cavities (Lstiburek and Carmody 1994). Moist insulation introduces the risk of biodeterioration in the surrounding wooden frame members through creating a lasting moist environment.

Hueck (as cited in Allsopp et al. (2004)) defined biodeterioration as “*any undesirable change in the properties of a material caused by the vital activities of organisms.*” Increased moisture within wooden materials increases the susceptibility to biodeterioration, especially when the moisture content of the wood exceeds 20 percent (Bowyer et al. 2003). Once

biodeterioration organisms have colonized a wooden member, these organisms can adapt to complete their lifecycles in drier, lower moisture content conditions (Morrell 2002). Thus, the damage from biodeterioration can continue after a wooden member dries.

4.2.3 INSULATION MATERIALS

Specific building insulation details depend on geographic location (ICC 2009). The standard index for rating insulation is called R-value, the ability of material to resist heat flow by conduction (Nisson and Wilson 2008). Units of R-value are given in $\text{ft}^2 \cdot \text{F} \cdot \text{h} / \text{BTU}$ and the SI-unit of $\text{m}^2 / \text{W} \cdot \text{C}$, (Germer 2006). Materials with higher R-values are preferable to use as insulation due to their ability to reduce thermal conductivity through the building enclosure. Widely used forms of residential insulation materials include fiberglass, mineral wool, vermiculite, cellulose, polystyrene, polyisocyanurate and polyurethane foam (Germer 2006, Nisson and Wilson 2008). All of these insulation materials have low thermal conductance values (e.g., high R-values) that impede thermal transmission. Green building standards in particular emphasize three forms of insulation: fiberglass, spray-applied polyurethane, and spray-applied cellulose (National Association of Home Builders 2009, U.S. Green Building Council 2008).

Fiberglass is the most common form of insulation used in residential buildings in the U.S. with a market share of approximately 90 percent (Nisson and Wilson 2008) due to low cost of thermal resistance per unit thickness. Batts are typically friction fit into cavities or stapled to framing if faced with kraft paper. However, neither installation method produces a reliable air seal and fiberglass batts perform poorly in preventing air from transferring through the building enclosure, potentially resulting in substantial energy loss (Nisson and Wilson 2008). However, fiberglass insulation does allow for higher moisture diffusion potential due to its large interconnected volumes of air (Germer 2006). Green building focuses on insulation materials

that form a better air seal and offer increased R-values have gained popularity (Department of the Interior 2011).

Superior insulation performance stipulated in green building standards has made spray-applied polyurethane and cellulose insulation popular (National Association of Home Builders 2009, U.S. Green Building Council 2008). Spray-applied forms of insulation, though typically more expensive to buy and install, are replacing traditional fiberglass batt insulation. Spray-applied insulation offers benefits such as the ability to completely fill the wall cavities, the elimination of the majority of air infiltration and exfiltration (Lstiburek and Carmody 1994), and higher thermal resistance per unit thickness of material (Germer 2006). However, besides the higher price, spray-applied insulation materials are at risk of settling when applied and potentially emit volatile organic compounds (VOCs, U.S. Department of Energy 2009). Also, though some forms of spray-applied polyurethane emit VOCs, it is still encouraged by green building standards because of the increased energy performance of these materials (Department of the Interior 2011). Additionally, spray-applied insulation, while offering improved thermal resistance and reduced air infiltration, also reduces the ability of moisture to be removed from the building enclosure. Fiberglass batt insulation lacks the capillary action that is characteristic of porous spray-applied insulation materials (Lstiburek and Carmody 1994).

The emergence of green building standards has changed insulation practices over the past few years. For example, as spray-applied insulation is rewarded with higher green building credits (National Association of Home Builders 2009, U.S. Green Building Council 2008) than, for example, fiberglass batt insulation due to higher R-values and the air sealing resulting from prevention of air infiltration and exfiltration (U.S. Green Building Council 2009), builders have made more frequent use of them. However, questions as to the impact of spray-applied insulation in regards to moisture movement through the wall and moisture accumulation inside

the walls remain unanswered. Observations have shown possible moisture-related damage due to spray-applied insulation, such as increased mold growth (Anonymous 2008). No research was found that measured the moisture content of wood framing in wall systems. This paper examined the change in moisture content of wood framing in a wall due to application of different insulation materials.

The resulting moisture content of the wood framing was compared with different insulation materials in a building enclosure subjected to winter-like conditions of below freezing temperatures on the exterior of the building enclosure with approximate 70 degree Fahrenheit temperatures on the inside of the building enclosure. In this study, moisture content differences within wooden framework used in building enclosures insulated with contemporary spray-applied insulation (polyurethane or cellulose-based) were compared to building enclosures insulated using traditional fiberglass batts.

4.3 METHODOLOGY

To determine differences in moisture content of the wood framing with different insulation, a series of wall sections were constructed. These wall sections were then subjected to simulated winter conditions with a cold exterior and a warm interior environment. A modified single-sided hot box was constructed to provide a temperature differential. The moisture content of stud specimens inside the different sections were compared. Insulation used included fiberglass batts, spray-applied cellulose, and spray-applied polyurethane foam.

4.3.1 EXPERIMENTAL CONDITIONS AND CHAMBERS

To simulate winter conditions on a wall section, a widely employed hot box-cold box arrangement was used. Hot box-cold box design subjects enclosure building section to controlled environments on both sides. Pavlik et al. (2002) designed an experiment that used a scaled down building enclosure allowing experiments to be performed within laboratory

conditions instead of on an actual building. The basic design created by Pavlik et al. (2002), which consisted of two climatic chambers imposing conditions on different sides of a sample wall system, is shown in Figure 4-1 (Pavlik et al. 2002). The two chambers were connected by a specially developed tunnel that can fit large specimens and simulate real-world temperature and moisture conditions (Pavlik et al. 2002). The construction of the chambers was based on common commercial solutions for controlling temperature and relative humidity conditions. Conditions of the chambers, such as temperature and humidity, simulated different climates and seasons. When two climatic chambers are impractical, a single-sided hot box design is acceptable option to test building enclosure materials as performed by Zheng et al. (2004).

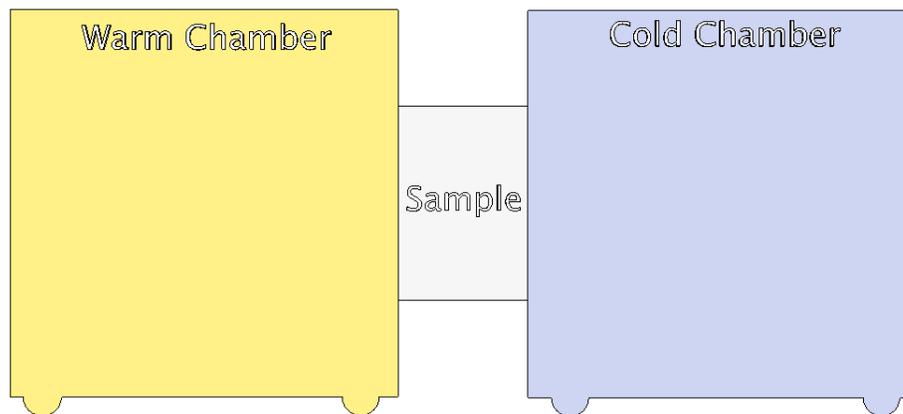


Figure 4-1: Dual climatic chamber set-up allowing two-dimensional flow of temperature and moisture. Both, temperature and moisture can be adjusted in each chamber (Pavlik et al. 2002).

Based on Pavlik et al. (2002), Zheng et al. (2004), Kudder et al. (2005), Lstiburek and Carmody (1994), and ASTM C1363 - 05 (American Society of Testing Materials 2005), two 60-day single-sided hot box experiments were performed using a conditioned laboratory and two freezers to create the temperature differential needed to measure the moisture content of wooden framework and different insulation materials. Warm side conditions were set to 70 (± 10) degrees Fahrenheit and 30 (± 10) percent relative humidity based on Zheng et al. (2004). Cold side conditions were 0 (± 10) degrees Fahrenheit with no regulation of relative humidity. To

create the cold side conditions, two 14.1 cubic foot upright freezers (Frigidaire freezers, 2009 model LFFU14240W) were used. Warm side conditions were maintained by the building HVAC system within the Microtechniques Laboratory located at the Brooks Forest Products Center at Virginia Tech. Wall sections were attached to the door openings of the freezers, creating a hot box-cold box design (Zheng et al. 2004). The two freezers were calibrated during a one month preliminary test, with the thermostat settings adjusted to achieve an average of 0 (± 10) degrees Fahrenheit temperature range within each freezer. To stabilize temperature fluctuations within each freezer, 48 red clay bricks (total mass approximately 275 lbs) were included as thermal mass. The red clay bricks measured 8 inches by 4 inches by 2 ¼ inches, with an approximate density of 0.08 pounds per cubic inch.

The average, minimum, maximum, and standard deviation of temperature and relative humidity within the two freezers and the laboratory during the experiment is shown in Table 4-1. The maximum temperatures in both freezers were exceeded for short periods of time due to changing sensor batteries and adjusting the freezer thermostat. However, the low standard deviation (all values less than or equal to 3.23) for the temperature in both freezers shows that the duration of non-compliance was brief and should not affect the results.

Table 4-1: Descriptive statistics for the actual environmental conditions of the freezers and laboratory conditions as well as the targeted temperature and humidity parameters.

		FREEZER TARGET	FREEZER 1	FREEZER 2	LAB TARGET	LAB
Temperature	Min	-10.00	-6.01	-4.41	60.00	71.00
	Avg	0.00	-2.17	-0.20	70.00	72.80
	Max	10.00	46.10	11.30	80.00	77.10
	Std Dev		2.98	3.23		0.33
Relative Humidity	Min	-	26.0	32.9	20.0	14.8
	Avg	-	32.0	37.2	30.0	30.6
	Max	-	82.8	80.3	40.0	50.7
	Std Dev		2.18	3.14		7.30

- Dashes indicate parameters that were unregulated by design

The temperature within the Microtechniques Laboratory during the experiment was within the targeted tolerances (Table 4-1). Though thermostatically controlled, the laboratory was not controlled for relative humidity. Relative humidity measurements exceeded both minimum and maximum tolerances yielding a moderate standard deviation. Despite the variation of the relative humidity during the experiment, the fluctuations remained balanced and resulted in an average relative humidity that was close to the targeted value of 30 percent.

4.3.2 WALL SECTION SPECIMENS

Figure 4-2 is a diagram of the building enclosure sections used in this research project. Each building enclosure section contained two separate insulation materials in subsections divided between the top and bottom halves of the building enclosure section (Figure 4-2). To separate the top and bottom halves of the building enclosure section, two stud plates were separated by 2 inch extruded foam insulation (approximate thermal resistance of R-4 per inch). Each top and bottom half had a center stud specimen placed 14 inches on center. Each stud specimen was fitted with 3 wireless sensors: one on the warm side of the stud and two on the cold side of the stud as shown in Figure 4-2.

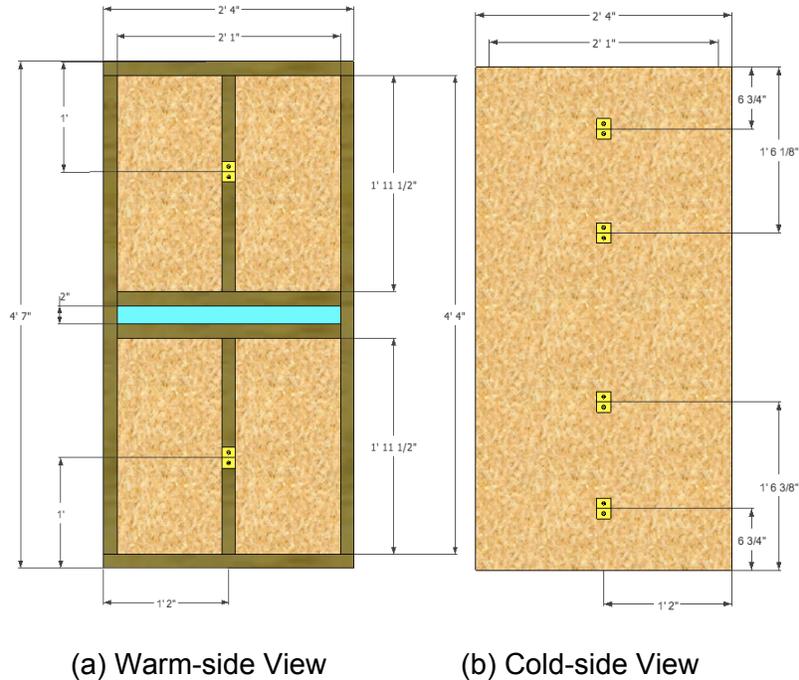


Figure 4-2: Schematic warm (a) and cold (b) side drawing, respectively shown, of the building enclosure sections with sensor location (on center stud vertically)

The materials used to construct the building enclosure sections are listed in Table 4-2. All 2x4 lumber was No. 2 grade spruce that was kiln-dried and heat-treated. The sheathing used was 19/32 inch oriented strand board (OSB). All wood materials were purchased together and conditioned in the Microtechniques Laboratory located at the Brooks Forest Products Center at Virginia Tech for 21 days. To build the framework and to attach the sheathing, 12d coated sinkers (3-1/8" long) were used. To isolate the top and bottom stud specimen of the building enclosure sections, extruded foam board was used. The fiberglass insulation was standard batt insulation sold at home improvement retailers, and was installed per the accompanying installation instructions. A professional contractor from the Blacksburg, VA region applied the spray-applied cellulose and polyurethane insulation. The building enclosure sections were built without any exterior cladding due to the insignificant influence of cladding for

this particular experimental design (Lstiburek and Carmody 1994). The R-value per inch of each insulation material is shown in Table 4-2.

Table 4-2: Specifications of materials used.

MATERIAL	SPECIFICATIONS
2x4 Lumber	No. 2 common grade spruce (<i>pinea spp.</i>); kiln-dried; heat-treated
Oriented Strand Board (OSB)	Georgia-Pacific Blue Ribbon OSB; 19/32" sheathing
Nails	12d coated sinkers; 3-1/8" long
Extruded Foam Board	Dow R-3.3 polyisocyanurate rigid foam insulated sheathing
Fiberglass	Owens Corning: PINK Fiberglas; 15" wide by 3-1/2" thick; R-13 (approximately R-3.71 per inch) (Owens Corning 2010)
Cellulose	Advanced Fiber Technology Loose-fill Cellulose; R-3.80 per inch (Advanced Fiber Technology 2010)
Polyurethane Spray	AirTight Open Cell Insulation; R-3.9 per inch (ICC Evaluation Service 2009)

The placement of insulation within each building enclosure section for each freezer is shown in Table 4-3. To ascertain differences in experimental results between the top and bottom subsections of the building enclosure sections, the building enclosure section on Freezer 1 was insulated with fiberglass at both positions. The second building enclosure section on Freezer 2 was insulated using spray-applied polyurethane foam in the top position and spray-applied cellulose on the bottom position. The setup design allows for stud specimen insulated with each form of spray-applied insulation (Freezer 2) to be compared to a stud specimen similarly located and insulated with fiberglass (Freezer 1).

Table 4-3: Placement of insulation materials for testing.

POSITION	FREEZER 1	FREEZER 2
Top	Fiberglass	Polyurethane
Bottom	Fiberglass	Cellulose

Figure 4-3a and Figure 4-3b are photographs of the building enclosure sections insulated with fiberglass insulation on both top and bottom sections (Freezer 1) as used in this

research. The three clamps attached the building enclosure sections to the freezer. The interior view (Figure 4-3b) shows the gasket used to create an airtight seal around the building enclosure section and the freezer. The gasket is an OEM gasket taken from the original door of the freezer, and attached to the OSB sheathing with wood screws and washers.

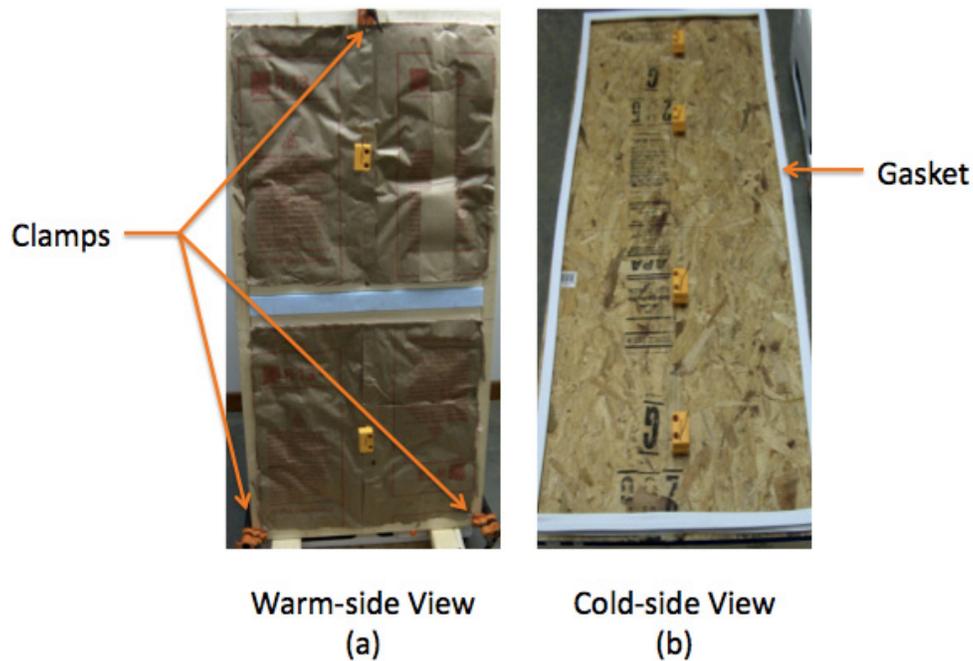


Figure 4-3: Final setup pictures of the building enclosure section insulated with fiberglass batt insulation.

4.3.3 MEASUREMENTS

Continuous temperature, relative humidity, and wood moisture content measurements were taken using Omnisense wireless sensors (Omnisense 2010). The wood moisture content was determined using a resistance meter that could not be calibrated for specific gravity differences. Specific gravity calibrations of the Omnisense wireless sensors were conducted post-hoc and adjustments were made to the raw data.

Two Omnisense sensors were attached to the cold side of the building enclosure section (Figure 4-3b), passing through the OSB to measure the moisture content of the wooden stud on

the cold side of the building enclosure specimens. These sensors were located 6 3/4" and 18 3/8" from the top (or bottom) of the assembly (Figure 4-3b). On the warm side, one sensor was attached at the middle of the center stud, or 12" from the top or bottom of the stud specimen (Figure 4-3a).

After the experiment proceeded for 60-days, the building enclosure sections were disassembled to destructively measure the final moisture content of the stud specimens. The stud specimens were removed from the enclosure and were cut into approximate one inch cubes, then weighed and oven-dried to determine moisture content according to ASTM D 4442 (ASTM 2007). The moisture content values from the oven-dry test were then compared to the final Omnisense sensor moisture content values. Once verified by the oven-dry method, the moisture content measurements of the wooden framework were used to compare the different spray-in insulation forms with the fiberglass insulation.

4.3.4 PREFACE TO DATA ANALYSIS

A complete random block design could not be completed for this experiment, so equivalent testing conditions for each building enclosure section were ascertained using statistical comparisons of freezer temperature, laboratory temperature, laboratory relative humidity, and moisture content of wooden framework for all different building enclosure sections tested. Relative humidity was not considered a test value since the experimental results would only be influenced if a pressure differential existed between the different sides of the wall. The absence of forced air movement within the freezers indicated that no such substantial pressure differential existed and relative humidity within the freezers was not monitored.

4.4 RESULTS AND DISCUSSION

Results from the comparison of the wooden studs moisture content within sections of walls utilizing different forms of insulation are presented and discussed below.

4.4.1 ANALYSIS OF ENVIRONMENTAL CONDITIONS

Figure 4-4 is a graph of the daily average cold side temperatures of the two freezers as the average of the four wireless sensors versus time. Slightly different temperatures between the cold side temperatures within the freezers were observed. Freezer 1 averaged -2.17 degrees Fahrenheit, while Freezer 2 averaged -0.20 degrees Fahrenheit. Both results were within the tolerances for this experiment. The laboratory temperature remained within a tolerance of $\pm 3^{\circ}\text{F}$ and averaged 72.80 degrees Fahrenheit for the duration of the experiment.

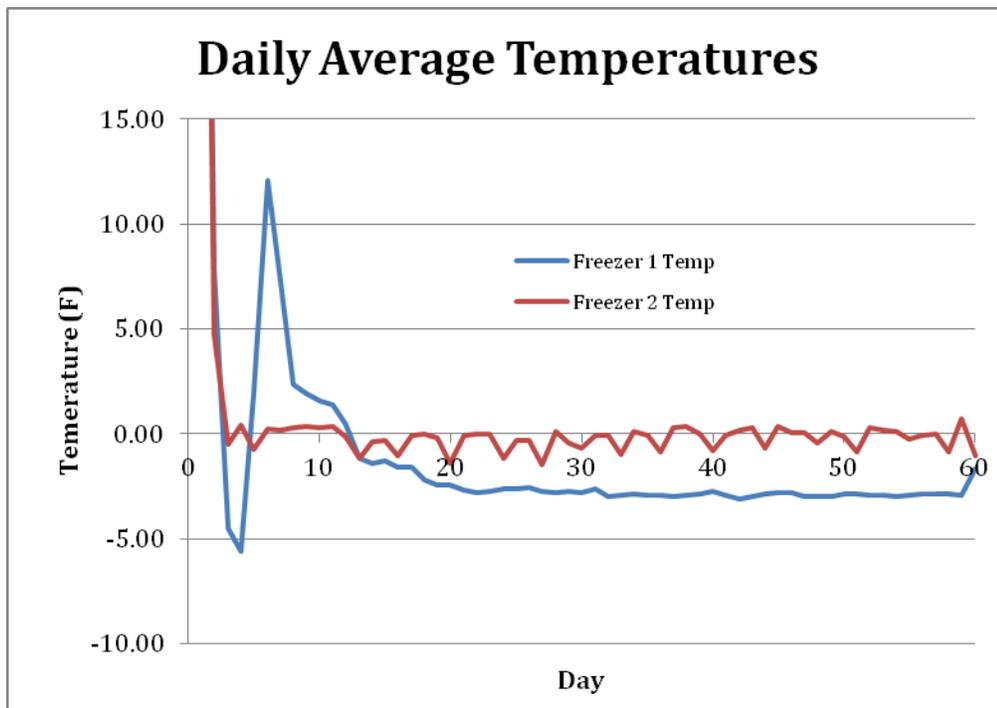


Figure 4-4: Average daily cold side temperatures during the 60-day experiment.

The large temperature change for Freezer 1 between day 3 and day 12 (Figure 4-4) in the sensors was caused by poor battery strength of the sensors. After low battery strength in the sensors on day 4, the building enclosure section was removed and new batteries were installed. The decrease in temperature was due to poor battery strength from the extreme cold condition, and the high spike in temperature was the result of removing the building enclosure section.

A one-way analysis of variation (ANOVA) statistical analysis was performed to determine the equivalency between temperatures for both freezers. Based on the consistent performance of Freezer 1 after the resolution of this problem, the battery issue did not affect these tests. However, significant differences in daily mean cold side temperatures over the complete length of the experiment were found, as shown in Table 4-4.

Table 4-4: Comparison of daily mean cold side temperatures for the two freezers and the two positions ($\alpha = 0.05$).^{1,2}

p-values	Position	Freezer1		Freezer 2	
		Top	Bottom	Top	Bottom
Freezer 1	Top				
	Bottom	0.1524			
Freezer 2	Top	0.063	<0.0017		
	Bottom	<0.0017	0.6995	0.0019	

¹**Bold text denotes p-values that indicate significantly different freezer temperature means.**

²**Shaded cells denote repetitive tests**

The p-values from one-way ANOVA test for the daily mean cold side temperatures for Freezers 1 and 2 in the top and bottom positions at an alpha (α) of 0.05 were shown in Table 4-4. No significant differences in daily mean cold side temperature were found between the equivalent sections of both freezers (Top Freezer 1 vs. Top Freezer 2, $P=0.063$; Bottom Freezer 1 vs. 2, $P=0.6995$). However, significant differences were discovered between the top versus the bottom of Freezer 2 (p-value = 0.0019). This is likely attributed to the natural temperature gradient that occurred within the freezers due to lack of air circulation. Because of the significant temperature differences, comparisons between the insulation sections tested at the top and bottom positions were not conducted.

The p-values from a one-way ANOVA test of the daily mean warm side temperatures for Freezers 1 and 2 top and bottom positions at an alpha (α) of 0.05 are shown in Table 4-5. The daily mean warm side temperatures for Freezer 1 top and Freezer 1 bottom were not significantly different (p-value=0.0720). However, all other temperature comparisons were

significantly different ($\alpha \leq 0.05$). Therefore, the only comparable insulation sections were in the top and bottom positions of Freezer 1 (e.g., comparing fiberglass insulation to fiberglass insulation used on Freezer 1). Since such a comparison was not the goal of this study, further analysis of the daily mean laboratory temperature data was performed to determine possible causes of statistical differences between the daily mean laboratory temperature subjected to the building enclosure specimen.

Table 4-5: Comparison of daily mean warm side temperatures for different freezers and positions ($\alpha = 0.05$).^{1,2}

p-values	Position	Freezer 1		Freezer 2	
		Top	Bottom	Top	Bottom
Freezer 1	Top				
	Bottom	0.0720			
Freezer 2	Top	<0.0001	<0.0001		
	Bottom	<0.0001	<0.0047	<0.0001	

¹Bold text denotes p-values that indicate significantly different laboratory temperature means.

²Shaded cells denote repetitive tests

Though the warm side temperatures were found to be significantly different for all comparisons except Freezer 1 top versus Freezer 1 bottom (Table 4-5), all daily warm side temperatures were within a tolerance of ± 1 degree Fahrenheit as set by the experiment's design. The mean daily warm side temperatures between like positions were within 0.63 degrees Fahrenheit for the top and 0.31 degrees Fahrenheit for the bottom with similar standard deviations as shown in Table 4-6. Because the tolerance of ± 1 degree Fahrenheit was deemed acceptable, a comparison of the building enclosure sections at the same position on each freezer (e.g., top Freezer 1 with top Freezer 2; bottom Freezer 1 with bottom Freezer 2) were conducted.

Table 4-6: Daily mean warm side temperatures for the two freezers and positions.

LAB TEMPERATURE (°F)	TOP		BOTTOM	
	Mean	Std Dev	Mean	Std Dev
Freezer 1	72.56	0.38	72.68	0.34
Freezer 2	73.19	0.32	72.99	0.36
Difference	0.63		0.31	

Figure 4-5 is a graph of the daily average warm side relative humidity of the building enclosure for the 60-day test duration. The daily average warm side relative humidity used the average of all eight sensors located on the warm side of the building enclosure sections. Because the relative humidity of the laboratory was uncontrolled, the relative humidity was quite variable during the experiment. Generally, the average relative humidity decreased as the experiment progressed from November to December. Due to the variance in relative humidity, a statistical analysis was performed to determine the equivalency of environmental conditions between freezer positions.

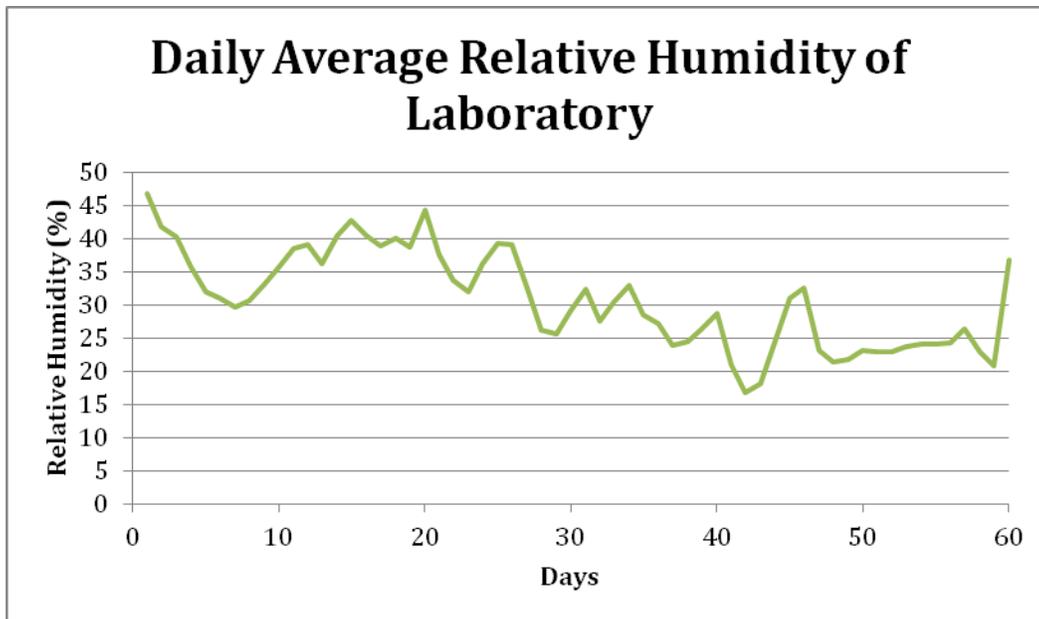


Figure 4-5: Average daily relative humidity of the laboratory subjected to the inside surface of the building enclosure sections for the duration of the experiment.

A one-way ANOVA test was conducted to compare the relative humidity at each stud specimen. The p-values of the daily mean laboratory relative humidity for Freezer 1 and 2 in the

top and bottom positions are shown in Table 4-7. Due to the close proximity of specimens in the same conditioned environment, none of the comparisons were significantly different. The relative humidity does not limit the comparison of insulation sections. Based on comparisons of the cold side temperature, the warm side temperature and the warm side relative humidity, the building enclosure samples in similar positions on each freezer (i.e., top freezer 1 vs. top freezer 2) can be compared.

Table 4-7: Comparison of daily mean warm side relative humidity for different freezers and positions ($\alpha = 0.05$).^{1,2}

p-values	Position	Freezer 1		Freezer 2	
		Top	Bottom	Top	Bottom
Freezer 1	Top				
	Bottom	0.745			
Freezer 2	Top	0.2435	0.4679		
	Bottom	0.4679	0.461	0.4989	

¹**Bold text denotes p-values that indicate significantly different laboratory relative humidity means.**

²**Shaded cells denote repetitive tests**

4.4.2 MOISTURE CONTENT OF WALL FRAMING

Figure 4-6 is a graph of the average daily moisture content readings for each stud specimen during the 60-day experiment. Note the variation in initial moisture content of each of the specimens in Figure 4-6. The intrinsic variability of the wood moisture content may explain some moisture content variation between the stud specimens, but the application methods for each insulation type may be related to these changes. Polyurethane and cellulose insulation were applied wet and initial moisture was absorbed into the stud specimens. Disregarding the errant readings from the last three days experimentation, the average moisture content of each stud specimen remained stable after the initial 15 days, which is likely due to the acclimation of each stud specimen to the experimental environment.

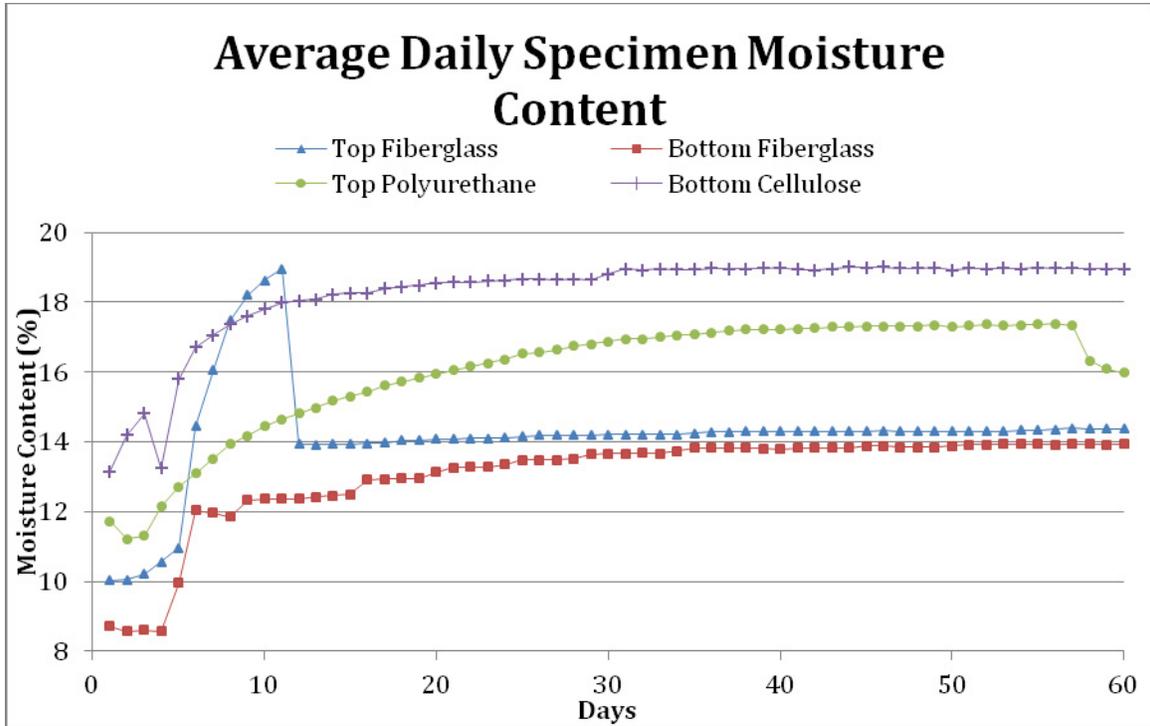


Figure 4-6: Daily average cold side moisture content for each insulation measured during the 60-day experiment

The sensor error induced by the low battery problem between day 4 and day 12 of the top fiberglass stud specimen discussed previously is shown in Figure 4-6, which also includes the moisture content of the test specimens stabilized before day 60 of the experiment. The top polyurethane section shows errant readings for the last three days of the experiment (days 58 through 60) due to data transmission error by the wireless sensor caused by a low battery. Though the low battery caused errant data, the top polyurethane section did stabilize before this battery issue. Disregarding the errant readings from the last three days of the top polyurethane section, the average moisture content of each stud specimen remained stable.

The cold side moisture content readings of the stud specimens from day 50 through day 60 are shown in Table 4-8. The average moisture content and standard deviation calculated for each specimen for days 50 through 60 are shown in Table 4-8. The moisture content appeared to stabilize before day 60 of the experiment. Using the calculated standard deviation and

number of measurements, none of our samples deviated more than plus or minus 0.026 percent moisture content with a 99 percent confidence ($\alpha=0.01$). Because there was little deviation in the moisture content of the stud specimen, stud specimens were found to reach stabilized moisture content after 50 days of experimental conditioning.

Table 4-8: Daily moisture content readings from stud specimen from day 50 through day 60.¹

DAY	FIBERGLASS BOTTOM (MC%)	FIBERGLASS TOP (MC%)	POLYURETHANE (MC%)	CELLULOSE (MC%)
50	14.31	13.89	17.29	18.92
51	14.31	13.92	17.33	18.98
52	14.31	13.92	17.36	18.96
53	14.31	13.93	17.34	18.97
54	14.33	13.93	17.35	18.96
55	14.33	13.93	17.36	19.00
56	14.35	13.92	17.39	18.98
57	14.39	13.93	17.33	18.97
58	14.38	13.93	-	18.96
59	14.38	13.91	-	18.95
60	14.38	13.93	-	18.96
Average	14.34 ²	13.92 ²	17.34	18.96
Standard Deviation	0.033	0.013	0.029	0.020
99% Confidence Interval	0.026	0.010	0.022	0.016

¹Errant readings from day 58 through day 60 of the polyurethane were assumed errant and not included in the average and standard deviation calculations.

² Combined average of fiberglass = 14.13% MC

Based on the observation of moisture content stabilization before completion of the 60-day experiment, the length of experiment could be reduced by 10 days without affecting the final moisture content of the framing specimen using the methods performed during this experiment. According to the *Wood Handbook: Wood as an Engineering Material* (U.S. Department of Agriculture 1999), the equilibrium moisture content of wood subjected to conditions like those in the experimental design (30-40 degrees Fahrenheit, average 30% relative humidity) ranged from 6.31% to 6.33%. The average moisture content of the wood samples used surpassed the

equilibrium moisture content. Therefore, the experimental conditions and materials used did cause increased moisture content in the stud specimens.

The average moisture content of the wood frame specimens measured at the sheathing/insulation interface over the entire 60 days insulated with either spray-applied polyurethane, spray-applied cellulose or fiberglass is shown in Table 4-9. The values were tested using one-way analysis of variance (ANOVA) and Tukey-Kramer honestly significant difference (HSD) testing (JMP Statistical Software 2009). The moisture content of the framing samples insulated with cellulose and polyurethane were significantly greater than the equivalent framing samples insulated with fiberglass. These results reflect the hygroscopic properties of cellulose and polyurethane foam and the inability of these materials to easily release moisture away from the stud specimen.

Table 4-9: Average cold side moisture content percentages of framing samples insulated with different forms of insulation ($\alpha = 0.05$).

Moisture Content of Top Samples	Cellulose	Fiberglass	p-value	T-K HSD
	18.27%	14.20%	0.0003	0.9201
Moisture Content of Bottom Samples	Polyurethane	Fiberglass	p-value	T-K HSD
	16.01%	13.03%	<0.0001	4.7886

Significant differences between both pairs of comparisons made for the average daily moisture content of the fiberglass batts and spray-applied cellulose at the top ($p=0.0003$; Tukey-Kramer HSD=0.9201) and the average daily moisture content of the fiberglass batts and spray-applied polyurethane insulation ($p<0.0001$; Tukey-Kramer HSD=4.7886). Both spray-applied polyurethane and spray-applied cellulose cause higher moisture content within wooden wall framing than framing insulated with traditional fiberglass batts.

The use of insulation materials recommended by green building standards may lead to increased moisture content of wooden framing. However, though the moisture content of the stud specimen increased for the polyurethane and spray-applied cellulose, none of the stud

specimens had moisture content values greater than the 20 percent value generally accepted as the threshold for biodeterioration (Boyer et al. 2003).

4.5 ADDITIONAL OBSERVATIONS

During these tests and at the disassembly of the specimens, observations of the building enclosure specimens were made. At the end of the 60-day experiment, ice accumulation was observed at the sheathing/insulation interface of all insulation materials. The ice accumulation was measured to be about one inch thick at the thickest point for each form of insulation tested in this experiment.

Voids occurred between the frame and the spray-applied cellulose insulation. Figure 4-7 is a photograph of these voids. Such voids are important as they allow air to circumnavigate the insulation thereby reducing the thermal insulation capability of the wall segment. Voids not only reduced the thermal resistance of insulation, but also allowed moist air to bypass the insulation and condense on the sheathing, thereby causing wetting of the insulation. It is possible that material properties, such as insulation shrinkage or settling caused the voids. Another possibility may include installation practices, such as installing insulation against wooden framework with too high or low a moisture content. The cause of these voids in this experiment is undetermined, and should be the subject of future studies to determine if this is a material or installation flaw.

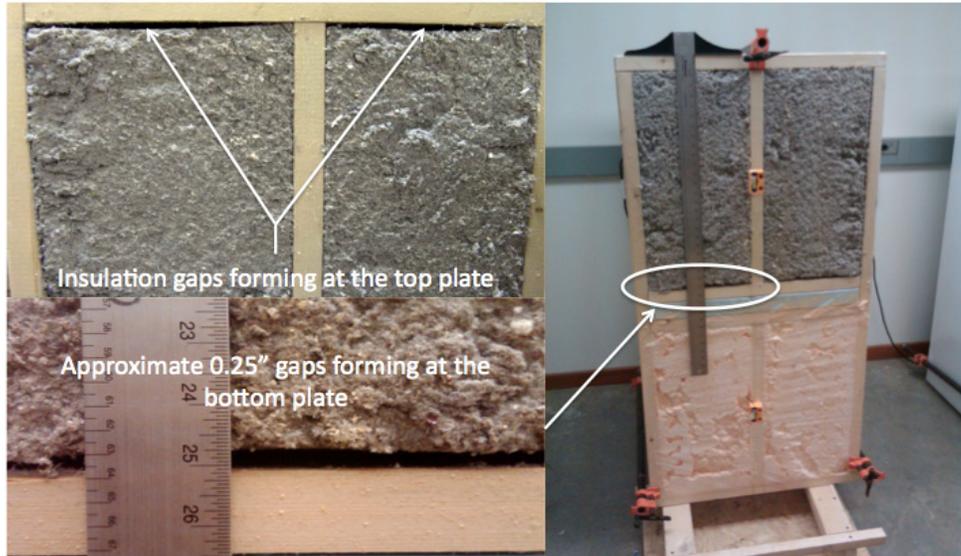


Figure 4-7: Images of voids formed by spray-applied cellulose insulation after cure.

Voids were also observed with the spray-applied polyurethane insulation. Unlike the voids that occurred with the cellulose insulation at the framing/insulation interface, these voids in the spray-applied polyurethane insulation occurred near the sheathing/insulation interface. Figure 4-8 is a picture of the cross section of the building enclosure sample insulated with spray-applied polyurethane insulation. The voids occurred throughout the middle region of the sections insulated with the spray-applied polyurethane insulation. The cause of this void could not be determined, but the void was observed as being filled with ice. The impact of the void on thermal and hygrothermal properties was not substantiated within this experiment, but it likely influences the efficiency of the insulation.



Figure 4-8: Image of the void that occurs near the sheathing/insulation interface in the spray-applied polyurethane insulation

4.5.1 REAL WORLD CONSIDERATIONS OF TEST PROTOCOL

The stud specimen should be further studied to determine if the specimen reached the maximum moisture content possible when used with the given insulation materials, or if the stud specimen was prevented from adsorbing moisture due to ice formation at the sheathing/insulation interface. Without the cyclical temperature swings that building enclosures are realistically subjected to (Lstiburek and Carmody 1994), an insulation-like layer of ice accumulated over time due to the lack of a thaw when the temperature rises. Without the opportunity for a thaw period, the ice layer likely inhibited the ability of the hygroscopic wood to adsorb moisture. Theoretically, cyclical temperatures would cause this ice layer to freeze and thaw, and likely allowing the stud specimen to adsorb increased moisture content.

As the accumulation of ice formed a thickening layer at the sheathing/insulation interface, the temperature gradient was altered. Ice accumulation would cause moisture near the sheathing/insulation interface to freeze, which could prevent liquid moisture from contacting the wooden framework. For a majority of residential structures in the US, conditions like the ones used in this experiment (60 days of constant 0 degree Fahrenheit weather) represent extreme condition. Theoretically, real world conditions would consist of fluctuating cyclical temperatures, with the sun warming up building components during daylight hours. This cyclical

temperature may allow for the thawing of ice, increasing the amount of liquid moisture in contact with the wooden framework. Increased liquid moisture would likely cause the wood to absorb more moisture, possibly up to fiber saturation of approximately 30 percent moisture content (USDA 1999), if subjected to a cyclical freezing and thawing of water vapor within the building enclosure.

4.6 CONCLUSIONS

This study examined the effect of different insulation types have on the moisture content of wood framing within a wall assembly. Spray-applied cellulose and spray-applied polyurethane insulation both increased moisture content within the wooden framing compared to traditional fiberglass batts. During the 60-day period of this experiment, none of the framing specimens reached the 20 percent moisture content recognized as the threshold to support biodeterioration.

The moisture content of the stud specimen was found to stabilize at 50 days. Ice accumulation and moisture content stabilization could possibly be related. A more realistic cyclic temperature on the cold side of the wall may increase moisture content of the stud specimens due to absorption between the freezing and thawing temperature cycles. Cyclical thawing would subject the building enclosure materials to more liquid condensation. Without the cyclical temperature schedule, as performed in this experiment, the water vapor forms an ice layer, which effectively restricts moisture movement through the building enclosure during the experiment.

Observations in this experiment recognized flaws with both spray-applied forms of insulation. The spray-applied cellulose was found to form voids between the surrounding framing after curing due to shrinkage and settling as shown in Figure 6-1. The shrinkage and/or

settling of the cellulose not only decreases the thermal resistance of the material, but it creates an incomplete air barrier, which undermines a main reason that cellulose insulation achieves higher energy efficiency as compared to fiberglass. Not only is an incomplete air barrier formed, but moisture can now more freely bypass the insulation and collect on the exterior sheathing in cold weather environments. Observations after the experiment also indicated that the spray-applied polyurethane was found to have large voids near the sheathing/insulation interface as shown in Figure 6-2. During the experiment, this void was found to have ice accumulation on the sheathing, indicating that moisture was allowed to navigate through or around the insulation material. These potential material or installation flaws should be subject to more testing to determine if flawed material or improper application may have caused the spray-applied insulation to include imperfections after application.



Figure 4-9: Picture depicting the spray-applied cellulose settling and shrinking, which created a gap between the insulation and wood framing.



Figure 4-10: Cross section view of air gap formed between the sheathing and the spray-applied polyurethane foam within a 2x4 building enclosure.

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5 RESULTS AND DISCUSSION: IMPACT OF GREEN BUILDING STANDARDS ON BIODETERIORATION OF WOOD FRAMING

This section includes results from a study investigating how different forms of insulation encouraged by Green Building Standards may increase the risk of biodeterioration within wooden framework of residential structures. This section is written in manuscript form for submission to the *Journal of Green Building*.

5.1 ABSTRACT

Green building standards, such as LEED for Homes (U.S. Green Building Council 2008) or the National Green Building Standard (National Association of Home Builders 2009) emphasize the application of green building methods and the use of green materials to create energy efficient structures with limited negative impact on the environment. However, green building practices employed to increase energy efficiency of the building enclosure may overlook the possible adverse effects that these practices may have on the durability of buildings. The purpose of this paper is to determine insulation materials encouraged by green building standards and analyze the risk of biodeterioration that these insulation materials may cause to a buildings' wooden framework. In particular, the two of the most widely followed green building standards, LEED for Homes and National Green Building Standard, encourage the use of cellulose or polyurethane foam compared to traditional fiberglass batts, a recommendation that may or may not affect the longevity of residential buildings' wooden frames.

Results show that spray applied cellulose and polyurethane insulation, both encouraged by green building standards, increase the moisture content of the wooden framework within residential building enclosures. Thus, energy efficient insulation can increase the risk of

moisture-related biodeterioration of a building's wooden framework. Results from this study imply that both LEED for Homes and the National Green Building Standard do not emphasize durability of wooden structures in their guidelines.

5.2 INTRODUCTION

Green building practices refer to unique qualities and characteristics of building construction emphasizing principles and methodologies resulting in minimal effects upon the environment (Kibert 2005). The goal of green building practices is to design structures to be constructed and operated in a resource efficient manner using ecological principles. Ecological principles help reduce resource consumption, allow for the reuse of resources, use recyclable resources, protect nature, eliminate toxins, apply life-cycle costing, and focus on quality (Kibert 2005). However, when following current recommended green building methods and using green building materials to meet these ecological principles, adverse effects may arise if building physics are not carefully considered.

Building enclosures consist of materials that separate the interior environment of a building from the exterior environment. According to the Building Science Corporation (2010, line 3), "... *Building physics is the cornerstone of designing, constructing, and operating high performance buildings,*" while the Journal of Building Physics defines buildings physics to be "... *All areas of non-structural performance of a building and particularly in heat, air [and] moisture transfer*" (SAGE Publications 2010, line 1). Without proper understanding of building physics, green building practices could potentially be detrimental to the building quality and to the environment. In particular, if green building insulation standards lead to moisture related issues in the building enclosure compared to traditional building practices, higher insulation efficiency would be shorter building life spans due to biodeterioration.

Thermal insulation is a pivotal building component that impacts the transfer of heat, air, and moisture through the building enclosure. The main use of thermal insulation is to impede thermal transmission through the building enclosure. Thermal energy travels through the building enclosure in three different ways: conduction, radiation, and convection (Straube and Burnett 2005, Hens 2008). In well-designed and well-built homes, the majority of heat enters and leaves the building primarily by conduction through the building enclosure (Germer 2006). The most effective way to minimize heat conduction through the building enclosure is by insulating the building elements (walls, roofs, floors) in direct contact with the outside environment (Straube and Burnett 2005, Germer 2006). As thermal insulation increases, the density of the building enclosure also increases as air voids are filled with insulation material.

However, increased insulation density affects how moisture dissipates through the building enclosure. Due to pressure imbalances between the interior and exterior environments moisture may accumulate within the building enclosure (Straube and Burnett 2005, Lstiburek and Carmody 1994, Hens 2008). The addition of insulation to a wall cavity reduces the amount of air movement, which results in reduced airflow through the building enclosure. Though energy efficiency is increased due to lower air infiltration and exfiltration, the drying capacity of the building enclosure is decreased due to lack of air movement (Straube and Burnett 2005, Lstiburek and Carmody 1994, Hens 2008). This phenomenon occurs in all forms of insulation and is not just associated with new forms of energy efficient insulation. However, some of the insulation materials encouraged by green building guidelines may amplify the accumulation of moisture in wooden building elements due to reduced air movement that causes restricted capacity for moisture to dry out.

5.3 BUILDING ENCLOSURE HISTORY

Before the 1950's, insulation was not commonly found within the building enclosure of residential structures. Once thermal insulation was widely introduced, it served the primary purpose of increasing occupant comfort by reducing heat flow as well as reducing air infiltration and exfiltration through the building (Lstiburek and Carmody 1994). However, with today's elevated energy prices and rising concerns regarding energy conservation, proper insulation aids in reducing a building's energy consumption (Nisson and Wilson 2008). Thus, while insulating building enclosures has achieved the goal of reducing building operating costs and energy costs in particular, there have been physical consequences of increasing the thermal insulation of building elements (Lstiburek and Carmody 1994, Hens 2008).

As insulation is added to the building enclosure, the drying capacity of the building enclosure decreases as the air voids are eliminated (Lstiburek and Carmody 1994, Straube and Burnett 2005). When infiltration and exfiltration are reduced, energy is conserved through reduced needs for heating and cooling. Yet, moisture may still accumulate within the building enclosure by means of pressure differentials, diffusion, and imperfections in the building enclosure. However, when heat flow and airflow through the building enclosure are reduced, the potential for accumulated moisture in the walls to dry is decreased, creating the potential for biodeterioration of organic material within the enclosure or the occurrence of undesirable, toxic fungi or mold (Hens 2008, Straube and Burnett 2005). Historically, excessive moisture in building elements has been the single greatest factor affecting the longevity of buildings, as excessive moisture causes adverse effects such as decay, corrosion, or separation of coatings from substrates (Lstiburek and Carmody 1994).

5.4 CURRENT INSULATION MATERIALS

As technology has progressed, insulation materials have become more efficient by providing greater resistance to thermal transmission and air movement (Germer 2006). The resistance a material has to thermal transmission is noted as an R-value. The higher a material's R-value, the more the material resists the flow of heat. With a temperature difference of 1 degree Fahrenheit, insulation with an R of 1.0 allows 1.0 Btu per hour heat flow per square foot of surface area (Nisson and Wilson 2008). Largely due to its high thermal resistance, the most commonly used insulation materials in current residential construction include fiberglass batts, spray-applied cellulose, and spray-applied polyurethane (Germer 2006). These three insulation materials are discussed in greater detail below.

5.4.1 FIBERGLASS BATTS

Fiberglass is the most commonly used insulation material in the U.S., accounting for roughly 90 percent of all insulation in new homes (Nisson and Wilson 2008). Fiberglass is available in blanket or batt form, with typical thickness between 3 to 12 inches. The widths of the batts are sized to fit between framing members spaced 16 or 24 inches on center. Batts are typically cut and rolled into bundles (Germer 2006). Blankets are rolls of material that are cut to length on site (Nisson and Wilson 2008). Table 5-1 shows the approximate nominal R-values for commonly installed thicknesses of fiberglass batts. Fiberglass batts of the same thickness can have varying R-values depending on the density and quality of the fiberglass used in the batt. Thus, the actual R-value of fiberglass batts is highly dependent on the quality of the installation and batts often do not achieve the nominal R-value due to air gaps created during installation (BPI 2005).

Table 5-1: Approximate R-values for common thicknesses of fiberglass batts (Nisson and Wilson 2008)

THICKNESS	R-VALUE
3-1/2"	R-11
3-1/2"	R-13
3-1/2"	R-15
6-1/4"	R-19
5-1/2"	R-21
8-1/2"	R-30
12"	R-38

Fiberglass batt insulation consists of glass fibers pressed together with a binding agent (Germer 2006). The standard type of fiberglass insulation can be difficult to work with, as fibers can become loose and cause irritation human skin, eyes, and nose. However, improvements have been made to fiberglass insulation that prevents fibers from breaking off and becoming airborne. Another innovation is a plastic wrap to completely encompass the batt (Germer 2006).

Fiberglass batts are available with or without paper or foil facing on one side of the material (Nisson and Wilson 2008). When faced with Kraft paper or foil, facing flanges allow the batt to be stapled to the framing (Nisson and Wilson 2008, Germer 2006). Unfaced batts are typically slightly wider than faced batts in order to be "friction fit" into stud wall cavities without sagging (Nisson and Wilson 2008). The facing can serve as a vapor barrier if the edges are thoroughly sealed with tape or caulk (Germer 2006). Kraft paper facing is considered a marginal vapor barrier (Germer 2006). Unfaced batts are suitable for any application as long as proper attention is paid to moisture control (Nisson and Wilson 2008).

Traditionally, fiberglass has been the insulation method of choice for residential structures (Germer 2006). With fiberglass batt insulation, the insulation typically remains dry and its thermal resistance is not noticeably affected by the interstitial condensation (Lstiburek and Carmody 1994). The insulation is not affected because the moisture accumulation occurs on the sheathing and not within the insulation. Fiberglass insulation also lacks any inward

capillary moisture movement, so the condensation is allowed to drain downward and exit out of the building enclosure (Lstiburek and Carmody 1994).

5.4.2 SPRAY-APPLIED PRODUCTS

A majority of heat loss through the building enclosure results from air infiltration and exfiltration, which can be greatly reduced by the application of spray applied insulation (Germer 2006, Nisson and Wilson 2008). Various polymers, typically either oil-based or cellulosic, are commonly used for spray-applied insulation. Spray-applied insulation offers increased resistance to air and moisture passage by filling voids in the building enclosure (US DOE 2009e).

Cellulose insulation is made from recycled newspaper treated with fire and pest retardant chemicals, typically a borate solution (Cellulose Insulation Manufacturers Association 2010). Besides being a recycled material, cellulose insulation has a low embodied energy compared to other forms of insulation, making it attractive for green buildings (Woolley et al. 1997). Sprayed cellulose is typically applied dry into horizontal areas such as floors and attics, but is mixed with water and adhesives (referred to as damp-spray cellulose) when sprayed into vertical wall cavities (Cellulose Insulation Manufacturers Association 2010). Damp-spray cellulose forms a denser layer of insulation, which creates better insulation and lower air infiltration compared to the dry application (Fisette 2005). Depending on the application method, cellulose insulation has an R-value ranging from 3.6 to 4.0 per inch of thickness (Cellulose Insulation Manufacturers Association 2010). Cellulose insulation has capillary action that draws condensed water from accumulated moisture on the sheathing, and therefore absorbs moisture into the insulation (Lstiburek and Carmody 1994). In an insulation material, capillary action can cause reduced insulation performance due to increased moisture content, which decreases thermal resistance.

Another spray-applied insulation material is polyurethane. Polyurethane is most commonly applied as open-cell foam in residential applications due to its flexibility and lack of off-gassing (Germer 2006, U.S. Department of Energy 2009). Spray-in polyurethane foam insulation is typically applied as liquid foam through a nozzle, where the liquid then expands as gas is entrapped during cure (Germer 2006). Plastic polymers, like polyurethane spray-applied foam insulation, offer the highest R-value per inch of insulation of all spray-in insulation materials commonly used in residential structures. Two types of plastic spray-foam commonly used are closed-cell or open-cell foam, with the main difference being the gas used as a foaming agent to fill the cells formed within the polymer (U.S. Department of Energy 2009). Closed-cell foam is produced with a low-conductivity gas, commonly hydrochlorofluorocarbons (HCFCs) that is known for causing ozone depletion, while open-cell foam commonly uses carbon dioxide (CO₂). Closed-cell polyurethane foam has an R-value of approximately 6.5 per inch of thickness and open-cell polyurethane has an R-value of approximately 3.6 per inch of thickness (U.S. Department of Energy 2009). These foams offer resistance to moisture passage and completely fill all voids within the building enclosure due to the expansion of the material (Germer 2006). Polyurethane foam can also have the added benefit of increasing the strength properties of the building enclosure because of the foam's rigid cure within the wall cavities (Nisson and Wilson 2008).

5.5 IMPACT OF INSULATION MATERIALS ON MOISTURE

ACCUMULATION WITHIN RESIDENTIAL BUILDING ENCLOSURES

Moisture naturally diffuses through the building enclosure due to thermodynamic laws (Straube and Burnett 2005, Hens 2008). Moisture diffusion occurs most substantially when residential buildings are heated in cold weather. These conditions cause a temperature gradient through the building enclosure, such that the dew point of the warmer, more humid

inside air occurs inside the building enclosure. When moisture from the interior conditioned space migrates through the insulation by means of diffusion, air movement, and imperfections within the building enclosure (Straube and Burnett 2005), moisture accumulates on the sheathing material attached to the exterior side of the studs or within the insulation as interstitial condensation in the form of liquid water or frost. The ability of this interstitial moisture to leave the building enclosure is highly dependent upon the type of insulation material used, and the ability of building enclosure materials to dry is diminished as thermal insulation increases (Lstiburek and Carmody 1994).

With green building standards emphasizing the use of thicker insulation to create a more energy efficient building enclosure, potential moisture-related durability issues may be more prevalent. Such moisture accumulation within building enclosures can decrease thermal resistivity of insulation due to the accumulation of water within the material, as water has a lower thermal resistance than air (Nisson and Wilson 2008). Also, moisture accumulation in the building enclosure can lead to biodeterioration of organic material within the enclosure (Lstiburek and Carmody 1994, Straube and Burnett 2005), negatively affecting the longevity of structures.

Wood, the most widely used material for the framing of residential structures, is an organic material and is subject to biodeterioration such as decay and insect infestation (Bowyer et al. 2003, Straube and Burnette 2005). H. J. Hueck (as cited in Allsopp et al. 2004, p. 1) defined biodeterioration as “*any undesirable change in the properties of a material caused by the vital activities of organisms.*” Due to the chemical composition of wood, which consists mostly of long chains of sugar units encased in lignin, the material is susceptible to biodeterioration (Lstiburek and Carmody 1994, Morris 1998) and is significantly increased at moisture contents greater than 20 percent (Forest Products Laboratory 1999). Biodeterioration

occurs most rapidly at temperatures in the range of 68 to 90 degrees Fahrenheit (Boyer et al. 2003), temperatures typically found within the walls of residential buildings.

5.5.1 PAST RESEARCH

Chapter 4 describes a series of single-sided hot box experiments emulating winter conditions for residential building enclosures to investigate the resulting moisture content of insulated wooden studs in building wall elements subjected to freezing exterior conditions. In particular, the moisture content of framing members within 2x4 building enclosure samples was measured after being insulated with different materials (fiberglass batts, spray-applied cellulose, and spray-applied polyurethane) for 60 days. The experimental design allowed for statistical comparison of moisture content on the building enclosure's wooden framework insulated with these three different forms of insulation.

During the 60 days of testing, the warm side relative humidity of the building enclosure was regulated to approximately 30 percent moisture content to allow for potential moisture to diffuse through the enclosure. There was no regulation of relative humidity on the cold side of the building enclosure, as only a pressure differential would cause moisture from the cold environment to enter the building enclosure (Lstiburek and Carmody 1994). The test design allowed for stud specimen insulated with two forms of spray-applied insulation (cellulose and polyurethane) to be compared to a stud specimen similarly located and insulated with more traditional fiberglass.

During the experiment, the moisture content of each wooden stud inside the building elements was continuously measured at the sheathing/stud interface. The two test samples with studs insulated with fiberglass averaged moisture content of 14.2 percent and 13.0 percent, respectively. The studs insulated with spray-applied cellulose and spray-applied polyurethane

insulated, had, with averages of 18.3 percent and 16.0 percent, respectively. This higher moisture content within the samples insulated with spray-applied cellulose and polyurethane was associated with capillary action that allowed the cellulose and polyurethane to absorb and store moisture around the framing members, thereby increasing the moisture content of the studs. Unlike the spray-applied insulation materials, fiberglass has larger, unrestricted air gaps that allow vapor to diffuse through the material and exit through the kraft facing. Thus, the fiberglass batt insulation caused less moisture to accumulate than did the spray-applied forms of insulation tested, due to these two main factors: fiberglass insulation lacks capillary action that is characteristic of porous insulation materials (Lstiburek and Carmody 1994) and fiberglass insulation allows for higher moisture diffusion potential due to its large interconnected volumes of air (Germer 2006). This increase in moisture content of studs within building elements can increase the risk of biodeterioration for spray applied cellulose and polyurethane insulation.

5.6 GREEN BUILDING STANDARDS

Green building standards were developed to encourage energy and material efficiency for buildings, during both the construction and the operation of the structure (U.S. Environmental Protection Agency 2009). Within these green building standards, there are specific requirements for the building enclosure and insulation. To assess the potential risk of biodeterioration induced by specific types of insulation, this section lists insulation requirements for the LEED for Homes and the National Green Building Standard systems.

5.6.1 LEED FOR HOMES

The LEED for Homes scheme employs a point system to award a specific rating of a given home construction project based on specific, predetermined criteria in several categories that the building addresses (Kibert 2005). All levels of LEED for Homes certification are based on 18 prerequisites that must be fulfilled before any credits can be earned (U.S. Green Building

Council 2008). These prerequisites are considered basic performance standards, and therefore have no points awarded. To achieve certification, builders must earn points by exceeding these minimum standards. In total, there are 136 credit points available within eight credit categories (U.S. Green Building Council 2008). The eight LEED for Homes credit categories are as follows:

- | | |
|--------------------------|---------------------------------|
| 1. Sustainable Sites | 5. Indoor Environmental Quality |
| 2. Water Efficiency | 6. Location and Linkages |
| 3. Energy & Atmosphere | 7. Awareness & Education |
| 4. Materials & Resources | 8. Innovation and design |

Within the LEED for Homes scheme there is a mandatory prerequisite that must be fulfilled to gain the two-point maximum awarded specifically for insulation within the Energy & Atmosphere category (U.S. Green Building Council 2008). The prerequisite for LEED for Homes requires that R-values listed in Chapter 4 of the 2004 International Energy Conservation Code (IECC, International Conservation Code 2004) must be met or exceeded and insulation installation must conform to Grade II specifications set by the National Home Energy Rating Standards (HERS) as shown in Table 5-2 (U.S. Green Building Council 2008). Installation of the insulation must be verified by an energy rater or Green Rater conducting a pre-drywall thermal bypass inspection as summarized in the LEED for Homes Reference Guide (U.S. Green Building Council 2008).

Table 5-2: Summary of HERS Installation Grades

GRADE	DESCRIPTION
I	Meet the requirements of Grade II (below), but allow only very small gaps, and compression or incomplete fill amounting to 2 percent or less of total cavity area
II	Moderate to frequent installation defects, gaps around wiring, electric outlets, etc. and incomplete fill amounting to 10 percent or less of total cavity area. Gaps running clear through the insulation amount to no more than 2 percent of the total surface area covered by the insulation. Wall insulation is enclosed on all six sides and in substantial contact with the sheathing material on at least one side (interior or exterior) of the cavity.

After the LEED for Homes prerequisite is met, two points are available for insulation standards representing 20 percent of the points available for the Energy & Atmosphere category, and representing 1.5 percent of the total 136 possible LEED for Homes points. Of the two available points, one point is given for enhanced insulation when insulation exceeds the R-value requirements listed in Chapter 4 of the International Energy Conservation Code by at least 5 percent (U.S. Green Building Council 2008). The other point requires that all insulation must meet Grade I specifications set by the National Home Energy Rating Standards explained in Table 5-2 (U.S. Green Building Council 2008).

5.6.2 THE NATIONAL GREEN BUILDING STANDARD

The National Association of Home Builders (NAHB) and the American National Standards Institute (ANSI) approved ICC-700-2008 National Green Building Standard (NGBS) as the first ANSI consensus standard on sustainable green building for residential construction in the U.S. (National Association of Home Builders 2009). The NGBS defines green building for single and multifamily homes, residential remodeling projects, and site development projects (National Association of Home Builders 2009). The NGBS employs a point system to award a rating based on how many specific, predetermined criteria in several categories (National Association of Home Builders 2009). The ratings in descending order are Emerald, Gold, Silver, and Bronze. The NGBS consists of seven categories that detail the criteria considered as green building practices:

1. Lot Design Preparation and Development
2. Resource Efficiency
3. Energy Efficiency
4. Water Efficiency
5. Indoor Environmental Quality
6. Operation, Maintenance, and Building Owner Education
7. Additional points from any category

The NGBS includes insulation requirements within the Energy Efficiency chapter (National Association of Home Builders 2009). The NGBS allows builders to take two different paths to earn points, a performance path and a prescriptive path. Only one path can be used, therefore points cannot be acquired by adding points from both paths. The performance path describes how well a building's components must perform. The prescriptive path lists specific implementation strategies that the building must incorporate in order to reach specific tiers of certification (National Association of Home Builders 2009). A disadvantage of using the prescriptive path is that a building is not eligible for the Emerald rating. Regardless of which path is chosen, proper installation of insulation in accordance to manufacturer's instructions or local code is mandatory. As an alternative, any building that is an ENERGY STAR Qualified Home automatically achieves Bronze certification for the Energy Efficiency category.

When using the performance path within the Energy Efficiency category, insulation can attain up to 120 points, which is 17.2 percent of points required to receive the Emerald level. For insulation to gain the maximum 120 points, the building enclosure must achieve an energy cost performance that exceeds the IECC (International Conservation Code 2004) by 60 percent as documented by software in accordance with the IECC. The performance path for energy efficiency within the NGBS includes points allocated based on energy cost performance that exceeds the IECC (International Conservation Code 2004) by a given percentage (National Association of Home Builders 2009). Because it is based on overall performance of the building enclosure as a whole, the performance path does not give points specifically for insulation. Thus, only the prescriptive path within the NGBS can be used to compare points awarded to insulation between different green building standards.

When using the prescriptive path, a maximum of 36 points (dependent on climate zone) can be earned, which is 30 percent of the points within the Energy Efficiency chapter and 6.4

percent of the points required to meet the standard’s gold rating, the highest rating attainable using the prescriptive path. The maximum 36 points within the prescriptive path can be achieved by exceeding the International Energy Conservation Code (International Conservation Code 2004) requirement by 20 percent as documented by RESCheck or equivalent software. If points are not awarded for exceeding the International Energy Conservation Code, points can be earned by achieving a Grade I insulation installation (Table 5-2) can earn a maximum of 15 points (National Association of Home Builders 2009).

If the thermal component of the building enclosure does not conform to the ICC IECC (see performance path), the total building thermal enclosure can earn points as measured by a metric called UA. UA is defined as the total U-factor times the area of a given component of a building. In this case, the UA would be considered the U-factor of the insulation multiplied by the area of insulation of a residence with units of BTU/(h °F). Table 5-3 shows the possible points awarded for UA improvement according to how much the UA improvement surpasses the given IECC code within the IECC defined climate zone. If the UA improvement is unable to earn any points, points can be earned if insulation installation is graded by a third party and is in accordance with specified installation grades within the Energy Efficiency chapter. The points awarded for insulation installation grades are shown in Table 5-4 if no points are earned by UA improvements as shown in Table 5-3.

Table 5-3: Points awarded for total building thermal enclosure UA as documented by RESCheck or equivalent software based on a comparison to the ICC IECC, IRC, or IBC (National Association of Home Builders 2009)

	Climate Zone				
	2	3	4	5-6	7-8
	Points				
10% UA improvement	10	12	14	16	18
20% UA improvement	20	24	28	32	36

Table 5-4: Points available for insulation installation grades; not to be used in conjunction with any points achieved by total building thermal enclosure UA (National Association of Home Builders 2009)

GRADE	POINTS
1	15
2	10
3	0

5.7 COMPARISON OF EXPERIMENTAL RESULTS AND INSULATION STANDARDS

The LEED for Homes and National Green Building Standard insulation requirements including prerequisites and points attainable are shown in Table 5-5. Once the prerequisites requirements are met, points can then be gained for insulation methods and materials. The maximum amount of points available to be awarded for insulation methods and materials along with a brief description of how these points can be awarded is shown in Table 5-5. The percentage of points available to be awarded for insulation within each green building standard is also shown in Table 5-5. To justify that the experimental wall sections constructed were insulated with materials that were able to gain points by these standards, Equation 1 was developed to calculate thermal resistance values (R-values) for the complete wall section:

$$\text{Assembly R-value} = 1 / (\text{Assembly U-value}) = 1 / (\text{U-studs} \times \% + \text{U-cavity} \times \%) \quad (1)$$

Table 5-5: A comparison of the insulation requirements for the various green building standards.

	PREREQUISITES	MAXIMUM INSULATION POINTS	INSULATION AS % OF WHOLE STANDARD	POSSIBLE POINTS
LEED for Homes	<ul style="list-style-type: none"> • Insulation must meet 2004 IECC code¹ • Insulation installation must meet Grade II specifications set by the NHERS³ 	2	1.5% of 136 Total Points	<ul style="list-style-type: none"> • 1 point: Insulation R-value exceeds IECC code by at least 5% • 1 point: Insulation installed to meet Grade I specifications set by the NHERS³
National Green Building Standard (Only prescriptive path considered)	<ul style="list-style-type: none"> • Building must obtain at least 30 points from the prescriptive path options² 	28	17.2% of 697 Points Required for Emerald Rating	<ul style="list-style-type: none"> • 14 points: 10% UA improvement • 28 points: 20% UA improvement --OR-- • 15 points: Grade I insulation as judged by the NHERS³ • 10 points: Grade II insulation as judged by the NHERS³

¹ 2004 International Energy Conservation Code (IECC) requirements that apply to insulation in climate zone 4

² The prescriptive path includes more than just insulation, but insulation alone accounts for a possibility of 28 points within climate zone 4.

³ National Home Energy Rating Standard

Using Equation 1, the R-values of the insulation materials were calculated using R-values for various building enclosure materials as documented by Colorado Energy (2009). Assembly R-values calculated for building enclosures with R-values of insulation from the previous chapter are displayed in Table 5-6. The required 2004 IECC code requirements for the building enclosure assembly, which is the prerequisite for LEED for Homes and the basis for earning points in the National Green Building Standard are shown in Table 5-6. None of the 2x4 building enclosure assembly R-values reached the required 2004 IECC Code requirement. To aid in comparison of materials, R-values of 2x6 wall assemblies were also calculated in Table 5-6. The R-values of 2x6 wall assemblies exceed the 2004 IECC Code requirement. Details about the values used to determine the total assembly R-value can be found in the Appendix (Table 5-9 through Table 5-14).

Table 5-6: Assembly R-values of building enclosure sections using different insulation choices as well as the 2004 IECC code requirement for thermal resistance of the building enclosure.

	2x4 Wall Assembly R-Value	2x6 Wall Assembly R-Value	2004 IECC Code Requirement R-Value
Fiberglass	12.30	17.07	15
Cellulose	14.62	20.56	
Polyurethane	14.84	20.88	

5.7.1 INSULATING A 2X4 WALL ASSEMBLY

The 2x4 building enclosure construction of the building enclosure does not include space for enough insulation to create sufficient thermal resistance (R-value) to meet IECC code requirements. Therefore, 2x4 building enclosures do not meet compliance requirements and can not earn any points related to meet or exceed the 2004 IECC code requirements. Since the 2004 IECC code is a prerequisite for LEED for Homes, no 2x4 building enclosures can gain building enclosure points within LEED for Homes.

The National Green Building Standard still can award points without the insulation meeting the 2004 IECC code requirements. Assuming the best insulation installation possible, a Grade I insulation as judged by the National Home Energy Rating System (HERS) can be given. A Grade I installation allows the fiberglass, cellulose, and polyurethane insulation are technically able to gain the 15 points for insulation (Table 5-4) within the total 28 maximum insulation specific points available.

5.7.2 INSULATING A 2X6 WALL ASSEMBLY

The 2x6 wall assembly allows for all insulation tested to theoretically exceed the five percent improvement of IECC requirements required by the National Green Building Standard (NAHB 2009). The 2x6 wall assembly values, IECC recommendations, and percentage improvement of each insulation material over the IECC code requirement R-value are shown in

Table 5-7. By exceeding the 2004 IECC requirements by five percent, all forms of insulation qualify for one point within the LEED for Homes system. For LEED for Homes, the fiberglass, cellulose, and polyurethane installation will earn an additional point if the insulation conforms to Grade I HERS designation (Table 5-5). Clearly, the installation of insulation is just as important as the insulation material within the LEED for Homes standard since both installation grade and material selection are needed to earn both points.

Table 5-7: Assembly R-values as compared to the 2004 IECC code and the percentage improvement of the IECC code requirement

	2x6 Wall Assembly R-Value	2004 IECC Code Requirement R-Value	Percentage Improvement of 2004 IECC Code Requirement
Fiberglass	17.07	15	13.80
Cellulose	20.56		37.07
Polyurethane	20.88		39.20

The NGBS awards points according to a UA improvement in the building enclosure. The UA values of the cellulose and polyurethane surpass the 20 percent improvement and allow for all 28 points to be earned thermal improvement of the wall assembly. Fiberglass insulation meets the 10 percent UA improvement, and is awarded 14 points. Because all three forms of insulation gain points by UA improvement, they cannot gain points for installation grades. Thus, had the fiberglass insulation failed to meet the 10 percent UA improvement, which earns 14 points. The fiberglass insulation could earn more points (15) if installed to meet Grade I installation according to HERS (Table 5-2).

5.7.3 SUMMARY OF GREEN BUILDING SYSTEM REQUIREMENTS

A comparison of possible points earned with each green building system for each wall assembly used in Chapter 4 is shown in Table 5-8. Spray-applied cellulose and polyurethane foam insulation gained the most points within the National Green Building Standard (NGBS) and

thus these insulation materials are encouraged by the NGBS. The fiberglass batts did not earn as many points, and were not considered preferable for the NGBS. The LEED for Homes standard did not encourage any particular form of insulation, though it should be noted that meeting a Grade I insulation installation of fiberglass batts is difficult. Determining forms of insulation that are awarded more points within the LEED for Homes and National Green Building Standard allows for a analysis of preferred insulation within these standards. The preferred insulation within these standards can then be analyzed to determine if specific insulation has a possible relationship with the increased risk of biodeterioration of wooden framework as discussed in Chapter 4.

Table 5-8: A comparison between insulation forms and possible points to be earned in green building systems. Those solutions that increase the risk of biodeterioration of wood framework are in bold.

Insulation Material	2X4 WALL ASSEMBLY		2X6 WALL ASSEMBLY	
	LEED for Homes (max 2)	National Green Building Standard (max 28)	LEED for Homes (max 2)	National Green Building Standard (max 28)
Fiberglass	0	15	2	15
Cellulose	0	15	2	28
Polyurethane	0	15	2	28

Because the NGBS encourages the use of spray-applied cellulose and polyurethane insulation, this green building system does not fully addresses issues involving building physics and structure durability. Because spray-applied forms of insulation are awarded more points as compared to fiberglass batt insulation, the NGBS's recommendations should be analyzed to determine if they ultimately encourage environmental sustainability. Further research is necessary to determine that, although specific insulation materials provide increased efficiency in reducing the transmission of thermal energy, if spray-applied insulation may increase risk of environmental damage due to increased demand of building materials due to biodeterioration of wooden frames within building enclosures.

5.8 CONCLUSIONS

The points awarded to insulation within LEED for Homes and the National Green Building Standard were examined and related to results of the experiment in Chapter 4. The National Green Building Standard (NGBS) encourages spray-applied forms of insulation, such as cellulose and polyurethane foam, over traditional fiberglass batts by awarding more points for cellulose and polyurethane insulation due to these materials' superior thermal resistance compared to traditional fiberglass batts. LEED for Homes does not encourage spray applied forms of insulation, as fiberglass batts can technically be awarded the same amount of points if installed to Grade I NHERS specifications. Both LEED for Homes and the NGBS encourage 2x6 framing construction over traditional 2x4 construction since an insulation level able to be awarded can only be attained by with a R-value that requires a 2x6 structure.

Encouragement of spray-applied polyurethane and cellulose insulation in the National Green Building Standard seems to lack focus on structure longevity as results of the analysis show that spray-applied polyurethane foam and cellulose materials can satisfy the energy efficiency requirement, but fail to fulfill building physics requirements in regards to moisture accumulation. Even though spray cellulose and polyurethane are considered energy efficient insulation materials, the wooden framework may be susceptible to biodeterioration due to increased moisture content. The National Green Building Standard should be further analyzed to determine if their guidelines put structures' durability at risk by encouraging particular insulation practices. In particular, before insulation materials and practices are encouraged by green building standards, focus should be placed on performing research testing to determine if insulation materials may negatively impact structural durability.

5.9 LITERATURE CITED

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5.10 APPENDIX

Table 5-9: Assembly R-value of a 2x4 wall section using fiberglass insulation material

Component	R-Value Studs	R-Value Cavity	Assembly R-Value
Wall - Outside Air Film	0.17	0.17	
Siding - Aluminum w/ 1/2" insulating board	1.80	1.80	
Plywood Sheathing - 1/2"	0.63	0.63	
3 1/2" Fiberglass Batt		9.80	
3 1/2" Stud	4.38		
1/2" Drywall	0.45	0.45	
Inside Air Film	0.68	0.68	
Percent for 16" O.C. + Additional Studs	0.15	0.85	
Total Wall Component R- Values	8.11	13.53	
Wall Component U-Values	0.1233	0.0739	
Total Wall Assembly R-Values			12.30

Table 5-10: Assembly R-value of a 2x4 wall section using cellulose insulation material

Component	R-Value Studs	R-Value Cavity	Assembly R-Value
Wall - Outside Air Film	0.17	0.17	
Siding - Aluminum w/ 1/2" insulating board	1.80	1.80	
Plywood Sheathing - 1/2"	0.63	0.63	
3 1/2" Cellulose Fill		13.30	
3 1/2" Stud	4.38		
1/2" Drywall	0.45	0.45	
Inside Air Film	0.68	0.68	
Percent for 16" O.C. + Additional Studs	0.15	0.85	
Total Wall Component R- Values	8.11	16.73	
Wall Component U-Values	0.1233	0.0598	
Total Wall Assembly R-Values			14.62

Table 5-11: Assembly R-value of a 2x4 wall section using polyurethane insulation material

Component	R-Value Studs	R-Value Cavity	Assembly R-Value
Wall - Outside Air Film	0.17	0.17	
Siding - Aluminum w/ 1/2" insulating board	1.80	1.80	
Plywood Sheathing - 1/2"	0.63	0.63	
3 1/2" Polyurethane Foam		13.65	
3 1/2" Stud	4.38		
1/2" Drywall	0.45	0.45	
Inside Air Film	0.68	0.68	
Percent for 16" O.C. + Additional Studs	0.15	0.85	
Total Wall Component R- Values	8.11	16.73	
Wall Component U-Values	0.1233	0.0598	
Total Wall Assembly R-Values			14.84

Table 5-12: Assembly R-value of a 2x6 wall section using fiberglass insulation material

Component	R-Value Studs	R-Value Cavity	Assembly R-Value
Wall - Outside Air Film	0.17	0.17	
Siding - Aluminum w/ 1/2" insulating board	1.80	1.80	
Plywood Sheathing - 1/2"	0.63	0.63	
5 1/2" Fiberglass Batt		15.40	
5 1/2" Stud	6.88		
1/2" Drywall	0.45	0.45	
Inside Air Film	0.68	0.68	
Percent for 16" O.C. + Additional Studs	0.15	0.85	
Total Wall Component R- Values	10.61	19.13	
Wall Component U-Values	0.0943	0.0523	
Total Wall Assembly R-Values			17.07

Table 5-13: Assembly R-value of a 2x6 wall section using cellulose insulation material

Component	R-Value Studs	R-Value Cavity	Assembly R-Value
Wall - Outside Air Film	0.17	0.17	
Siding - Aluminum w/ 1/2" insulating board	1.80	1.80	
Plywood Sheathing - 1/2"	0.63	0.63	
5 1/2" Cellulose Fill		20.90	
5 1/2" Stud	6.88		
1/2" Drywall	0.45	0.45	
Inside Air Film	0.68	0.68	
Percent for 16" O.C. + Additional Studs	0.15	0.85	
Total Wall Component R- Values	10.61	24.08	
Wall Component U-Values	0.0943	0.0415	
Total Wall Assembly R-Values			20.56

Table 5-14: Assembly R-value of a 2x6 wall section using polyurethane insulation material

Component	R-Value Studs	R-Value Cavity	Assembly R-Value
Wall - Outside Air Film	0.17	0.17	
Siding - Aluminum w/ 1/2" insulating board	1.80	1.80	
Plywood Sheathing - 1/2"	0.63	0.63	
5 1/2" Polyurethane Foam		21.45	
5 1/2" Stud	6.88		
1/2" Drywall	0.45	0.45	
Inside Air Film	0.68	0.68	
Percent for 16" O.C. + Additional Studs	0.15	0.85	
Total Wall Component R- Values	10.61	24.08	
Wall Component U-Values	0.0943	0.0415	
Total Wall Assembly R-Values			20.88

6 SUMMARY & CONCLUSIONS

This research investigated the popular use of energy efficient cellulose and polyurethane insulation materials and the critical juncture with hygrothermal performance of the building enclosure. The first part of this study examined the effect that different insulation types have on the moisture content of wood framing within a wall assembly. Spray-applied cellulose and spray-applied polyurethane insulation were both found to cause increased moisture content within the wooden framing as compared to traditional fiberglass batts. However, during the 60-day period of this experiment, none of the framing specimens tested reached the 20 percent moisture content recognized as the threshold to start and support biodeterioration.

The moisture content of the stud specimen within the building assemblies was found to reach steady state after about 50 days. Ice accumulation and moisture content stabilization could possibly be related. A more realistic cyclic temperature on the cold side of the wall may increase moisture content of the stud specimens due to moisture absorption of the framing members between the freezing and thawing temperature cycles. In fact, a more cyclical temperature gradient would more closely approximate the accumulation of ice in a building's exterior interface during the winter that is occasionally melted due to solar radiation on the exterior of the building enclosure. Cyclical thawing would subject the building enclosure materials to more liquid condensation. Without the cyclical temperature schedule, as performed in this experiment, the water vapor forms an ice layer, which effectively restricts moisture movement through the building enclosure during the experiment.

Observations in this experiment recognized flaws with both spray-applied forms of insulation. The spray-applied cellulose was found to form voids between the surrounding framing after curing due to shrinkage and settling as shown in Figure 6-1. The shrinkage and/or

settling of the cellulose not only decreases the thermal resistance of the material, but it creates an incomplete air barrier, which undermines a main reason that cellulose insulation achieves higher energy efficiency as compared to fiberglass. Not only is an incomplete air barrier formed, but moisture can now more freely bypass the insulation and collect on the exterior sheathing in cold weather environments. Observations after the experiment also indicated that the spray-applied polyurethane was found to have large voids near the sheathing/insulation interface as shown in Figure 6-2. During the experiment, this void was found to have ice accumulation on the sheathing, indicating that moisture was allowed to navigate through or around the insulation material. These potential material or installation flaws should be subject to more testing to determine if flawed material or improper application may have caused the spray-applied insulation to include imperfections after application.



Figure 6-1: Picture depicting the spray-applied cellulose settling and shrinking, which created a gap between the insulation and wood framing.



Figure 6-2: Cross section view of air gap formed between the sheathing and the spray-applied polyurethane foam within a 2x4 building enclosure.

The National Green Building Standard (NGBS) encourages spray-applied forms of insulation, such as cellulose and polyurethane foam, over traditional fiberglass batts by awarding more points for cellulose and polyurethane insulation due to these materials' superior thermal resistance compared to traditional fiberglass batts. LEED for Homes does not encourage spray applied forms of insulation, as fiberglass batts can technically be awarded the same amount of points if installed to Grade I NHERS specifications. Both LEED for Homes and the NGBS encourage 2x6 framing construction over traditional 2x4 construction since 2x6 construction allows for increased thermal resistance due to increased insulation thickness.

Encouragement of spray-applied polyurethane and cellulose insulation by LEED for Homes and NGBS seems to lack focus on structure longevity as results of the analysis showing that spray-applied polyurethane foam and cellulose materials can satisfy the energy efficiency requirement, but fail to fulfill building physics requirements in regards to moisture accumulation. Even though spray cellulose and polyurethane are considered energy efficient insulation materials, the wooden framework may be susceptible to biodeterioration due to increased moisture content. The LEED for Homes and the National Green Building Standard should be further analyzed to determine if their guidelines put structures' durability at risk by encouraging

particular insulation practices. In particular, before insulation materials and practices are encouraged by green building standards, focus should be placed on performing research testing to determine if insulation materials may negatively impact structural durability.

Green building standards could rely on computer energy modeling programs, such as WUFI (ORNL 2011), to simulate one-dimensional heat and moisture transport through building enclosures using specific insulation types in various climates. Tools, such as WUFI, are available to the residential building construction community, and should be utilized along with real world testing to ensure that green building practices do not risk structural durability for increased energy efficiency.

6.1 LIMITATIONS TO THE RESEARCH

This research was developed to assess possible moisture related biodeterioration that may be caused as a result of using popularly recommended energy efficient insulation methods and materials, thereby causing an increase in susceptibility to biodeterioration of wooden structures. The methods and techniques used in this experimentation are subject to uncontrolled variables, which should be acknowledged by the reader when interpreting the experimental results. Critical limitations were unavoidable during this research, and some of these limitations should be noted. One limitation of this work is that the freezers used were not meant for scientific research, and therefore were not able to be set to standard tolerances of temperature. Another limitation deals with the regulation of relative humidity within the Microtechniques Laboratory within the Brooks Forest Products Center at Virginia Tech. The relative humidity was difficult to control within the Microtechniques Laboratory, and varied often depending on the occupancy of the building and the weather. A third critical limitation to this research is the possibility of insulation errors. Possible insulation installation errors, such as

improper application or improper mixture, may lead to inconsistent insulation within the wall cavity.

6.2 FUTURE RESEARCH

Based on the limitations of this work, future research should be pursued by the development of a hot box-cold box environment designed to meet specific temperature and relative humidity tolerances, and large enough to test sample building enclosure sections. The hot box-cold box experimental setup could eliminate variables such as drastic changes in temperature and relative humidity. The hot box-cold box set-up should also imitate cyclical temperature fluctuations that are likely to occur in real-life building enclosures.

Though most existing homes use 2x4 framing, new construction often uses 2x6 framing members. Future research should also test 2x6 wooden framework as well as 2x4 framework to determine if changing insulation depth alters the hygrothermal performance of insulation materials. During moisture content measurements, future research should include as many sample measurements as possible, thereby increasing the reliability of the moisture content results when analyzed statistically.

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APPENDIX A: NORTH AMERICAN INSULATION MANUFACTURERS ASSOCIATION: COPYRIGHT PERMISSION



VIA E-MAIL AND REGULAR MAIL

June 16, 2010

Mr. Kevin Knight
Virginia Tech – Mail Code 0503
1650 Ramble Road
Blacksburg, VA 24061

RE: Permission to Reproduce or Copy NAIMA's R-value Map Image in the Master of Science Thesis

Dear Mr. Knight:

By this letter, the North American Insulation Manufacturers Association ("NAIMA") grants Kevin Knight the right to reproduce or copy NAIMA's R-value map image from NAIMA's Simply Insulate website in the Master of Science thesis to be submitted to Virginia Tech.

NAIMA's grant of reproduction rights is contingent upon the following conditions:

- It shall be acknowledged in the Master of Science thesis that NAIMA has granted reproduction rights.
- Kevin Knight may not extend this grant of reproduction rights to third parties without NAIMA's written permission.
- NAIMA's grant of reproduction rights to Kevin Knight remains exclusively restricted to inclusion in the Master of Science thesis to be submitted to Virginia Tech and no other publications. If the thesis is published, NAIMA must grant reproduction rights anew.
- The image shall not be revised or altered. Kevin Knight may edit as needed, such as enlarging, but the editing should not alter the substance or intent of the material.
- Kevin Knight shall not employ the image from NAIMA's website to criticize, denigrate, or defame NAIMA or its members and their products.
- NAIMA shall NOT assume any liability arising from the presence of the aforementioned content in the Master of Science thesis to be submitted to Virginia Tech.

Based on the acceptance of these conditions, NAIMA grants Kevin Knight the right to use and reprint NAIMA's R-value map image from NAIMA's Simply Insulate website in the Master of Science thesis to be submitted to Virginia Tech. NAIMA would appreciate a copy of the thesis upon completion.

Sincerely,

Angus E. Crane

Angus E. Crane
Executive Vice President, General Counsel