# Mapping Thermal Mass Benefit

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# 1 INTRODUCTION

Residential and commercial buildings consume 41% of the total energy used by all sectors of the economy [1]. As climate change becomes an increasingly important concern, identifying strategies to ensure energy efficiency in buildings has become a key focus of the building industry. These strategies are typically cumulative, requiring the integration of multiple methods and systems, while responding to the local climate and context. This report addresses one such strategy: thermal mass benefit.

For residential construction, approximately 50% of total energy consumption is due to heating (41%) and cooling (8%) a residence. As such, individual homes in heating climates consume more energy than homes in cooling climates; however, geographically, the distribution of energy consumption is dependent on demographic patterns. For example, as population growth increased in the Southern US, that region now consumes more energy than other regions in the US [2]. See Figures 1 through 3 for the relationship between energy consumption, end use, region and household. As a result, focus on energy efficiency strategies should be multipronged and nuanced, addressing the specific needs of different climates and locations.

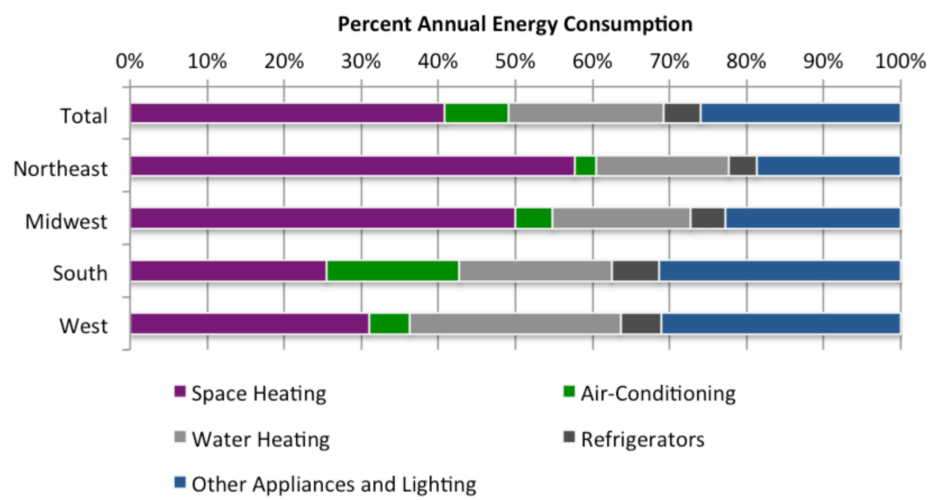


**Figure 1** Percent energy consumption by end use for US and its sub-regions [2]

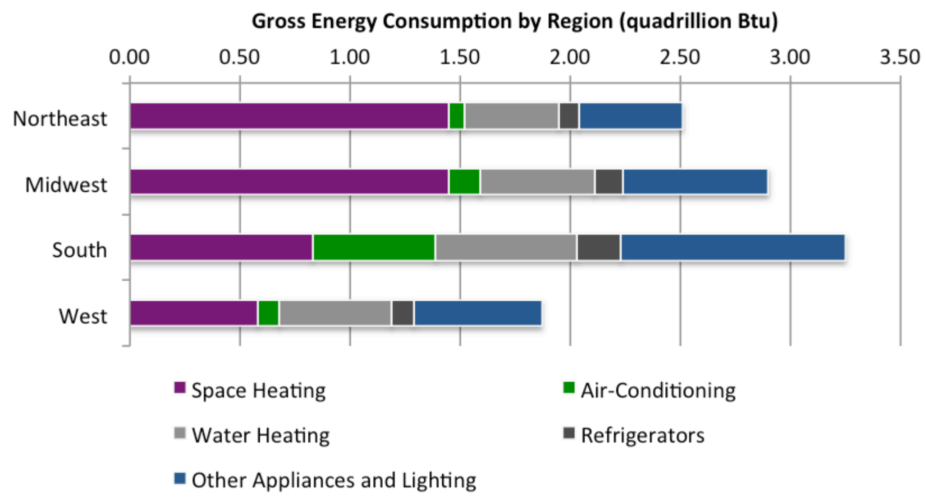


**Figure 2** Gross energy consumption by US region [2]

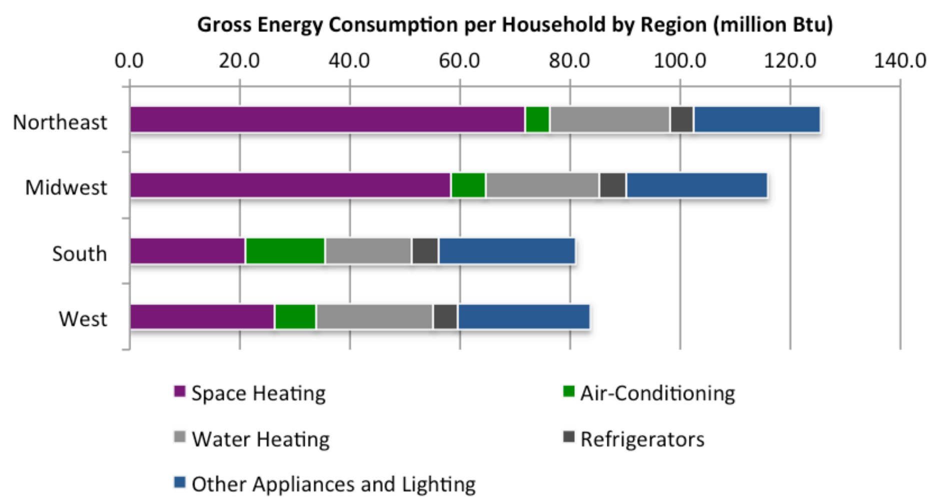


**Figure 3** Gross energy consumption per household by US region [2]

# 2 PURPOSE

The adoption of different energy efficiency strategies is dependent on context, and best when employed as a holistic approach to the design of buildings. In residential construction, the benefits of thermal mass strategies can be understood within this framework. Thermal mass strategies take advantage of the energy storage characteristics of high mass materials to moderate temperature. When integrated with other strategies, such as orientation, windows placement, shading, and insulation, they form the basis of a passive solar design strategy that can reduce the use of energy.

This report discusses a method developed by the CSHub to map thermal mass benefit across the US using a range of material and envelope parameters. The method uses a simplified model in order to identify the range of impacts that result from the relationship between climate, design strategies and envelope thermal properties. The intention of the research is to influence the early decision making process in design and product development.

# 3 APPROACH

The CSHub Cube Model is based on a simplified single-family residence in the shape of a cube, to which the conditions can be changed and the results observed and quantified. It is defined only by length, width, and height; no roof overhangs or geometric irregularities are considered in this building model. Windows have been selected to meet a typical glazing percentage per face and are equally distributed in all directions to ensure an even distribution of sunlight. The thermal properties, such as conductivity, specific heat and density, of the individual construction materials of the roof, walls, and slab are summed to determine equivalent envelope parameters. Values for equivalent envelopes for standard wall sections can be found in Appendix C.

The model combines simplified geometry and equivalent envelope parameters with available climate data and internal loading assumptions. Climate data has been provided by the Typical Meteorological Year 3 (TMY3) study of the US Department of Energy (DOE), allowing for full annual simulations of the building in response to climate [3]. The Building America House Simulation Protocols (BAHSP), a publication of the National Renewable Energy Laboratory (NREL) at the DOE, has been used to determine internal loading assumptions [4]. Detailed information on the model's parameters can be found in Appendix A. For more in-depth analysis of the model, see *Thermal Mass Performance in Residential Construction: An Energy Analysis Using a Cube Model,* by Alison Ledwith [18].

*Thermal Mass and Diffusivity:*

Thermal mass is the ability of a material to store energy at one point in time and release this energy at another. It is dependent on the relationship between the specific heat capacity, density, thickness and conductivity of a material [11]. Typically, materials with high thermal mass, such as brick, concrete and stone, have high density and specific heat while exhibiting moderate conductivity [12]. Multiple factors impact the behavior of thermal mass. Climate is the driving force as it determines the ambient temperature, solar access, humidity, wind patterns, and the diurnal temperature variation of a location. Other factors are defined by the boundary conditions of the building and include building geometry, internal loads, infiltration, ventilation, and occupancy [13].

Diffusivity measures heat flow through a material, or, in other words, the ratio of heat transmittance to heat storage (conductivity divided by density and specific heat)[14]. For a given material or equivalent wall thickness, diffusivity captures both the relationship between the thermal mass of the wall and the heat flow through the wall due to the temperature differential between inside and outside. This is due to the fact that, for a given conductivity, the higher the density and specific heat, the lower the diffusivity. As a result, diffusivity is used in the research as the main tool to quantify thermal mass benefit of the equivalent envelope in relation to climate.

In addition, mapping diffusivity provides an opportunity to identify key parameters impacting energy consumption. Because there is more than one governing parameter driving energy consumption, the research aims to identify the most effective means to reduce energy consumption. That is, given a certain diffusivity, what are the effects of increasing or decreasing density and specific heat, conductivity, and thickness.

With regards to typical materials, some values for typical materials are noted in the table below. Brick, concrete, and solid wood exhibit low diffusivity. Concrete and bricks exhibit low diffusivity due to the high density and specific heat and moderate conductivity. Solid wood has low diffusivity because it has very low conductivity, despite its thermal mass. Even though steel has high density and specific heat, its really high thermal conductivity makes for high diffusivity and hence high heat flow through the material.

**Table 1** Thermal Properties of Typical Building Materials [12]

| Material | Density, kg/m$^3$ (lb/ft$^3$) | Thermal Conductivity, W/mK (Btu/h-ft-F) | Specific Heat, J/kgK (Btu/lb-F)°F) | Diffusivity, m$^2$/s (ft$^2$/h) | Thermal Mass |
|---|---|---|---|---|---|
| **Timber** | 500 (31.21) | .13 (.075) | 1600 (.38) | 1.6E-7 (.006) | Low |
| **Steel** | 7800 (486.94) | 50 (28.89) | 450 (.11) | 1.4E-5 (.542) | Low |
| **Precast and in-situ blocks** | 2300 (143.58) | 1.75 (1.01) | 1000 (.24) | 7.6E-7 (.029) | High |
| **Brick and dense blocks** | 1750 (109.25) | .77 (.44) | 1000 (.24) | 4.4E-7 (.017) | High |

# 4 RESULTS

The following sections present the results of simulations performed with the purpose of mapping diffusivity of equivalent walls in relation to energy consumption. Simulations of equivalent walls were based on using a wall with a constant thickness and a constant conductivity while varying density and specific heat. This provided a method for understanding the impact of density and specific heat of a wall with a given thickness as well as the role of conductivity on energy consumption. A typical wall is defined as having an equivalent thickness of 0.15m (6 in.) and conductivity of 0.9W/m-K (.52 Btu/h-ft-F). Additional information on experiment setup is available in Appendix B.

Four climates are evaluated in detail: a mild, marine climate (San Francisco, CA, zone 3C), hot, dry climate (Phoenix, AZ, zone 2B), hot, humid climate (Miami, FL, zone 1A), and a cold climate (Anchorage, AK, zone 7). Results for annual and season impacts are discussed below, highlighting the key takeaways for each region. More detailed results are available in Appendix E.

## 4.1 Local Results: Annual and Seasonal Impacts

### 4.1.1 General Comments:

Four key trends are evident from the simulations.

1. At all conductivities, equivalent walls with higher values for specific heat and density reduce energy consumption annually.
2. Climate is a key factor in determining the range of benefits from low diffusivity walls.

3. Reducing the conductivity of an equivalent wall is a key factor in reducing energy consumption.
4. Thermal mass benefit has the most impact when daily outdoor temperature variations are above and below the balance point of a building [12]. Hence, cold climates benefit most in the summer season and hot climates in the winter season.
5. For walls with the same density and specific heat and different conductivities, there is less thermal mass benefit at lower conductivities.

### 4.1.2 Mild, Marine Climate
Mild climates benefit most from the use of walls with low diffusivity. Annually, the potential savings is in the range of 22% annually for a typical wall. In addition, a wall with a higher conductivity and low diffusivity can be exchanged with a wall with low conductivity and high diffusivity as a tool to achieve comparable energy consumption. Hence, there is a double benefit of using a wall with low diffusivity at lower conductivities. Seasonally, there is greater energy savings in the summer.

### 4.1.3 Hot, Dry Climate
Thermal mass benefit is in the range of 4.9% annually for a typical wall in a hot, dry climate. In addition, lowering conductivities is a key factor in reducing energy consumption. However, lower conductivities reduces the impact of thermal mass benefit. Seasonally, there is greater energy savings in the winter.

### 4.1.4 Hot, Humid Climate
Hot, humid climates exhibit similar characteristics to a hot, dry climate, but the impact of the thermal mass benefit is lower. Thermal mass benefit is in the range of 3.1% annually for a typical wall.

### 4.1.5 Cold Climate
The conductivity of an equivalent wall is the primary driving force in reducing energy consumption in a cold climate. When considered annually, thermal mass benefit is minimal in a cold climate. For a typical wall, the annual benefit is in the range of 1.5% annually. The amount of thermal mass benefit is dependent on the seasons, with greater impact in the summer than winter.

Starting with a typical wall, the table below outlines the relative relationship between decreasing conductivity and increasing density and specific heat to improve the energy performance of the wall. Highlighted cells imply an opportunity to exchange a wall with high diffusivity and low conductivity with a wall with low diffusivity and high conductivity:

**Table 2** Prioritizing Strategies to Improve the Energy Efficiency of a Typical Wall

| | Mild, Marine | Hot, Dry | Hot, Humid | Cold |
|---|---|---|---|---|
| Lowering conductivity | high | high | high | high |
| Increasing density and specific heat | medium | medium-low | medium-low | low |

## 4.2 Mapping the Results

Figures 4 through 6 show an overview of the results of the simulations for annual, summer and winter energy saving potential based on varying the density and specific heat of a 0.9 W/m-K (.52 Btu/h-ft-F) conductivity and 0.15 m (6 in.) thick equivalent wall. Annual, summer and winter savings were normalized in order to identify percentage benefits of the variations in diffusivity.

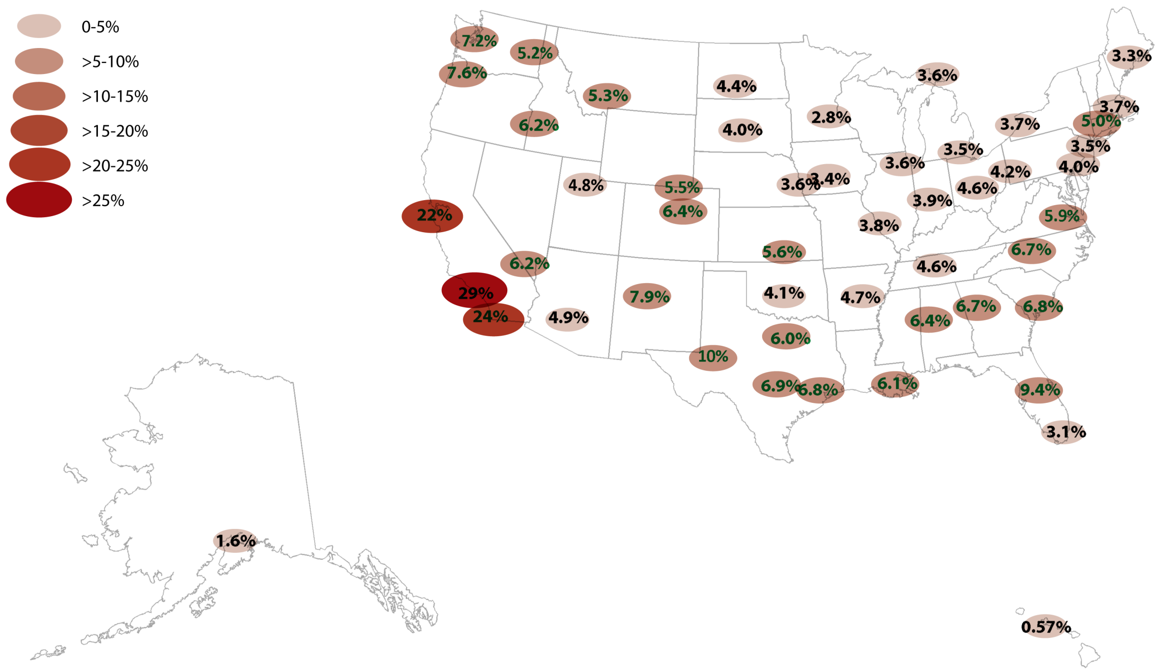


**Figure 4** Percentage Annual Energy Savings vs Diffusivity for a Typical Wall

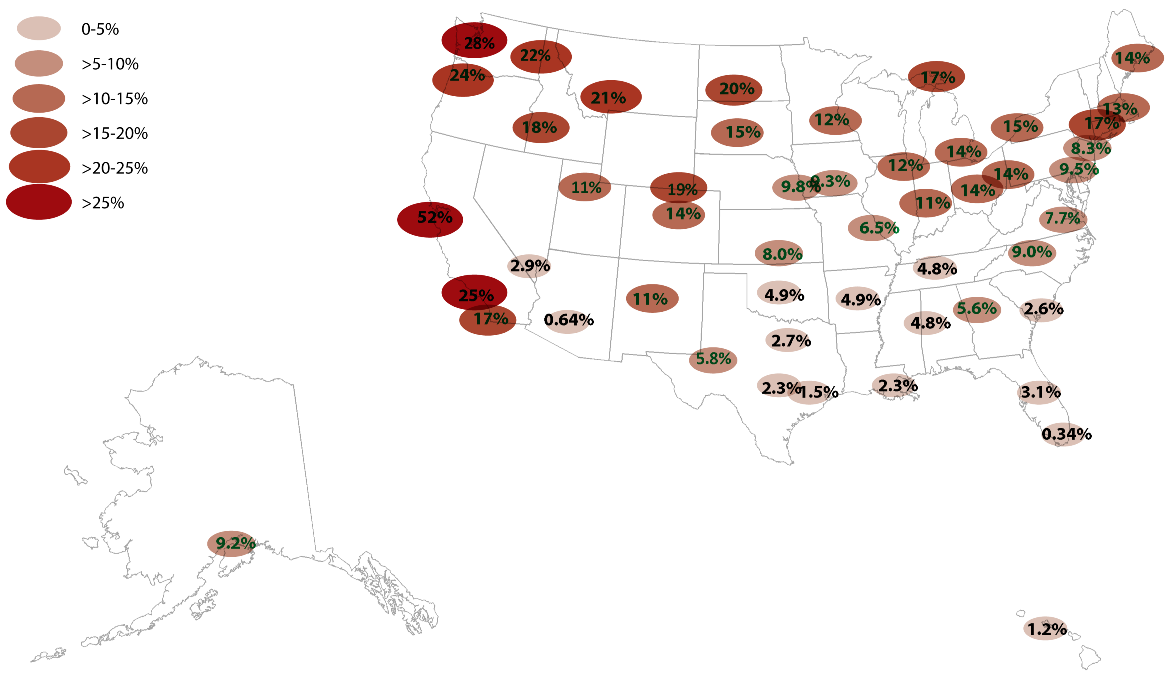


**Figure 5** Percentage Summer Energy Savings vs Diffusivity for a Typical Wall

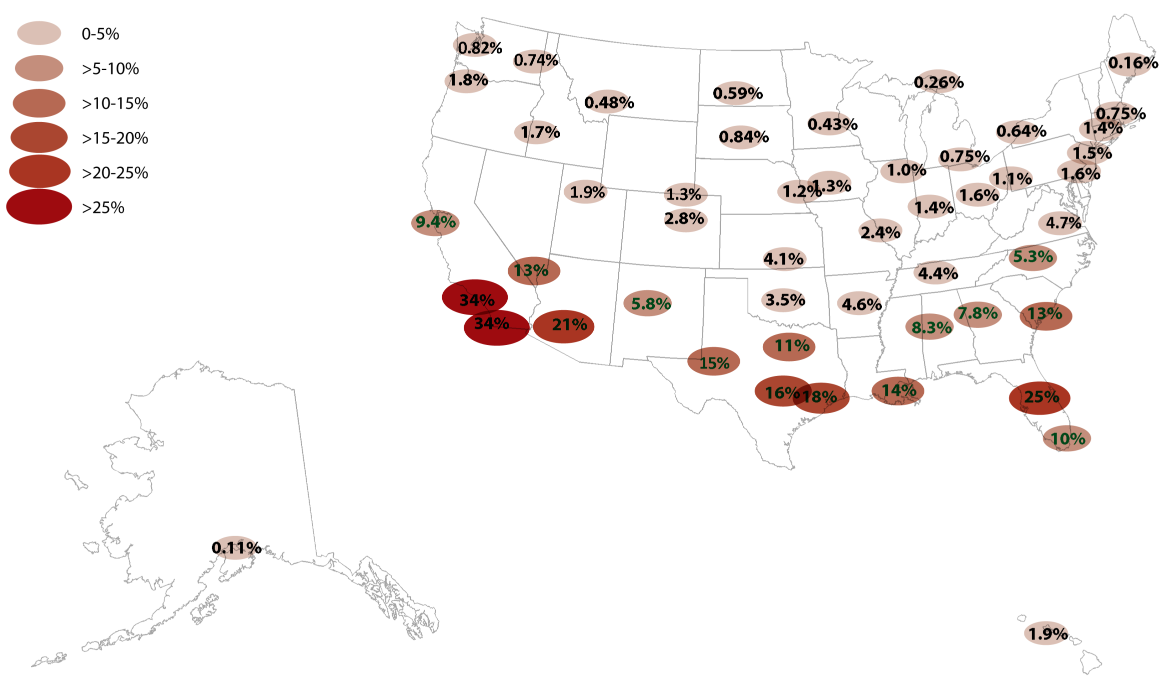


**Figure 6** Percentage Winter Energy Savings vs Diffusivity for a Typical Wall

As the figures indicate, on an annual scale, thermal mass benefits appear to be strongest along the coast of California, with parts of the southeast, southwest, and west also showing impacts. The smallest annual performance gain is located in the northeast, Alaska, and Hawaii. The summer thermal mass benefit is highest for most of the northern U.S. and the west coast, while the winter benefit is highest in the southern U.S.

# 5 SENSITIVITY ANALYSIS

The following section will present results from a sensitivity analysis performed varying the boundary conditions for the Cube Model in the four climates considered in this report. Two of the boundary conditions, infiltration and glazing percentages, will be discussed below. These analyses allow us to see the relationship between changing the parameters of the Cube Model and the impact on energy consumption and diffusivity. See Appendix G for further detail on simulation setup and results.

## 5.1 Infiltration:

Infiltration is the uncontrolled exchange of air between the indoor and outdoor environments through the building envelope. This phenomenon functions as a mechanism of heat loss or heat gain and is responsible for a substantial share of energy usage. As a result, new building codes and voluntary initiatives seek to limit infiltration levels by favoring mechanical ventilation and tight building construction [15].

This work will present results for infiltration in relation to diffusivity and energy consumption. Infiltration was modeled at different levels based on current standards and metrics (from .6 $ACH_{50}$ to 7 $ACH_{50}$). The intention was to determine the relationship between infiltration, diffusivity and energy consumption.

### 5.1.1 Mild, Marine and Hot, Dry Climates:

Mild, marine climates and hot, dry climates exhibit similar characteristics with regards to the impact of infiltration on diffusivity. Here, walls with low diffusivity and high infiltration perform similarly to walls with high diffusivity and low infiltration. At the same time, lowering the diffusivity of the wall provides more benefits than lowering infiltration in terms of reducing energy consumption. The range of benefits vary, with mild, marine climates saving more energy than hot, dry climates by using low diffusivity walls.

### 5.1.2 Hot, Humid Climate and Cold Climates:

While walls with low diffusivity provide opportunities to reduce energy consumption, infiltration is the dominant factor in reducing energy consumption in those two climates. The range of benefits vary, with hot, humid climates favoring a more balanced approach to the use of infiltration and low diffusivity walls.

Starting with a typical wall, the table below outlines the relative relationship between lowering infiltration and increasing density and specific heat to improve the energy performance of the wall. Highlighted cells imply an opportunity to exchange walls with high diffusivity and low infiltration with walls with low diffusivity and high infiltration:

**Table 3** Prioritizing Strategies to Improve the Energy Efficiency of a Typical Wall

| | Mild, Marine | Hot, Dry | Hot, Humid | Cold |
|---|---|---|---|---|
| Lowering infiltration | low | medium | high | high |
| Increasing density and specific heat | high | high | medium-low | low |

## 5.2 Glazing Percentage:

Three levels of window percentage were considered in relation to its impact on thermal mass benefit and energy consumption in the four climates considered. The window percentages studied are 5%, 15%, and 25%.

### 5.2.1 Mild, Marine and Hot, Dry Climates:

Energy consumption decreases as window percentage increases, even though there is a significant difference in the range of thermal mass benefit by climate, with mild, marine climates benefiting most. In addition, there is greater flexibility and more trade-offs in decisions around reducing energy consumption, window percentage, and choice of equivalent walls. For example, a low diffusivity wall with a low percentage of glazing can be exchanged for a high diffusivity wall with a high percentage of glazing and have comparable energy savings. If both high glazing and low diffusivity are combined, additional energy savings can be obtained.

### 5.2.2 Hot, Humid Climate:

The impact of increasing window percentage increases energy consumption in hot, humid climates. Like the mild, marine and hot, dry climates, there is flexibility in how glazing percentage and thermal mass benefit are used, even though the relationships are the reverse. In addition, low diffusivity walls can provide added benefit if both strategies are combined to minimize energy consumption.

### 5.2.3 Cold Climates:

Energy consumption decreases as window percentage increases. Even though there is a benefit to using low diffusivity walls, window percentage is the driving force in reducing energy consumption.

Starting with a typical wall, the table below outlines the relative relationship between changing the percentage of glazing (increasing glazing for mild, marine, hot, dry and cold climates and decreasing glazing for hot, humid climates) and increasing density and specific heat to improve the energy performance of the wall. Highlighted cells imply an opportunity to exchange walls with high diffusivity and high glazing and low diffusivity and low glazing (the inverse in hot, humid climates):

**Table 4** Prioritizing Strategies to Improve the Energy Efficiency of a Typical Wall

| | Mild, Marine | Hot, Dry | Hot, Humid | Cold |
|---|---|---|---|---|
| Modifying glazing percentage | medium | medium | medium | high |
| Increasing density and specific heat | high | high | medium | low |

# 6 CONCLUSION

Analyzing energy efficiency measures requires a whole systems approach to buildings. This ensures that the factors that impact energy efficiency in relation to other design features are taken into account. The approach is incremental, addressing the impacts of one strategy against another. In an attempt to understand one such strategy, thermal mass benefit, this report analyzes the impact of the multiple thermal properties of equivalent walls through the lens of diffusivity. The methodology developed is targeted toward understanding first order impacts and quantifying those impacts in relation to different envelope and design strategies in different climates.

Mapping the results to the U.S. illustrates the trends and emphasizes the importance of climate and context in understanding the impact of thermal mass benefit. It also provides a birds-eye view of thermal mass benefit and its potential for energy savings. The sensitivity analyses ties those results to the other design factors in different contexts. In all cases, trade-offs between different strategies and dominating factors in reducing energy consumption become evident as different strategies are compared to each other and to diffusivity.

By providing first order impacts to decision makers, the methodology allows for more informed decision making in the early phases of the design process. It also provides a guide to the potential opportunities available in making these design decisions. In addition, because the research identifies the most effective means to reduce energy consumption and because the problem of energy consumption is dependent on multiple factors, the methodology can be used to identify methods to optimize the energy consumption by modifying different material - structural parameters. In the end, however, further analysis and simulations would be required to identify the actual impacts of existing and potentially new wall systems in relation to the many design decisions for a specific residence in a specific climate.

# APPENDIX A: SIMULATION APPROACH

## Simplified Geometry

The Cube Model can be controlled by volume, by plan aspect ratio, or by individual dimension assumptions. The parametric nature of the dimensioning of the cube allows many building geometry options to be explored quickly. The baseline dimensions are 10m x 10m x 4m and include no attic or basement.

## Equivalent Wall

The Cube Model uses an equivalent envelope rather than modeling the full construction details of the envelope. Therefore, there is only one layer to the floor, walls, and roof. Each layer comprises the effective thickness, thermal conductivity, density, and specific heat capacity of the overall construction. Material property assumptions have been obtained from ASHRAE Handbook of Fundamentals 2009 and the materials data set available with EnergyPlus, based on the ASHRAE Handbook of Fundamentals 2005 [3][5]. Values for typical wall assemblies are provided in Appendix A.

## Idealized HVAC

The Cube Model utilizes the Ideal Loads Air System in EnergyPlus. This system calculates the combined sensible and latent cooling and heating loads as a result of design decisions, but it does not obtain energy values in electricity or fuel consumed. This system is intended for applications where building performance is the primary target of the study, not HVAC performance. The system has been programmed with infinite capacity, no economizer, no heat recovery, and EnergyPlus default inputs for supply air temperature and humidity [6].

Building setpoints, or desired temperature levels, have been defined in accordance with the procedure outlined from BAHSP. There is a heating setpoint of 21.67 C (71°F) and a cooling setpoint of 24.44 C (76°F), which are based on ASHRAE 55. Heating and cooling availability and the switch between the setpoints has been established using the BAHSP procedure based on the monthly average temperatures, 99% design days provided by ASHRAE, and adjustment parameters exclusive to BAHSP. Finally, the setpoint for dehumidification in the winter is set at 60% relative humidity [4]. Natural ventilation is not provided, as allowed by BAHSP and to accommodate the simplified airflow network in the idealized HVAC system [6][4].

## Climate

The climate data is obtained from the available information on the EnergyPlus website. All U.S. data comes from the Typical Meteorological (TMY3) data set, maintained by NREL [3]. Fifty locations were selected to provide a representative sample of the U.S. climate landscape. The goal of the selected locations is to include a variety of climates, though the actual city selections are somewhat arbitrary. The locations are listed in Appendix B along with their climate zones as indicated in 2012 International Energy Conservation Code (IECC) [7].

## Loads

The types of loads considered are internal mass, occupation gains, lighting, appliances, and domestic hot water. The magnitudes of these loads have been established through BAHSP methods. According to these methods, some loads are fixed in magnitude, some vary by the finish floor area, and others vary by the number of bedrooms in the residence [4]. For the finish floor assumptions, the square footage of the cube is considered as the main living area.

The Cube Model has 2.90 bedrooms, based on the average household size from the 2010 U.S. Census of 2.58 [8] and the BAHSP formula for occupants per bedroom [4]. Internal loads have been programmed with the BAHSP vacation schedule off in order to model a home that is fully occupied year round.

### *Internal Mass*

BAHSP requires the internal mass of the building to be 8 lb/ft$^2$ [4]. The use of wood is recommended by the EnergyPlus data set [3]. From an EnergyPlus standpoint, this translates to the use of a typical wood material with an exposed surface area of 65% of the finished floor area.

### *People*

While the number of people occupying the cube reflects the 2010 Census data, the magnitude of the load has been set from BAHSP assumptions for occupancy [4][8]. The baseline sensible internal load for occupation is 220 Btu/person/h and the baseline latent internal load is 164 Btu/person/h [4]. Schedule assumptions have also been obtained from BAHSP [9].

### *Appliances*

Appliance loads have been obtained from BAHSP assuming that the Cube Model is an electric home. Only those loads used in the benchmark home have been included [4]. The calculated values used in the model for the appliance equipment are shown in Table 1.

**Table 5** Internal Load Assumptions (FFA = Finish Floor Area) by BAHSP [4]

| Equipment Type | Load (kWh/yr) |
|---|---|
| Refrigerator | 434 |
| Range | 490.56 |
| Clothes Washer | 76.19 |
| Clothes Dryer | 1058.16 |
| Dishwasher | 172.23 |
| Miscellaneous Electric Load | $2473.95 + FFA \cdot 0.454$ |

### *Domestic Hot Water*

The baseline hot water use values, taken from BAHSP, are listed in Table 2. In addition, the hot water distribution system increases the overall loads in the building. Due to the substantial seasonal variation, BAHSP recommends calculating a different value per month and then modifying these values through schedules [4]. The monthly loads from the distribution system have been included in Table 3.

**Table 6** Domestic Hot Water Load Assumptions [4]

| Source of Gain | Load (kWh/yr) |
|---|---|
| Shower | 303.90 |
| Bath | 39.01 |
| Sinks | 94.64 |

**Table 7** Domestic Hot Water Distribution System Load Assumptions [4]

| Month | Load (kWh/month) |
|---|---|
| January | 39.37 |
| February | 37.93 |
| March | 36.32 |
| April | 34.97 |
| May | 34.24 |
| June | 34.32 |
| July | 35.20 |
| August | 36.63 |
| September | 38.24 |
| October | 39.60 |
| November | 40.33 |
| December | 40.24 |

### *Lighting*

The cube's lighting is based the BAHSP protocol, which assumes a standard quantity of lighting based on the finished floor area. One important exception is that no garage lighting has been modeled for the cube [4]. In addition, the lighting values are not considered replaceable; only the heat transfer from the radiation of daylight is included in the model. The magnitude of lighting is indicated in Table 4.

**Table 8** Lighting Loads (where FFA = Finish Floor Area) [28]

| Lighting Type | Lighting Load (kWh/yr) |
| --- | --- |
| Internal hard-wired lighting | $0.8(FFA \cdot 0.542 + 334)$ |
| Internal plug-in lighting | $0.2(FFA \cdot 0.542 + 334)$ |
| External lighting | $FFA \cdot 0.145$ |

### *Window Parameters*

One equivalent window is modeled per wall, centered with respect to the height and width. The window has the same aspect ratio as the wall to prevent geometric irregularities. The window size is set based on the BAHSP standard and solar neutrality criteria of 15% glazing per wall [4]. The material composition of the window is based on its equivalent U-factor, solar heat gain coefficient, and visible transmittance as defined by IECC 2012 code requirements [7].

### *Infiltration and Ventilation*

Infiltration is defined as the air changes per hour of the structure. The baseline values are from IECC 2012 and are set by climate zone. Note that these values are denoted in $ACH_{50}$, which is the exchange rate from a door blower test conducted at 50 Pascals [7].

Values for ventilation in excess of infiltration are from ASHRAE 62.2, the relevant standard for the information. The required ventilation has been scaled by the floor area and fixed with respect to the number of bedrooms [10].

# APPENDIX B: EXPERIMENTAL SIMULATION SETUP

In order to study the range of relationships that impact diffusivity, simulations using the cube model varying the material properties that impact diffusivity were conducted. The material properties are thickness, thermal conductivity, density, and specific heat capacity. Each property is varied across a range of values, in order to identify trends and relationships. The ranges and increments used for the experiment are shown in Table 5.

**Table 9** Ranges and Increments for Envelope Parameters

| Parameter | Minimum Value | Maximum Value | Increment |
|---|---|---|---|
| Thickness | 0.05 m | 0.75 m | 0.05 m |
| Thermal Conductivity | 0.1 W/m-K | 2.0 W/m-K | 0.1 W/m-K |
| Density | 100 kg/m$^3$ | 3000 kg/m$^3$ | 100 kg/m$^3$ |
| Specific Heat Capacity | 100 J/kg-K | 2000 J/kg-K | 100 J/kg-K |

Since a complete set of combinations of these parameters would result in 180,000 simulations per climate location, six sub-experiments were conducted where two parameters were varied and two remain constant. This reduced the final scope of the experiment to 2,650 experiments per climate location.

**Table 10** Sub-Experiment Setup

| Parameters Varied | Constant 1 | Constant 2 |
|---|---|---|
| Thermal Conductivity versus Specific Heat | Thickness = 0.15 m | Density = 2300 kg/m$^3$ |
| Thermal Conductivity versus Density | Thickness = 0.15 m | Specific Heat = 650 J/kg-K |
| Thermal Conductivity versus Thickness | Density = 2300 kg/m$^3$ | Specific Heat = 650 J/kg-K |
| Thickness versus Density | Thermal Conductivity = 0.9 W/m-K | Specific Heat = 650 J/kg-K |
| Thickness versus Specific Heat | Thermal Conductivity = 0.9 W/m-K | Density = 2300 kg/m$^3$ |
| Specific Heat versus Density | Thermal Conductivity = 0.9 W/m-K | Thickness = 0.15 m |

# APPENDIX C: EQUIVALENT WALL SAMPLE CALCULATIONS

The table below shows the properties of standard wall sections provided with EnergyPlus [3]. These properties show the magnitudes of input parameters for an equivalent wall section that should be considered in an analysis.

| Construction Name | Thickness (m) | Conductivity (W/m-K) | Density (kg/m$^3$) | Specific Heat (J/kg-K) |
|---|---|---|---|---|
| Composite 2x4 Wood Stud R11 | 0.127 | 0.0636 | 274 | 1048 |
| Composite 2x6 Wood Stud R19 | 0.177 | 0.0577 | 209 | 1006 |
| Composite ICF Wall With Steel Ties | 0.273 | 0.138 | 1173 | 971 |
| Composite Concrete/Foam/Concrete With Steel Connectors | 0.204 | 0.151 | 1395 | 1069 |
| Composite Concrete/Foam/Concrete With Plastic Connectors | 0.204 | 0.108 | 1521 | 975 |
| Composite 2x4 Steel Stud R11 | 0.127 | 0.0816 | 230 | 1048 |
| Composite Brick Foam 2x4 Steel Stud R11 | 0.223 | 0.0989 | 824 | 814 |
| Composite 2x6 Steel Stud R19 | 0.177 | 0.0886 | 175 | 1006 |
| Composite Foam 2x6 Steel Stud R19 | 0.210 | 0.0786 | 329 | 876 |
| Composite Brick Foam 2x6 Steel Stud R19 | 0.273 | 0.100 | 695 | 964 |
| Composite 2-Core Filled Concrete Block Uninsulated | 0.295 | 1.24 | 1405 | 706 |
| Composite 2-Core Filled Concrete Block Insulated | 0.295 | 0.732 | 1186 | 838 |

# APPENDIX D: CLIMATE ZONES

The table below shows locations mapped for diffusivity and the climate zone of those locations as defined by IECC 2012 [7].

**Table 11** Climate Zones for Simulations

| Location | Climate Zone |
|---|---|
| Anchorage, AK | 7 |
| Tuscaloosa, AL | 3A |
| Little Rock, AR | 3A |
| Phoenix, AZ | 2B |
| Los Angeles, CA | 3B |
| San Diego, CA | 3B |
| San Francisco, CA | 3C |
| Denver, CO | 5B |
| Hartford, CT | 5A |
| Miami, FL | 1A |
| Orlando, FL | 2A |
| Atlanta, GA | 3A |
| Honolulu, HI | 1A |
| Des Moines, IA | 5A |
| Boise, ID | 5B |
| Chicago, IL | 5A |
| Indianapolis, IN | 5A |
| Wichita, KS | 4A |
| New Orleans, LA | 2A |
| Boston, MA | 5A |
| Bangor, ME | 6A |
| Detroit, MI | 5A |
| Sault Ste. Marie, MI | 7 |
| Minneapolis, MN | 6A |
| St. Louis, MO | 4A |

| Location | Climate Zone |
|---|---|
| Bozeman, MT | 6B |
| Greensboro, NC | 4A |
| Bismarck, ND | 6A |
| Omaha, NE | 5A |
| Albuquerque, NM | 4B |
| Las Vegas, NV | 3B |
| Buffalo, NY | 5A |
| New York, NY | 4A |
| Columbus, OH | 5A |
| Oklahoma City, OK | 3A |
| Portland, OR | 4C |
| Philadelphia, PA | 4A |
| Pittsburgh, PA | 5A |
| Charleston, SC | 3A |
| Pierre, SD | 6A |
| Nashville, TN | 4A |
| Austin, TX | 2A |
| Dallas, TX | 3A |
| Houston, TX | 2A |
| Midland, TX | 3B |
| Salt Lake City, UT | 5B |
| Richmond, VA | 4A |
| Seattle, WA | 4C |
| Spokane, WA | 5B |
| Cheyenne, WY | 6B |

# APPENDIX E: DETAILED LOCAL CLIMATIC RESULTS

In Figures 4, 5, and 6, specific annual energy consumption is plotted against diffusivity for each climatic zone. Each curve represents variations in density and specific heat of an equivalent wall with a thickness of 0.15m and a constant conductivity. The curves are shifted vertically by changing the conductivity of the material. A few trends are evident from the graphs. Equivalent walls with low diffusivity reduce energy consumption at all conductivities. However, the range of benefits varies depending on climate. At lower conductivities, the dip in the curve is less significant and hence, the benefit from using materials with low diffusivity is smaller. Furthermore, a key factor in reducing energy consumption is reducing the conductivity of an equivalent wall at a particular density and specific heat. And finally, depending on climate, there are different relationships between the role of conductivity, density and specific heat. For example, in a cold climate, such as Anchorage, conductivity is the driving factor in managing energy consumption. In a mild, marine climate, such as San Francisco, overlaps between the curves imply a tradeoff of using a material with low diffusivity at higher conductivities instead of a material with lower conductivity with higher diffusivity and, as a result, an added bonus of capitalizing on both factors.

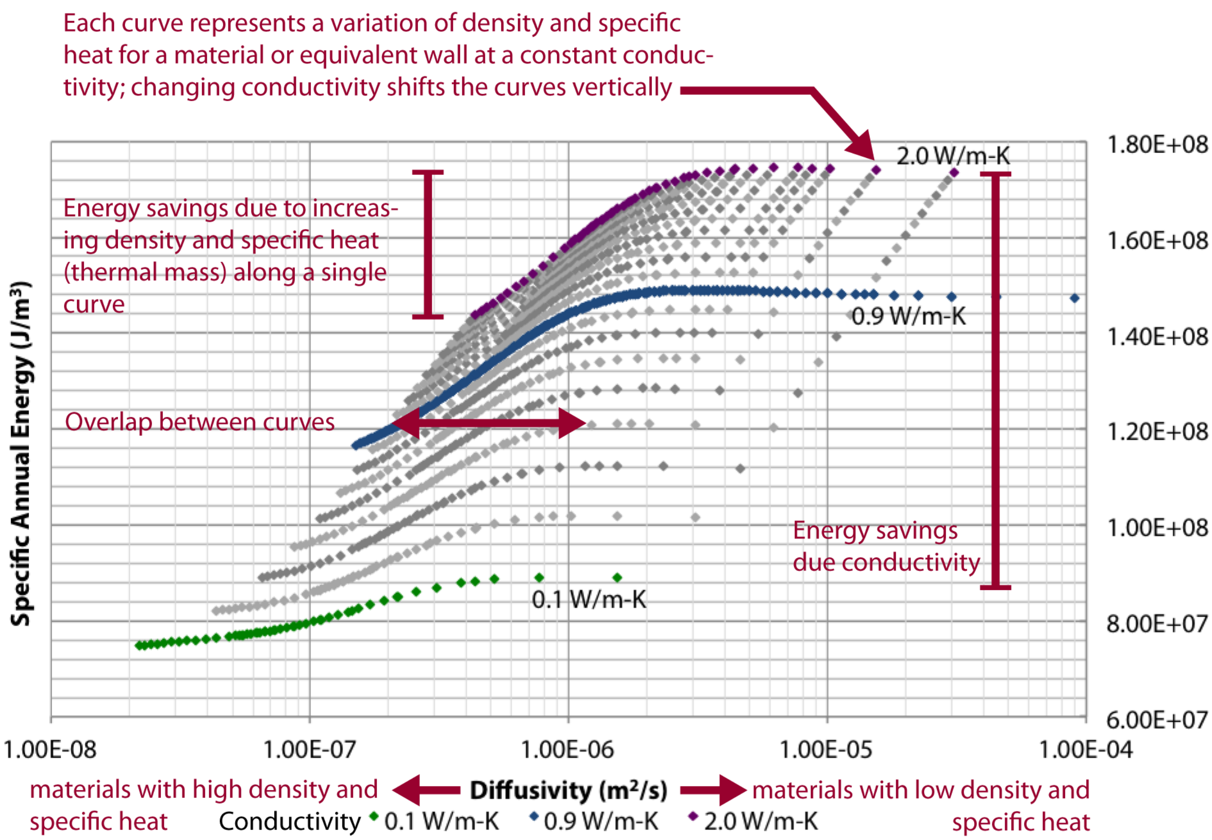


**Figure 7** Specific Annual Energy Consumption vs Diffusivity and Conductivity in a Mild, Marine Climate (San Francisco, CA)

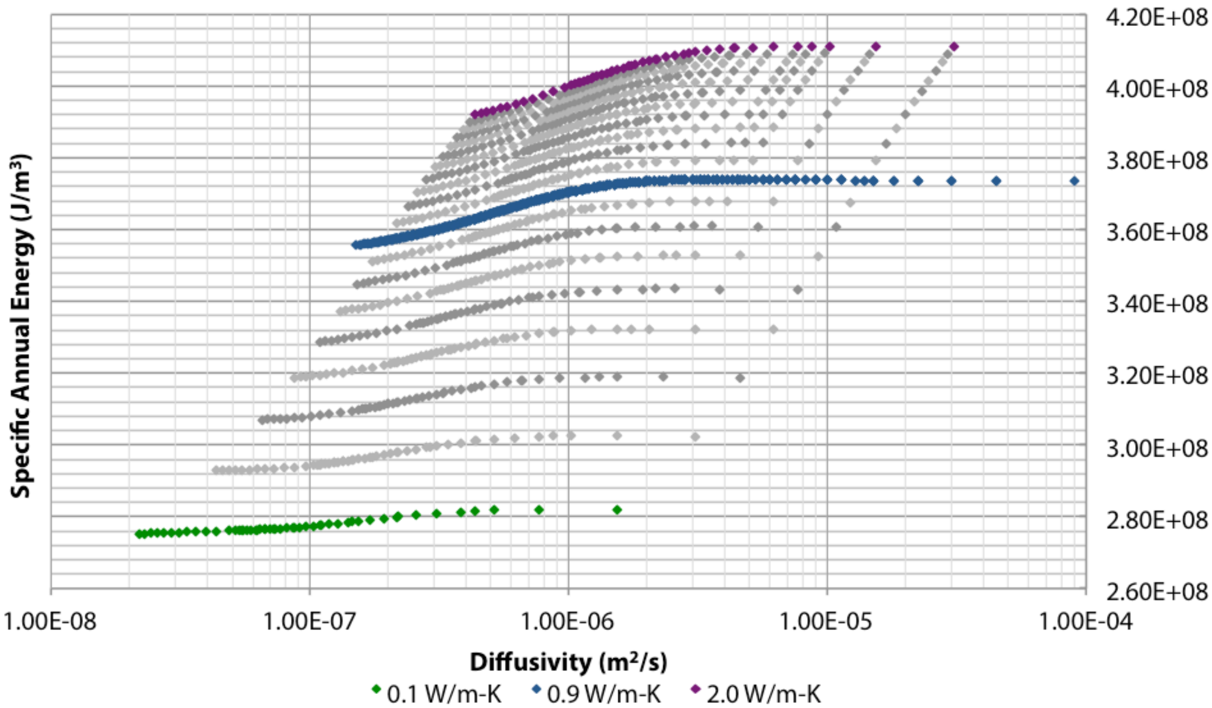


**Figure 8** Specific Annual Energy Consumption vs Diffusivity and Conductivity in a Hot, Dry Climate (Phoenix, AZ)

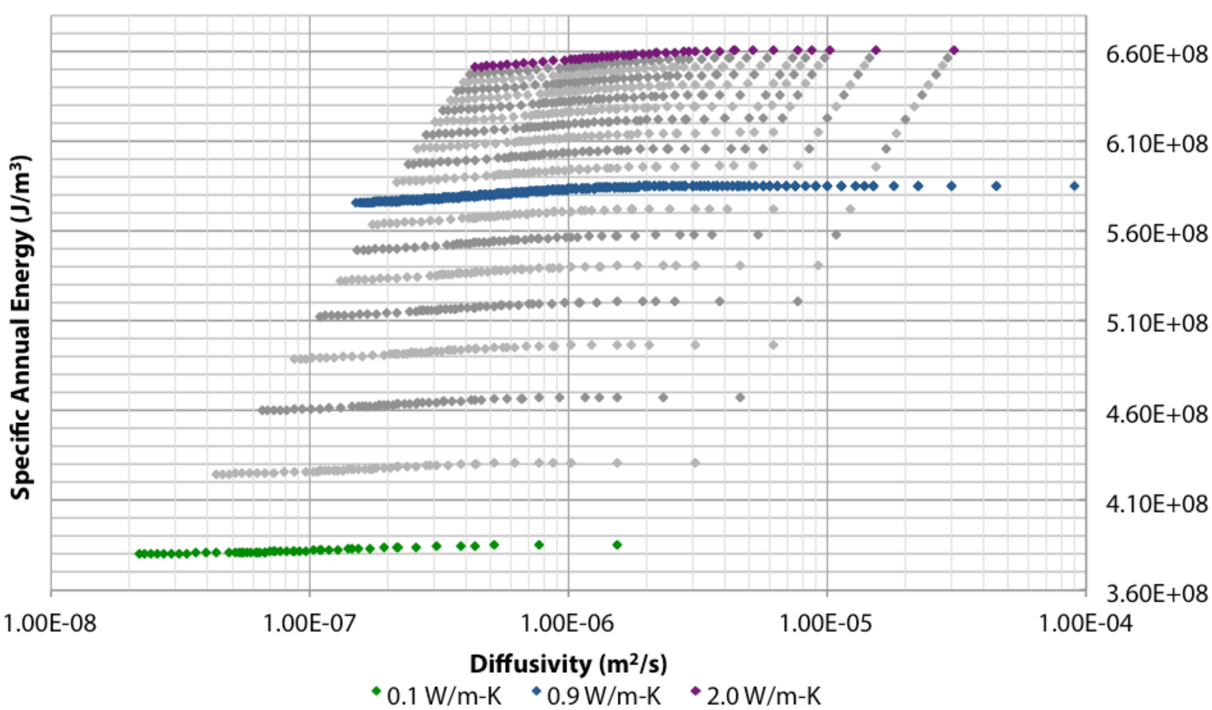


**Figure 9** Specific Annual Energy Consumption vs Diffusivity and Conductivity in a Cold Climate (Anchorage, AK)

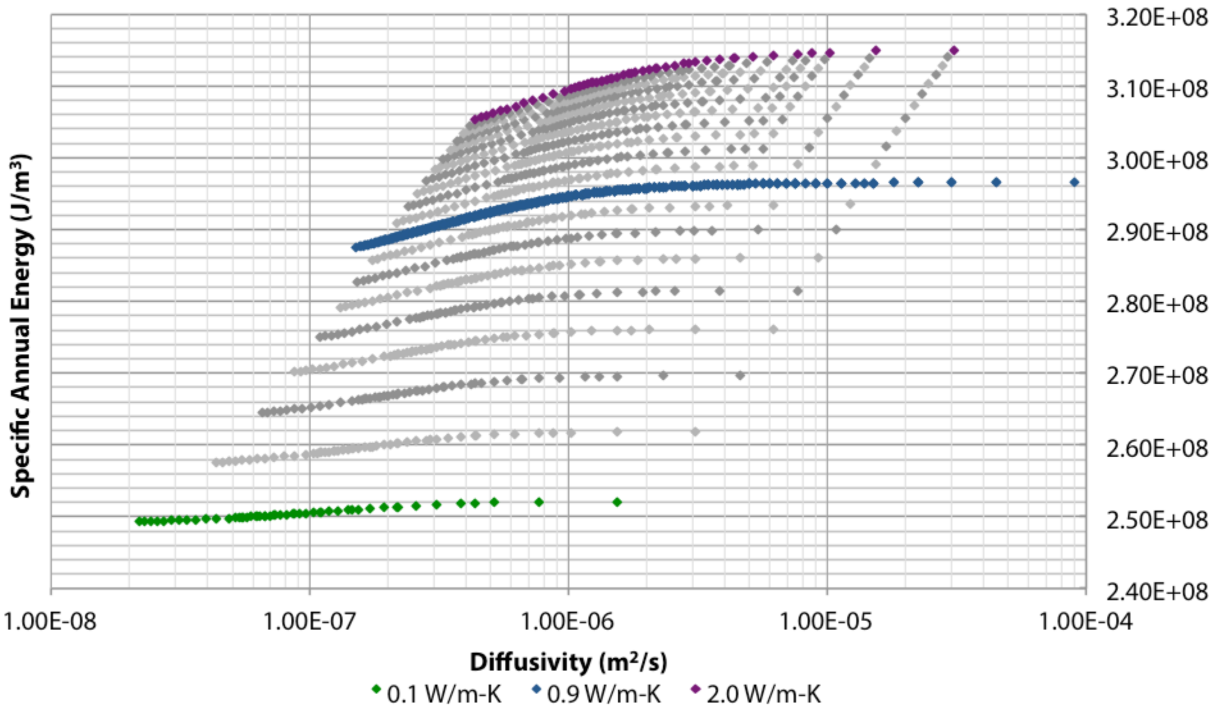


**Figure 10** Specific Annual Energy Consumption vs Diffusivity and Conductivity in a Hot, Humid Climate (Miami, FL)

# APPENDIX F: DETAILED LOCAL SEASONAL RESULTS

Simulations were conducted to understand the impact of the seasons on the diffusivity curve using a similar process. The graphs below show the seasonal variation of changing density and specific heat for a 0.9 W/m-K conductivity and 0.15 m thick equivalent wall. For the purpose of this graph, summer data is the total energy consumption from April to September, while winter data is the total energy consumption from October to March. The graphs are normalized so that comparisons can be made based on percentages.

The graphs below indicate that, in mild, marine and cold climates, equivalent walls with low diffusivity perform better in the summer. In hot, dry and hot, humid climates, the pattern is reversed. This conforms to the fact that when outside temperatures variations are above and below the balance point of a building, materials or walls with low diffusivity perform best [12]. Finally, because the results are normalized to determine thermal mass benefit as a percentage, it is evident that the range of benefits varies depending on climate. For example, San Francisco shows a benefit of 22% annually, while Anchorage, on the other extreme, showing a benefit of 1.6% annually.

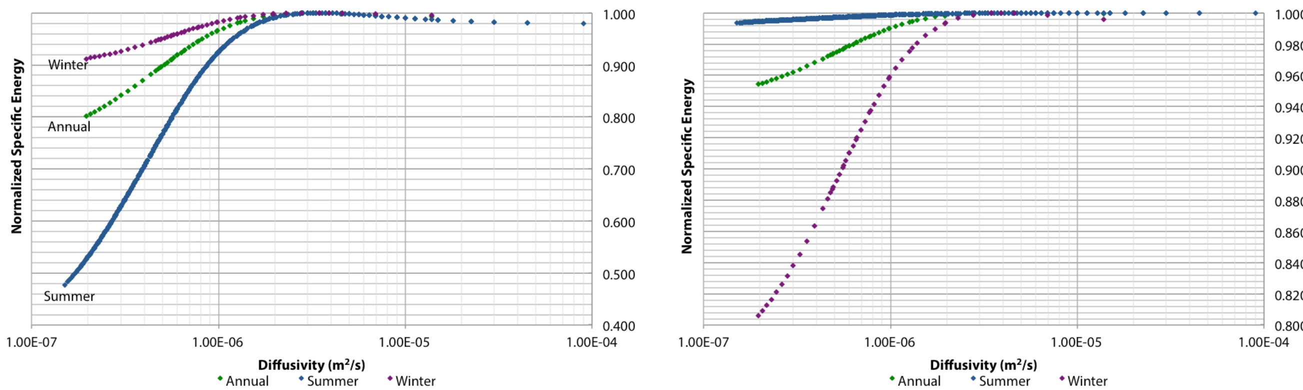


**Figure 11** Normalized Specific Annual Energy Consumption vs Diffusivity and Conductivity by Season in a Mild, Marine Climate (San Francisco, CA) and Hot, Dry Climate (Phoenix, AZ)

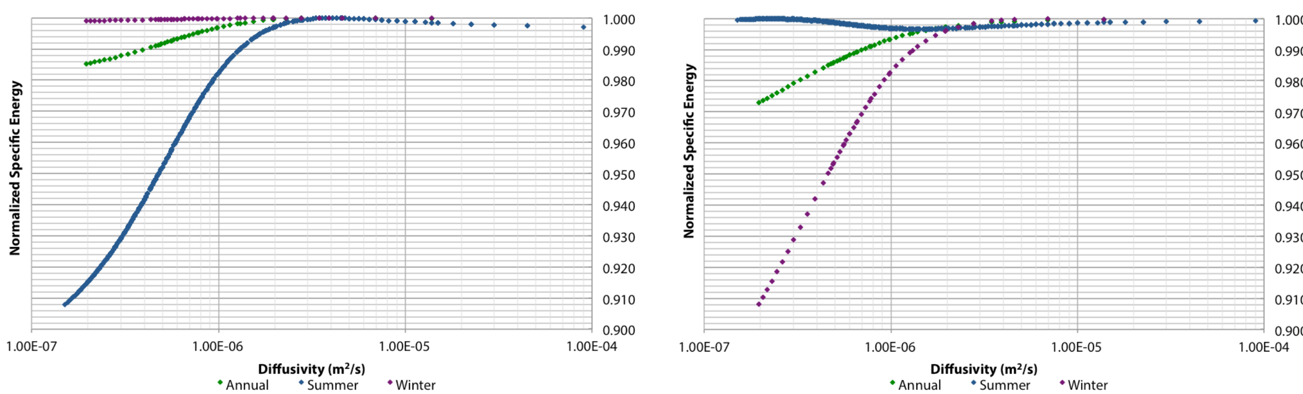


**Figure 12** Normalized Specific Annual Energy Consumption vs Diffusivity and Conductivity by Season in a Cold Climate (Anchorage, AK) and Hot, Humid Climate (Miami, FL)

# APPENDIX G: SENSITIVITY ANALYSIS

## Infiltration

This work will present results for infiltration in relation to diffusivity and energy consumption. Infiltration was modeled at five different levels to determine whether the change has an impact on diffusivity. The infiltration levels, presented in Table 7, are based on current standards and metrics. These standards measure infiltration as the parameter $ACH_{50}$, which is the infiltration rate measured when a blower door test pressurized at 50 Pascals is used [7].

**Table 12** Levels of Infiltration According to Different Standards

| Infiltration Level Description | Infiltration Limit ($ACH_{50}$) |
|---|---|
| Passive House Standard [15] | 0.6 / h |
| German Legal Limit for Buildings with Mechanical Ventilation [16] | 1.5 / h |
| International Energy Conservation Code 2012 (Climates 1+2, Climates 3-8) [7] | 3.0 / h, 5.0 / h |
| International Energy Conservation Code 2009 [17] | 7.0 / h |

For each level of infiltration, simulations were conducted varying density and specific heat for the different climates. The values of wall thickness and conductivity were set to 0.15 m and 0.9 W/m-K respectively. The values for specific heat and density were varied across 100 trials per infiltration level. The experiment setup for the varying parameters is presented in Table 8.

**Table 13 Ranges and Increments for Infiltration Study**

| Parameter | Minimum Value | Maximum Value | Increment |
|---|---|---|---|
| Density | 300 kg/m$^3$ | 3000 kg/m$^3$ | 300 kg/m$^3$ |
| Specific Heat | 200 J/kg-K | 2000 J/kg-K | 200 J/kg-K |

### *Local Results*

The following analysis will present findings for the four climates analyzed in the previous section. Because the diffusivity curves are constant at different infiltration levels, the results indicate that there is little or no impact on the diffusivity curves from varying the infiltration rate for a building. Also, they confirm that tighter construction results in lower energy consumption. In addition, the graphs show which strategy or strategies, infiltration and/or diffusivity, dominate in a particular climate in relation to energy consumption. For example, in a mild, marine climate and in a hot, dry climate, there is significant overlap between the diffusivity curves at different infiltration levels in relation to energy consumption. Hence, using an equivalent wall with low diffusivity can save more energy than improving the air-tightness of construction. Similarly, using a wall with high diffusivity and low infiltration can save the same energy as an equivalent wall with low diffusivity and high infiltration. On the other hand, in a cold climate, even though there is a benefit to using walls with low diffusivity, the benefits of reducing air infiltration provide for more significant savings. In a hot and humid climate, there is a balance between both strategies as a means to reduce energy consumption.

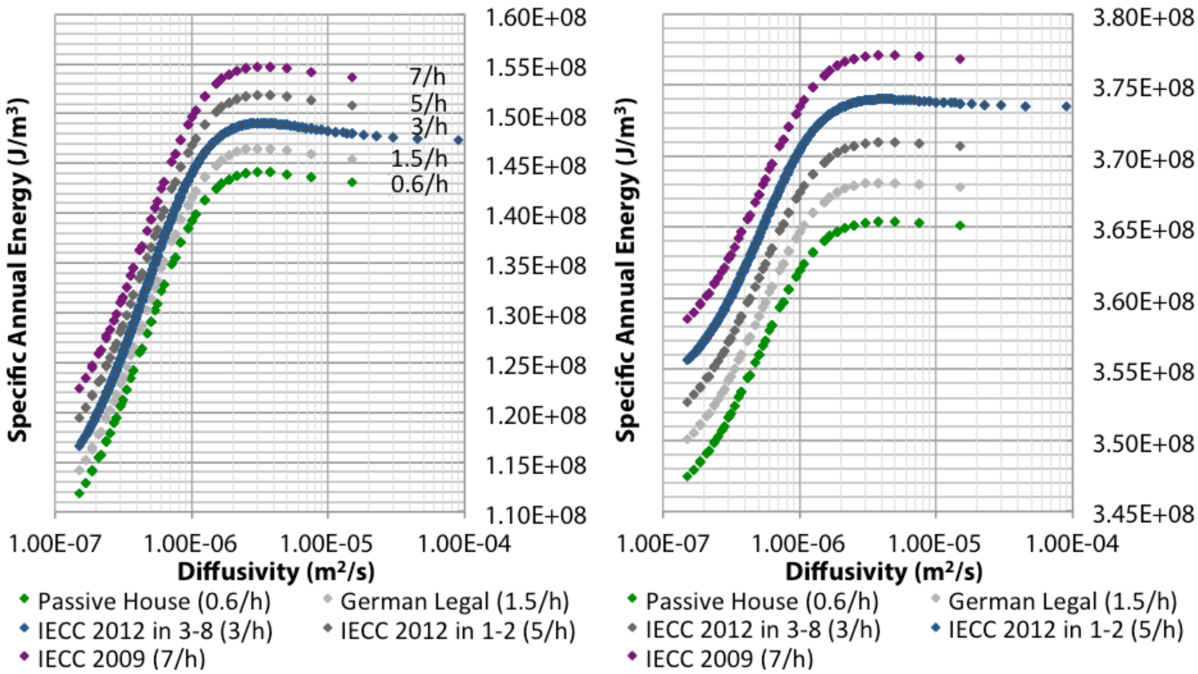


**Figure 13** Specific Annual Energy Consumption vs Diffusivity and Infiltration in a Mild, Marine Climate (San Francisco, CA) and Hot, Dry Climate (Phoenix, AZ)

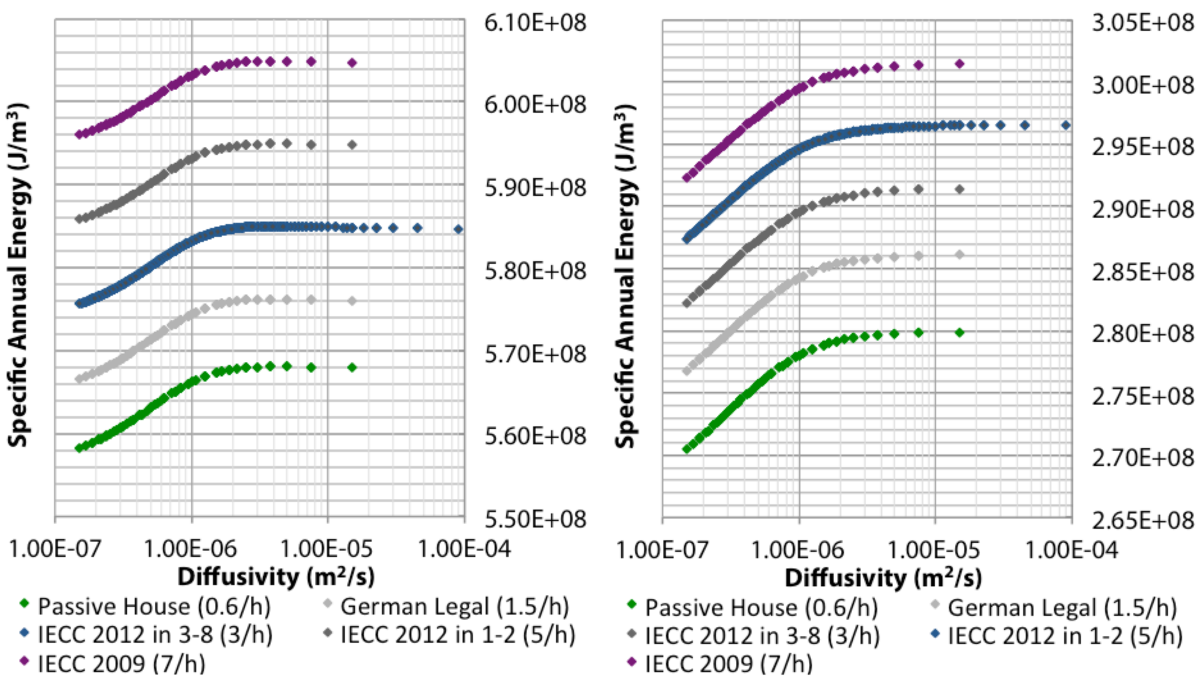


**Figure 14** Specific Annual Energy Consumption vs Diffusivity and Infiltration in a Cold Climate (Anchorage, AK) and Hot, Humid Climate (Miami, FL)

# Geometry

This section will determine how changes in height, plan dimensions, and glazing percentage impact the relationship between geometry and diffusivity. Like infiltration, this will identify the tradeoffs in using these strategies in relation to the diffusivity of an equivalent wall.

Each simulation experiment has unique parameters that will be discussed individually, but all of the experiments maintained a few constant parameters. In all of the experiments, the conductivity and material thickness were fixed at 0.9 W/m-K and 0.15 m, respectively. In addition, each experiment used the same variable parameters as shown in Table 9.

**Table 14** Ranges and Increments for Geometry Studies

| Parameter | Minimum Value | Maximum Value | Increment |
|---|---|---|---|
| Density | 300 kg/m$^3$ | 3000 kg/m$^3$ | 300 kg/m$^3$ |
| Specific Heat | 200 J/kg-K | 2000 J/kg-K | 200 J/kg-K |

### *Plan Aspect Ratio and Height*

The following results show the impact of changes to the height and plan aspect ratio of the cube in relation to diffusivity and energy consumption. Cube heights of 6m and 8m were compared against the 4m baseline cube assumption. One experiment increased the cube height while maintaining the floor area constant. Here, an increase in volume (400, 600, 800 m$^3$) is combined with additional exposed wall surface area of 160, 240, and 320m$^2$ respectively. A second experiment increased the height while maintaining the volume constant. A constant volume of 400m$^3$ is combined with an increase of exposed wall surface area of 160, 195.84, and 226.24m$^2$.

The results from the first experiment show that changing the height while maintaining a constant footprint reduces the energy consumption. In addition, in a mild, marine climate, there is an overlap between the diffusivity curves. Here, structures with a baseline volume of 10 x 10 x 4m having walls with low diffusivity can have the same impact as higher structures with more volume having walls with high diffusivity. In other climates, changing the height governs and provides the most energy savings.

In the second experiment, where the height is changed while maintaining a constant volume, the results show that plan aspect ratio does impact energy consumption and that the relationship between diffusivity and climate determines where the benefits are. In the mild, marine, hot, dry, and cold climates, the more compact plan with the 6m height shows the most savings at low diffusivity. Similarly, using walls with low diffusivity in a climate like San Francisco mitigates the impact of changing aspect ratio. In other climates, there is a divergence or convergence depending on aspect ratio. What becomes clear in this analysis is that there are optimum relationships between wall diffusivity and aspect ratio in a particular climate.

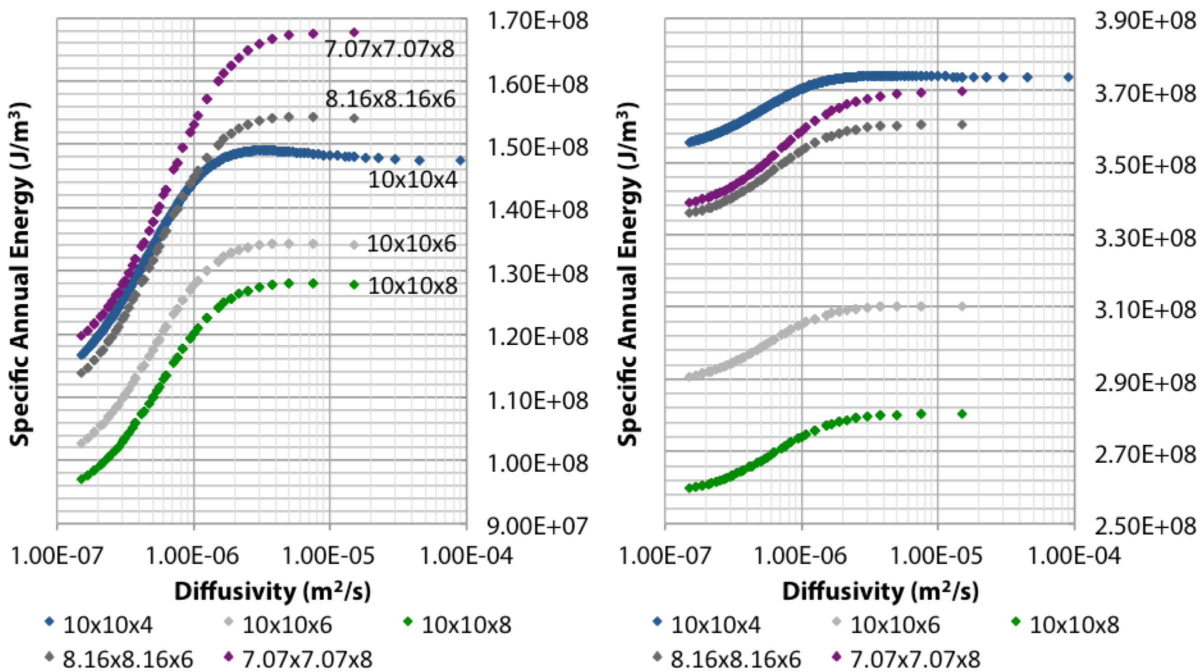


**Figure 15** Specific Annual Energy Consumption vs Diffusivity and Building Height in a Mild, Marine Climate (San Francisco, CA) and Hot, Dry Climate (Phoenix, AZ)

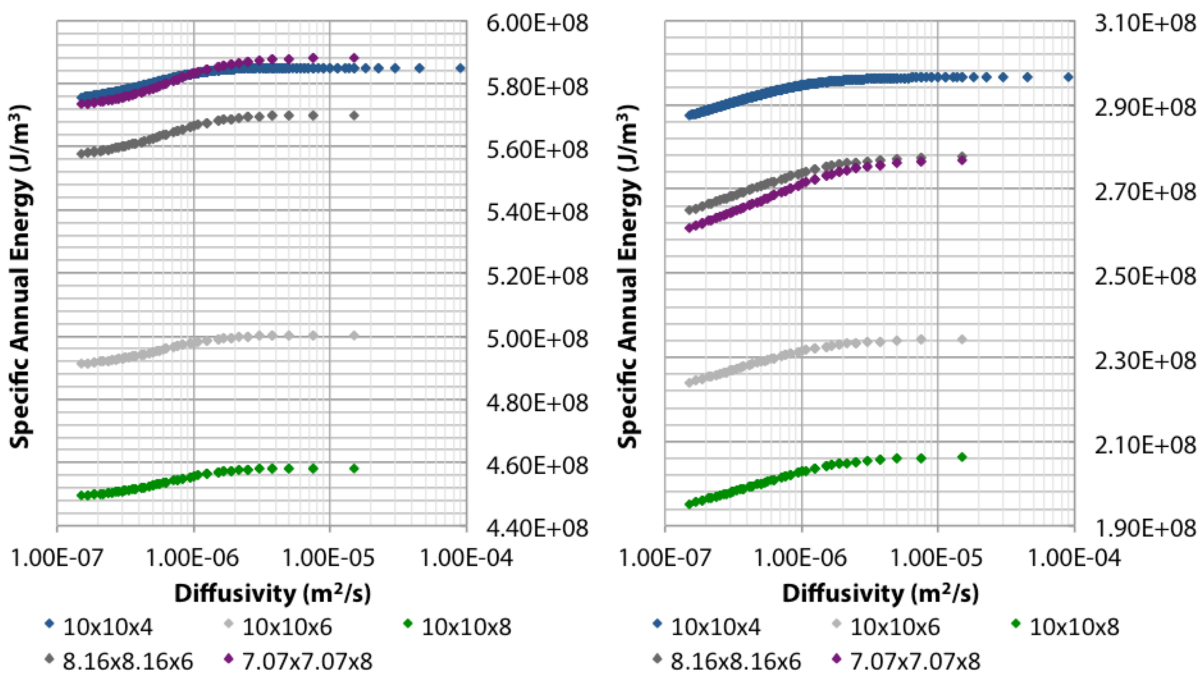


**Figure 16** Specific Annual Energy Consumption vs Diffusivity and Building Height in a Cold Climate (Anchorage, AK) and Hot, Humid Climate (Miami, FL)

*Plan Aspect Ratio and Orientation*

The following results illustrate the impact of varying plan aspect ratio in relation to orientation on diffusivity and energy consumption. Volume is kept constant. In addition to the 10m by 10m cube, a 13.33m by 7.5m cube and a 20m by 5m cube were modeled in two directions, N-S or E-W.

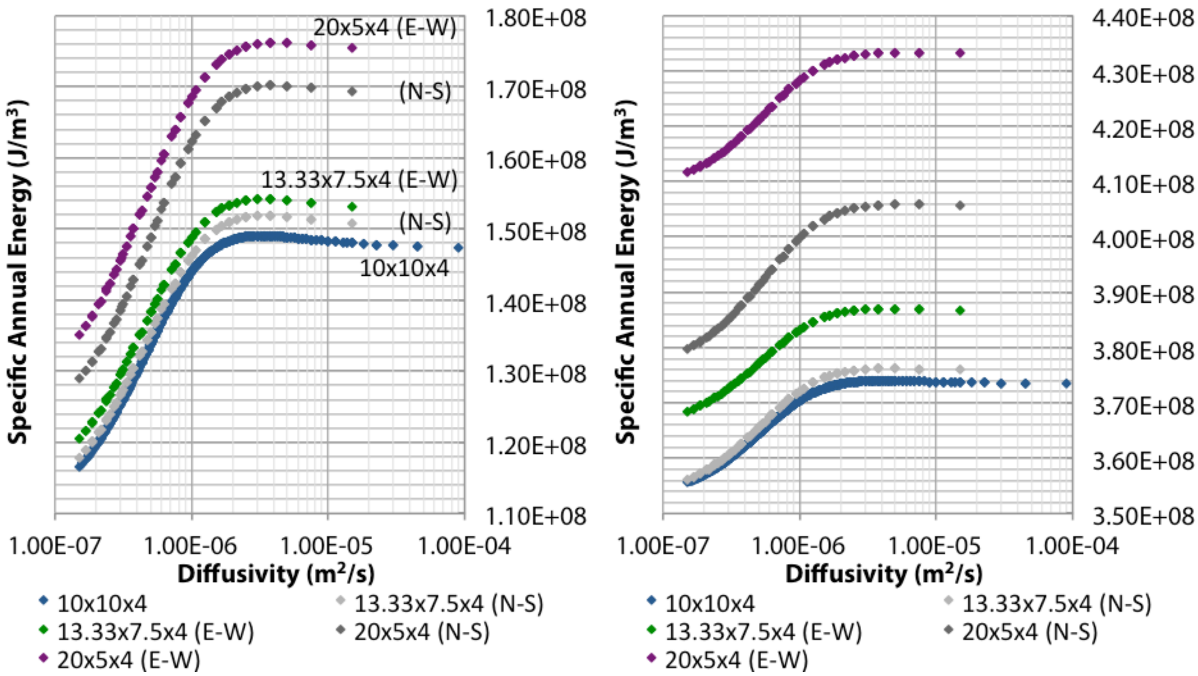


**Figure 17** Specific Annual Energy Consumption vs Diffusivity and Plan Aspect Ratio in a Mild, Marine Climate (San Francisco, CA) and Hot, Dry Climate (Phoenix, AZ)

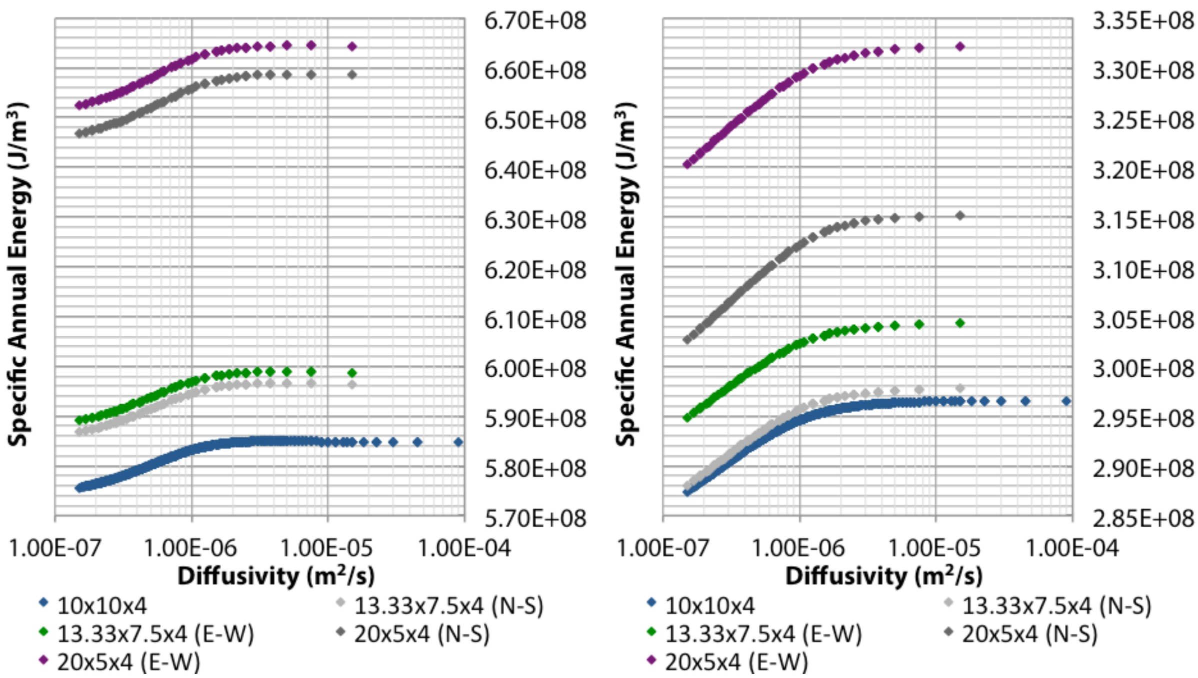


**Figure 18** Specific Annual Energy Consumption vs Diffusivity and Plan Aspect Ratio in a Cold Climate (Anchorage, AK) and Hot, Humid Climate (Miami, FL)

The results indicate that the lowest overall energy consumption is for the cube plan, while increasingly rectangular buildings will result in higher overall energy consumption. In the mild, marine climate, there is a great overlap in the diffusivity curves, meaning that walls with low diffusivity can be used to obtain the same energy performance for a rectangular building as that of the cube. In the other climates, however, plan aspect ratio governs, with more rectangular forms consuming more energy. With regards to the orientation of a rectangular form, the N-S orientation performs best for each option at all diffusivities. In addition, the slightly greater dip in the curves for the N-S orientation for San Francisco, Phoenix, and Miami as the diffusivity of the wall decreases signifies that diffusivity can mitigate the impacts of increased energy consumption due to form. This is particularly obvious in the convergence of the curves of the 13.33 x 7 x 4m form and the cube at lower diffusivities. For a cold climate, however, form is the main driver for reducing energy consumption, with orientation and low diffusivity providing additional, yet small benefits.

### *Glazing Percentage*

The final geometry parameter studied is the glazing percentage and its impact on energy consumption and diffusivity. In addition to the 15% standard window percentage, 5% and 25% percentages were tested as points of comparison. All other parameters remain constant, and the results for the four climates are presented below.

The results indicate that energy consumption decreases as window percentage increases in three of the four climates: the mild, marine, hot, dry and cold climates. In the hot, humid climate, the impact of increasing window percentage increases energy consumption. However, using equivalent walls of low diffusivity reduces energy consumption in all climates. In the mild, marine, hot, dry and hot, humid climates, overlaps between the curves at different levels of window percentage implies greater flexibility and more trade-offs in decisions around reducing energy consumption, window percentage, and choice of equivalent walls. In cold climates, however, window percentage is the driving force in reducing energy consumption.

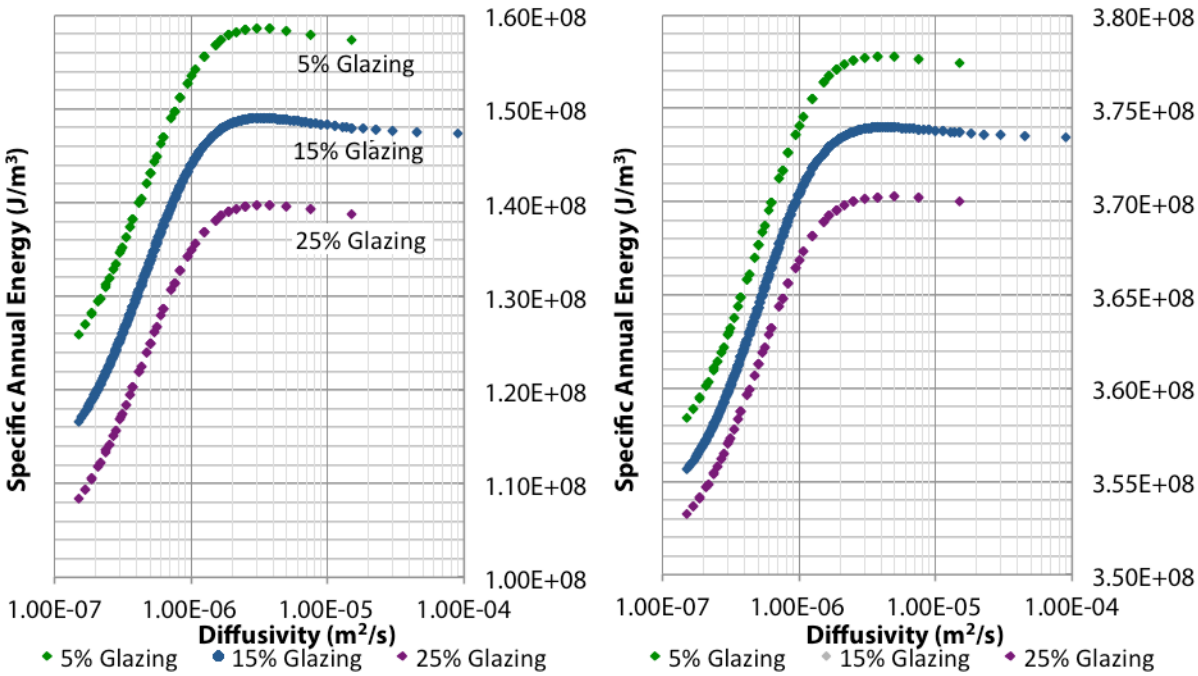


**Figure 19** Specific Annual Energy Consumption vs Diffusivity and Glazing Percentage in a Mild, Marine Climate (San Francisco, CA) and Hot, Dry Climate (Phoenix, AZ)

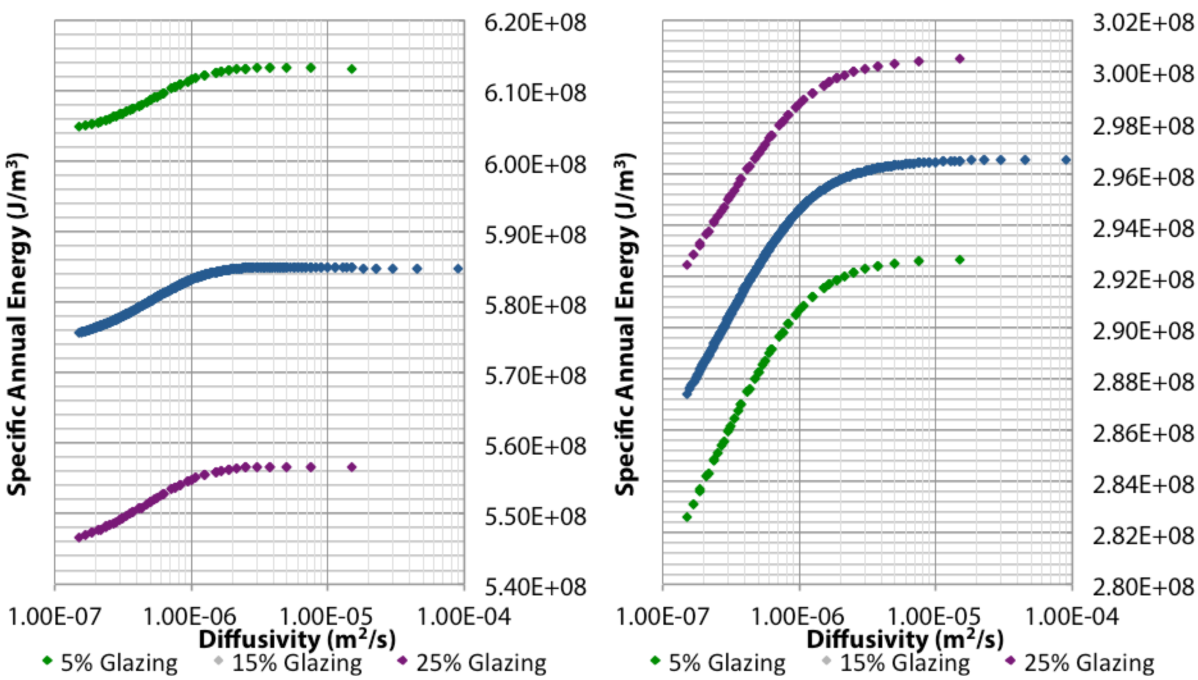


**Figure 20** Specific Annual Energy Consumption vs Diffusivity and Glazing Percentage in a Cold Climate (Anchorage, AK) and Hot, Humid Climate (Miami, FL)

# REFERENCES

[1] U.S. Energy Information Administration, *2012 Annual Energy Review*, September 27, 2012. Available: http://www.eia.gov/totalenergy/data/annual/.

[2] U.S. Energy Information Administration, *2005 RECS Survey Data*, 2009. Available: http://www.eia.gov/consumption/residential/data/2005/.

[3] EnergyPlus Energy Simulation Software version 7.1.0. US Department of Energy, 2012. Available: http://www.energyplus.gov.

[4] R. Hedron and C. Engebrecht, *Building America House Simulation Protocols*, Oak Ridge, TN: National Renewable Energy Laboratory, U.S. Department of Energy, 2010.

[5] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., *2009 ASHRAE Handbook - Fundamentals (SI Edition)*, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2009.

[6] University of Illinois and Ernest Orlando Lawrence Berkeley National Laboratory, *Input/Output Reference*, May 2012. Available: http://apps1.eere.energy.gov/buildings/energyplus/pdfs/inputoutputreference.pdf.

[7] International Code Council, *2012 International Energy Conservation Code*, Falls Church, VA: International Code Council, 2011. Available: http://publicecodes.citation.com/icod/iecc/2012/.

[8] U.S. Census Bureau. *Profile of General Population and Housing Characteristics: 2010*, 2010. Available: http://factfinder2.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=DEC_10_DP_DPDP1&prodType=table.

[9] U.S. Department of Energy. *Building America -- Resources for Energy Efficient Homes: Analysis Spreadsheets*, 2011. Available: http://www1.eere.energy.gov/buildings/building_america/analysis_spreadsheets.html.

[10] Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Standard 62.2-2010, 2010.

[11] M.G. Davies, *Building Heat Transfer*, Chichester, England: John Wiley & Sons, Ltd, 2004.

[12] D. Bennett. *Sustainable Concrete Architecture*. London: RIBA Publishing, 2010.

[13] C.A. Balaras. (1996). The Role of Thermal Mass on the Cooling Load of Buildings. An Overview of Computational Methods. *Energy and Buildings 24*, pp. 1-10.

[14] P. von Böckh and T. Wetzel. *Heat Transfer: Basics and Practice*. New York: Springer, 2012.

[15] H. Erhorn-Kluttig, H. Erhorn, and H. Lahmidi. "Airtightness Requirements for High Performance Building Envelopes," ASIEPI Information Paper P157, 2009. Available: http://www.buildup.eu/publications/5656.

[16] International Code Council, *2009 International Energy Conservation Code*, Falls Church, VA: International Code Council, 2009. Available: http://publicecodes.citation.com/icod/iecc/2009/.

[17] U.S. Census Bureau, *State & County QuickFacts*. Available: quickfacts.census.gov.

[18] Alison Ledwith. *Thermal Mass Performance in Residential Construction: An Energy Analysis Using a Cube Model*, Thesis, Department of Civil and Environmental Engineering, MIT, 2012.