An Investigation of Alternative Energy Efficient Designs in Medium Sized Single Wythe Masonry Buildings

Phase 1 – Warehouse Buildings

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INTRODUCTION / BACKGROUND AND SIGNIFICANCE

The demand and cost of energy will increase as the population and economy of the United States continues to grow. For example, Kentucky's energy use is expected to rise more than 40 percent over current levels by the year 2025[1]. Moreover, the rapidly increasing demand for energy by developing nations such as China and India will strain energy production globally, and exacerbate our domestic concerns about energy production, reliability of supply, and cost. China's yearly energy consumption nearly tripled from 36.5 to 90.25 quadrillion Btu between 1999 and 2009, while India's nearly doubled from 13 to 21.7 quadrillion Btu during the same period[2]. These significant increases in energy demand, and thus costs, will negatively impact the US economy and its global competitiveness unless measures are taken domestically to control and mitigate the unfavorable effects.

In recognition of the fact that a significant amount of energy in the US is used to heat, cool and light buildings, a number of code development bodies and standards developing organizations, including The International Code Committee (ICC) and ASHRAE, have been actively developing and updating energy efficiency standards, code requirements, and guidelines for the built environment. As these documents evolved over the past several decades, the required minimum energy efficiencies of the construction permitted by each have been steadily increasing. As a result of these improvements, more energy efficient buildings are now being constructed with higher performance building envelope systems, larger use of day-lighting and occupancy sensors, and more efficient heating and cooling systems.

The International Energy Conservation Code (IECC) is referenced by the International Building Code (IBC), and is generally the basis by which energy related systems within new building construction are designed. Although IECC has its own design provisions, it also allows new designs to meet the requirements of "*ASHRAE 90.1" (ANSI/ASHRAE/IES Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings) [3]*.

The ASHRAE 90.1 provisions define two compliance paths for meeting the energy efficiency goals with each new building design. The first is prescriptive in nature, wherein the minimum energy-related characteristics for all significant elements within a building are defined quantitatively for different system types (such as building envelope and HVAC), space uses, and climates. The prescriptive path effectively defines a minimum baseline energy performance and consumption for a building. The second design compliance path requires a sophisticated whole building energy analysis to be conducted on the proposed building and compared to the same (the virtual, or "budget") building designed using the prescriptive provisions; for compliance, comparable energy performance is required. Additionally, under the Building Envelope Section of ASHRAE 90.1, a building envelope “trade-off option” may be used as an alternative compliance path to the fully prescriptive envelope option. It is used where the energy performance of one or more components in the building envelope of the proposed building does not meet its minimum performance level required under the prescriptive option, yet, other components exceed their minimum. It requires a performance trade-off analysis to be conducted on the building envelope components for both the proposed building and the base envelope design using the concept of an “envelope performance factor”. Both buildings are similarly modeled. For compliance, the performance factor of the proposed building must be not less than that of the base building which provides approximately equivalent performance to the fully prescriptive requirement option. Despite the various compliance options provided by ASHRAE 90.1, due to ease of use, presently most buildings are designed using the prescriptive approach. However, increasingly more designs are using whole building energy analysis as new software makes this easier to do and reduces cost, as LEED and other energy efficiency provisions require more detailed analyses, and as building owners and designers demand more flexibility in design and construction to demonstrate equivalent performance and compliance.

In most climates in the US, the code mandated prescriptive envelope requirements would require that single wythe exterior masonry walls be designed with thermal resistances varying from 5.7 $ft^2 \cdot °F \cdot h/Btu$ to over 15 $ft^2 \cdot °F \cdot h/Btu$. This requirement, and more specifically, the consequent need to apply continuous insulation on the interior or exterior surfaces of the single wythe wall, greatly impacts the cost of these wall systems and oftentimes detrimentally affects their durability and maintenance costs. Moreover, most design guides developed for energy efficient design begin with the assumption that increases in building envelope thermal resistance are needed to improve whole building energy efficiency. Thus, most designers are conditioned to believe that a building envelope with high thermal resistance is essential for an energy efficient building. A recent study, however, has shown that increasing insulation in a building envelope may have only a minimal effect on the overall energy performance of the building, especially where the building is constructed of walls having a high thermal mass such as concrete block masonry[4]. Providing large increases in the thermal resistance of the building envelope (doubling the R-value from code prescribed minimums) will not necessarily result in a corresponding reduction in building energy use (this study showed that a 50% increase in thermal resistance had less than a 1% effect on overall building energy use in Climate Zone 4). After a certain threshold of resistance, “more is not necessarily better”. This type of building energy behavior is quite evident under a whole building energy analysis. Unfortunately, by using the prescriptive methods, designers rarely achieve the most cost effective, or energy efficient building designs. In fact, most designers simply use the prescriptive provisions to design the building systems and these are not always the most cost effective or efficient systems that can be used.

There are similar energy provisions and compliance paths in the Canadian codes, along with the accompanying shortcomings.

There is, therefore, a need to develop guides that describe how to design buildings that offer energy efficient designs that are code-compliant without sacrificing economics. This is particularly true for building envelope components such as single wythe concrete block masonry wall systems which may not comply with the simple prescriptive requirements for thermal resistance in a heating-controlled climate but act to improve energy efficiency as a result of thermal mass, the effects of which are not fully accounted for except by using whole-building analysis. In addition, single wythe masonry walls have traits that make them preferable choices for uses and occupancies where other building performance considerations dominate such as resistance to sound, fire, structure loads, property and personal protection, resistance to mechanical damage, indoor air quality, and durability.

This guide for the design of code compliant, energy efficient buildings, intends to:

1. Identify representative (archetype/prototype) commercial and light industrial buildings that are commonly constructed with single wythe masonry walls.

2. Develop models for whole building energy analysis for each of the prototype buildings and conduct a series of energy analyses on these models over a range of climates using code prescriptive building configurations.

3. Evaluate the energy used by these prototype building models for a range of alternative building system configurations that produce equivalent performance to the code prescriptive building configurations.

4. Conduct differential cost analyses for the code prescriptive and the alternative compliant building system configurations.

5. Develop a series of recommendations on how to produce cost effective buildings of a specific archetype/prototype that are code compliant and use single wythe masonry wall systems.

The investigation is divided into two phases of work. Phase 1 was a proof of concept phase where the process was applied to one archetype (prototype) building (warehousing). Specially, the Phase 1 investigation focused on the effects on energy consumption of various building envelope systems, and heating/cooling and lighting system configurations that can be incorporated practically and economically into typical commercial and light industrial designs that use single wythe masonry wall systems. Phase 2 will apply the process to two additional archetype/prototype buildings yet to be selected.

In both phases, the design criteria and climates in both the US and Canada were addressed. Because design and building code provisions vary between the US and Canada, the steps described above will be applied using the provisions and climates of each country separately.

This report summarizes the results of the first phase of this investigation for both the US and Canada. The first section describes the investigation of cost effective energy efficient single wythe masonry warehouse structures in the US and the second section similarly describes the investigation for single wythe masonry warehouse structures in Canada.

PROTOTYPE BUILDING DESIGN AND ANALYSIS – UNITED STATES

Prototype Building and Energy Analysis

In Phase 1, a prototype warehouse building was identified and detailed. In accordance with the requirements of ASHRAE 90.1, the base energy use by the building prototype was calculated using whole building energy analyses and the prescribed minimum energy performances for its various components.

This particular prototype was selected because:

1. It is one of the 16 reference buildings used for the evaluation of energy analysis software by the Department of Energy. (This is listed as one of their reference – benchmark buildings)[5].
2. It was used for The *Advanced Energy Design Guide for Small Warehouses and Self-Storage Buildings*[6].
3. It was found to be representative of the vast majority of the warehouses in the country:

   "F.W. Dodge data suggested a 50,000 ft^2 size non-refrigerated warehouse would cover about 80% of the most recent new construction in warehouses" [6].

4. There are energy use results from previous analyses by others that can be used to calibrate the building energy analysis model used herein[5].
5. The building model and the rationale for its development have been vetted by experts in the energy modeling field[5],[6],[7].

The configuration of the warehouse prototype used for the energy model is shown below in Figure 1.

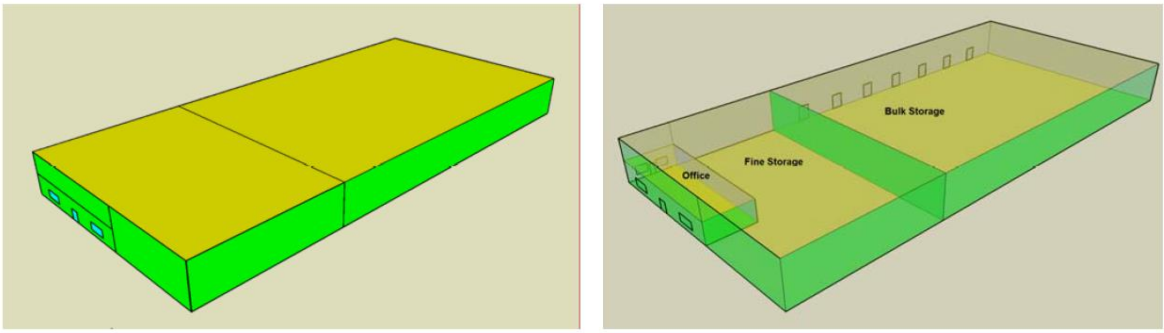

Figure 1. Prototype Warehouse Configuration for the Energy Model (≈ 50000 ft^2 warehouse).

The following description of the prototype is excerpted from the technical report published with The *Advanced Energy Design Guide for Small Warehouses and Self-Storage Buildings"[7]. (Note that the report was written in metric units with US standard units shown in parentheses.):*

> *"Occupancy hours for each [SIC] warehouse were based on normal business operating schedules derived from 2003 CBECS* (Commercial Buildings Energy Consumption Survey)*[6]. Heating and cooling equipment and lighting operational schedules were developed based on occupancy hours. In addition, for the warehouse, four of the seven loading dock doors were assumed to be occupied by trucks either loading or unloading, and dock doors were assumed to be closed when trucks were not being loaded or unloaded. This assumption was developed based on the consultations with the industrial experts."*[6]
>
> *"Zoning for the HVAC systems was broken down into three zones for the 4835 m^2 (≈ 50,000-ft^2) warehouse: office space, fine storage space and bulk storage space. Each zone requiring cooling (office, fine storage) was served by a single packaged rooftop unitary equipment with electric direct expansion (DX) cooling and gas heating, sized to meet the space's load. The air conditioning units were operated with setback and setup control strategies, and ventilation air was supplied as required by ASHRAE Standard 62 (ANSI/ASHRAE). Heating and cooling set points in the…fine storage area of the non-refrigerated warehouse…were 80°F for cooling and 60°F for heating. The bulk storage area of the non-refrigerated warehouse was defined as a semi-heated zone with heating set-point of 45°F*[6].

The set points in the office area were designed to keep the temperatures between 69 and 76 °F. These are consistent with the limits placed in the ASHRAE Standards (Standard 90.1, Standard 62 and Standard 55) and those recommended by the DOE committee in the development of the prototype building configuration[6]. Effects of higher door infiltration when operating (32 versus 783 CFM) in the bulk storage areas was evaluated during the investigation.

Table 1 summarizes the building zone data for the warehouse.

Table 1. Building Zone Data.

Zone	**Climate**	**Area (ft^2)**
Office	Conditioned	2,550
Fine Storage	Conditioned	12,450
Bulk Storage	Semi-conditioned	34,500
	Total Area	49,500

The warehouse exterior envelope was tilt-up concrete wall. Glazing was limited to the entrance wall of the small office spaces, and was less than 5% of gross floor area. Each window contained a 5-ft. overhang for shading and weather protection. The warehouse floor-to-ceiling height was 24 ft. The roofing construction was a steel deck with rigid insulation, protected by a membrane exterior surface. The warehouse has a slab-on-grade floor. Values for the thermal and solar performance of the envelope characteristics, mechanical equipment efficiencies, and mechanical system requirements for the original model came from ASHRAE Standard 90.1-1999 and these were updated to meet the minimum requirements in ASHRAE 90.1-2004. The office area was assumed to have insulated steel joist ceilings. A complete description of the baseline building and the development of the prototype warehouse is available in the reports by NREL and DOE [5],[6] and can be downloaded for free.

Note that the NREL and DOE [5],[6] studies describe the exterior wall in the prototype building as both a tilt-up concrete wall and a fully grouted concrete block wall. Examination of the building model file reveals that, indeed, a fully grouted concrete masonry wall was used in the baseline analyses. The prototype building model included building envelope components and equipment that met the (minimum) prescriptive requirements of ASHRAE 90.1 - 2007. It should be noted that these provisions are the same in the 2010 edition of the standard.

Also, to allow direct comparisons from previously published DOE studies, the weather data from the cities listed in Table 2 were used to represent the various climate zones. The listed cities were determined to be representative of the corresponding climate zone and known to contain significant numbers of buildings[5]. In accordance with ASHRAE 90.1, the climate zones are based on heating degree days, annual precipitation and mean daily temperatures.

Due to its limited scope and based on the recommendations of the reference building groups [5],[6], only packaged gas heating units and electrical DX cooling systems were used in the study. These are the most commonly used systems for this type of building due to their low heating costs.

Table 2. Cities for Climate Zones 3-7.

City	State	Zone	Climate
Atlanta	Georgia	3A	hot, humid
Las Vegas	Nevada	3B	hot, dry
San Francisco	California	3C	hot, marine
Baltimore	Maryland	4A	mild, humid
Albuquerque	New Mexico	4B	mild, dry
Seattle	Washington	4C	mild, marine
Chicago	Illinois	5A	cold, humid
Boulder	Colorado	5B	cold, dry
Minneapolis	Minnesota	6A	cold, humid
Helena	Montana	6B	cold, dry
Duluth	Minnesota	7	cold, dry

The AECOsim Energy Simulator software by Bentley was used for this study. This software uses the latest and more advanced EnergyPlus energy modeling software. Although this program is more difficult to use than other energy analysis software, such as eQuest, it has been found to give a more realistic evaluation of the thermal response of mass wall systems and thus, is more suitable for modeling buildings using masonry wall systems.

A first task of this phase was to develop a building energy model for the warehouse prototype and to calibrate this model in order to validate the model and ensure that the results were accurate. This calibration was done by creating a building energy simulation model of a warehouse that was similar to the prototype building for which validation data were available. The DOE warehouse reference building has published data [5] and this configuration was used for the validation.

The AECOsim energy simulator is relative new to the market and was not fully released at the time of this study. Thus, a comparison model was created in AECOsim energy simulator to calibrate the model against the DOE reference study. The EnergyPlus building model files (IDF) archived on the DOE website were imported into the AECOsim program using an IDF translating program[8],[9]. Each major schedule and building system was checked to ensure that the critical characteristics were consistent between the AECSim and the EnergyPlus file (IDF). Minor adjustments were made in building system configurations to facilitate use with the AECOsim program including slight reduction in zone sizes (office space, fine storage space, and bulk storage space). Significant work was needed to calibrate the mechanical systems on both models. A comparison of the results from the yearly energy use predicted by the AECOsim and DOE analysis programs is shown in Table 3.

Table 3. Energy Analysis Comparison of AECOsim and DOE Results.

	DOE Ref-Building[8]	**AECOsim**	**% Diff**
Heating (MJ)	56,480	56,263	0.38%
Cooling (kWh)	102,244	100,575	1.63%
Interior Lighting (kWh)	151,403	150,492	0.60%
Interior Equipment (kWh)	29,006	29,718	-2.46%
Fans (kWh)	108,011	88,451	18.11%
Total (kWh)	447,144	425,499	4.84%

The total difference in yearly energy use between the models is 21,645 kWh annually, or approximately 4.84%. Approximately 90% of the difference in energy use is from fan energy. This may be due to a slight change in the algorithm used to size the fans. The results were sufficiently close to validate the model.

After validation, the building model was modified to meet the minimum prescriptive baseline requirements defined in ASHRAE Standard 90.1 – 2007 for each of the Climate Zones 3 through 7. This modification was required because the building configuration used for validation did not use code minimum configurations in all cases. These baseline warehouse building models were designed to meet the minimum prescriptive requirements of ASHRAE 90.1 2007 for each climate and humidity zone. The baseline buildings all had the same floor plan and area, thermal mass, and schedules as the DOE model but all exterior walls were changed to a single wythe masonry assembly. Mechanical systems were also adjusted to meet ASHRAE 90.1 minimums. For the various building envelope assemblies, Figures 2 through 6 show the prescriptive requirements specified for Zones 3-7 from the ASHRAE 90.1 ANSI/ASHRAE/IES Standard 90.1-2007, *Energy Standard for Buildings Except Low-Rise Residential Buildings* [3]. (These provisions are the same as those of ASHRAE 90.1-2010).

TABLE 5.5-3 Building Envelope Requirements for Climate Zone 3 (A, B, C)*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.173	R-5.0 c.i.
Metal Building[a]	U-0.055	R-13.0 + R13.0	U-0.055	R-13.0 + R13.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.053	R-19.0
Walls, Above-Grade						
Mass	U-0.123	R-7.6 c.i.	U-0.104	R-9.5 c.i.	U-0.580	NR
Metal Building	U-0.084	R-19.0	U-0.084	R-19.0	U-0.113	R-13.0
Steel-Framed	U-0.084	R-13.0 + R-3.8 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.089	R-13.0	U-0.089	R-13.0	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.107	R-6.3 c.i.	U-0.087	R-8.3 c.i.	U-0.322	NR
Steel-Joist	U-0.052	R-19.0	U-0.052	R-19.0	U-0.069	R-13.0
Wood-Framed and Other	U-0.051	R-19.0	U-0.033	R-30.0	U-0.066	R-13.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.730	NR	F-0.730	NR
Heated	F-0.900	R-10 for 24 in.	F-0.900	R-10 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Nonswinging	U-1.450		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[c]	U-0.65	SHGC-0.25 all	U-0.65	SHGC-0.25 all	U-1.20	SHGC-NR all
Metal framing (curtainwall/storefront)[d]	U-0.60		U-0.60		U-1.20	
Metal framing (entrance door)[d]	U-0.90		U-0.90		U-1.20	
Metal framing (all other)[d]	U-0.65		U-0.65		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}-1.17	$SHGC_{all}$-0.39	U_{all}-1.17	$SHGC_{all}$-0.36	U_{all}-1.98	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-1.17	$SHGC_{all}$-0.19	U_{all}-1.17	$SHGC_{all}$-0.19	U_{all}-1.98	$SHGC_{all}$-NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}-1.30	$SHGC_{all}$-0.65	U_{all}-1.30	$SHGC_{all}$-0.27	U_{all}-1.90	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-1.30	$SHGC_{all}$-0.34	U_{all}-1.30	$SHGC_{all}$-0.27	U_{all}-1.90	$SHGC_{all}$-NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}-0.69	$SHGC_{all}$-0.39	U_{all}-0.69	$SHGC_{all}$-0.36	U_{all}-1.36	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-0.69	$SHGC_{all}$-0.19	U_{all}-0.69	$SHGC_{all}$-0.19	U_{all}-1.36	$SHGC_{all}$-NR

*The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), NR = no (insulation) requirement.
[a] When using R-value compliance method, a thermal spacer block is required; otherwise use the *U-factor* compliance method. See Table A2.3.
[b] Exception to Section A3.1.3.1 applies.
[c] Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[d] Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance *doors*.

Figure 2. Prescriptive Requirements for Zone 3 from ASHRAE 90.1-2007[3].

TABLE 5.5-4 Building Envelope Requirements for Climate Zone 4 (A, B, C)*

Opaque Elements	Nonresidential Assembly Maximum	Nonresidential Insulation Min. R-Value	Residential Assembly Maximum	Residential Insulation Min. R-Value	Semiheated Assembly Maximum	Semiheated Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.173	R-5.0 c.i.
Metal Building[a]	U-0.055	R-13.0 + R-13.0	U-0.055	R-13.0 + R-13.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.053	R-19.0
Walls, Above-Grade						
Mass	U-0.104	R-9.5 c.i.	U-0.090	R-11.4 c.i.	U-0.580	NR
Metal Building	U-0.084	R-19.0	U-0.084	R-19.0	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.089	R-13.0	U-0.064	R-13.0 + R-3.8 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-0.119	R-7.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.087	R-8.3 c.i.	U-0.074	R-10.4 c.i.	U-0.137	R-4.2 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.038	R-30.0	U-0.069	R-13.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.066	R-13.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.540	R-10 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.860	R-15 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[c]	U-0.40	SHGC-0.40 all	U-0.40	SHGC-0.40 all	U-1.20	SHGC-NR all
Metal framing (curtainwall/storefront)[d]	U-0.50		U-0.50		U-1.20	
Metal framing (entrance door)[d]	U-0.85		U-0.85		U-1.20	
Metal framing (all other)[d]	U-0.55		U-0.55		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}-1.17	$SHGC_{all}$-0.49	U_{all}-0.98	$SHGC_{all}$-0.36	U_{all}-1.98	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-1.17	$SHGC_{all}$-0.39	U_{all}-0.98	$SHGC_{all}$-0.19	U_{all}-1.98	$SHGC_{all}$-NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}-1.30	$SHGC_{all}$-0.65	U_{all}-1.30	$SHGC_{all}$-0.62	U_{all}-1.90	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-1.30	$SHGC_{all}$-0.34	U_{all}-1.30	$SHGC_{all}$-0.27	U_{all}-1.90	$SHGC_{all}$-NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}-0.69	$SHGC_{all}$-0.49	U_{all}-0.58	$SHGC_{all}$-0.36	U_{all}-1.36	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-0.69	$SHGC_{all}$-0.39	U_{all}-0.58	$SHGC_{all}$-0.19	U_{all}-1.36	$SHGC_{all}$-NR

*The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), NR = no (insulation) requirement.
[a]When using R-value compliance method, a thermal spacer block is required; otherwise use the *U-factor* compliance method. See Table A2.3.
[b]Exception to Section A3.1.3.1 applies.
[c]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[d]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance *doors*.

Figure 3. Prescriptive Requirements for Zone 4 from ASHRAE 90.1-2007[3].

TABLE 5.5-5 Building Envelope Requirements for Climate Zone 5 (A, B, C)*

Opaque Elements	Nonresidential Assembly Maximum	Nonresidential Insulation Min. R-Value	Residential Assembly Maximum	Residential Insulation Min. R-Value	Semiheated Assembly Maximum	Semiheated Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.119	R-7.6 c.i.
Metal Building[a]	U-0.055	R-13.0 + R-13.0	U-0.055	R-13.0 + R-13.0	U-0.083	R-13.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.053	R-19.0
Walls, Above-Grade						
Mass	U-0.090	R-11.4 c.i.	U-0.080	R-13.3 c.i.	U-0.151[b]	R-5.7 c.i.[b]
Metal Building	U-0.069	R-13.0 + R-5.6 c.i.	U-0.069	R-13.0 + R-5.6 c.i.	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.064	R-13.0 + R-3.8 c.i.	U-0.051	R-13.0 + R-7.5 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.119	R-7.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.074	R-10.4 c.i.	U-0.064	R-12.5 c.i.	U-0.137	R-4.2 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.038	R-30.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.051	R-19.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.540	R-10 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.860	R-15 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[c]	U-0.35	SHGC-0.40 all	U-0.35	SHGC-0.40 all	U-1.20	SHGC-NR all
Metal framing (curtainwall/storefront)[d]	U-0.45		U-0.45		U-1.20	
Metal framing (entrance door)[d]	U-0.80		U-0.80		U-1.20	
Metal framing (all other)[d]	U-0.55		U-0.55		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.17	$SHGC_{all}$–0.49	U_{all}–1.17	$SHGC_{all}$–0.49	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.17	$SHGC_{all}$–0.39	U_{all}–1.17	$SHGC_{all}$–0.39	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–1.10	$SHGC_{all}$–0.77	U_{all}–1.10	$SHGC_{all}$–0.77	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.10	$SHGC_{all}$–0.62	U_{all}–1.10	$SHGC_{all}$–0.62	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–0.69	$SHGC_{all}$–0.49	U_{all}–0.69	$SHGC_{all}$–0.49	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.69	$SHGC_{all}$–0.39	U_{all}–0.69	$SHGC_{all}$–0.39	U_{all}–1.36	$SHGC_{all}$–NR

*The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), NR = no (insulation) requirement.
[a]When using R-value compliance method, a thermal spacer block is required; otherwise use the *U-factor* compliance method. See Table A2.3.
[b]Exception to Section A3.1.3.1 applies.
[c]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[d]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance *doors*.

Figure 4. Prescriptive Requirements for Zone 5 from ASHRAE 90.1-2007[3].

TABLE 5.5-6 Building Envelope Requirements for Climate Zone 6 (A, B)*

Opaque Elements	Nonresidential Assembly Maximum	Nonresidential Insulation Min. R-Value	Residential Assembly Maximum	Residential Insulation Min. R-Value	Semiheated Assembly Maximum	Semiheated Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.093	R-10.0 c.i.
Metal Building[a]	U-0.049	R-13.0 + R-19.0	U-0.049	R-13.0 + R-19.0	U-0.072	R-16.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.034	R-30.0
Walls, Above-Grade						
Mass	U-0.080	R-13.3 c.i.	U-0.071	R-15.2 c.i.	U-0.151[b]	R-5.7 c.i.[b]
Metal Building	U-0.069	R-13.0 + R-5.6 c.i.	U-0.069	R-13.0 + R-5.6 c.i.	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.051	R-13.0 + R-7.5 c.i.	U-0.051	R-13.0 + R-7.5 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.119	R-7.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.064	R-12.5 c.i.	U-0.057	R-14.6 c.i.	U-0.137	R-4.2 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.032	R-38.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.051	R-19.0
Slab-On-Grade Floors						
Unheated	F-0.540	R-10 for 24 in.	F-0.520	R-15 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.688	R-20 for 48 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[c]	U-0.35	SHGC-0.40 all	U-0.35	SHGC-0.40 all	U-0.65	SHGC-NR all
Metal framing (curtainwall/storefront)[d]	U-0.45		U-0.45		U-0.60	
Metal framing (entrance door)[d]	U-0.80		U-0.80		U-0.90	
Metal framing (all other)[d]	U-0.55		U-0.55		U-0.65	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}-1.17	$SHGC_{all}$-0.49	U_{all}-0.98	$SHGC_{all}$-0.46	U_{all}-1.98	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-1.17	$SHGC_{all}$-0.49	U_{all}-0.98	$SHGC_{all}$-0.36	U_{all}-1.98	$SHGC_{all}$-NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}-0.87	$SHGC_{all}$-0.71	U_{all}-0.74	$SHGC_{all}$-0.65	U_{all}-1.90	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-0.87	$SHGC_{all}$-0.58	U_{all}-0.74	$SHGC_{all}$-0.55	U_{all}-1.90	$SHGC_{all}$-NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}-0.69	$SHGC_{all}$-0.49	U_{all}-0.58	$SHGC_{all}$-0.49	U_{all}-1.36	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-0.69	$SHGC_{all}$-0.49	U_{all}-0.58	$SHGC_{all}$-0.39	U_{all}-1.36	$SHGC_{all}$-NR

*The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), NR = no (insulation) requirement.
[a]When using R-value compliance method, a thermal spacer block is required; otherwise use the *U-factor* compliance method. See Table A2.3.
[b]Exception to Section A3.1.3.1 applies.
[c]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[d]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance *doors*.

Figure 5. Prescriptive Requirements for Zone 6 from ASHRAE 90.1-2007[3].

TABLE 5.5-7 Building Envelope Requirements for Climate Zone 7*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.093	R-10.0 c.i.
Metal Building[a]	U-0.049	R-13.0 + R-19.0	U-0.049	R-13.0 + R-19.0	U-0.072	R-16.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.034	R-30.0
Walls, Above-Grade						
Mass	U-0.071	R-15.2 c.i.	U-0.071	R-15.2 c.i.	U-0.123	R-7.6 c.i.
Metal Building	U-0.057	R-19.0 + R-5.6 c.i.	U-0.057	R-19.0 + R-5.6 c.i.	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.042	R-13.0 + R-15.6 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.051	R-13.0 + R-7.5 c.i.	U-0.051	R-13.0 + R-7.5 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.092	R-10.0 c.i.	C-1.140	NR
Floors						
Mass	U-0.064	R-12.5 c.i.	U-0.051	R-16.7 c.i.	U-0.107	R-6.3 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.032	R-38.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.051	R-19.0
Slab-On-Grade Floors						
Unheated	F-0.520	R-15 for 24 in.	F-0.520	R-15 for 24 in.	F-0.730	NR
Heated	F-0.843	R-20 for 24 in.	F-0.688	R-20 for 48 in.	F-0.900	R-10 for 24 in.
Opaque Doors						
Swinging	U-0.500		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[c]	U-0.35	SHGC-0.45 all	U-0.35	SHGC-NR all	U-0.65	SHGC-NR all
Metal framing (curtainwall/storefront)[d]	U-0.40		U-0.40		U-0.60	
Metal framing (entrance door)[d]	U-0.80		U-0.80		U-0.90	
Metal framing (all other)[d]	U-0.45		U-0.45		U-0.65	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.17	$SHGC_{all}$–0.68	U_{all}–1.17	$SHGC_{all}$–0.64	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.17	$SHGC_{all}$–0.64	U_{all}–1.17	$SHGC_{all}$–0.64	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–0.87	$SHGC_{all}$–0.77	U_{all}–0.61	$SHGC_{all}$–0.77	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.87	$SHGC_{all}$–0.71	U_{all}–0.61	$SHGC_{all}$–0.77	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–0.69	$SHGC_{all}$–0.68	U_{all}–0.69	$SHGC_{all}$–0.64	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.69	$SHGC_{all}$–0.64	U_{all}–0.69	$SHGC_{all}$–0.64	U_{all}–1.36	$SHGC_{all}$–NR

*The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), NR = no (insulation) requirement.
[a]When using R-value compliance method, a thermal spacer block is required; otherwise use the *U-factor* compliance method. See Table A2.3.
[b]Exception to Section A3.1.3.1 applies.
[c]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[d]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance *doors*.

Figure 6. Prescriptive Requirements for Zone 7 from ASHRAE 90.1-2010[3].

The model for the baseline building for each climate zone typically involved minor changes in building envelope configuration. Interior use schedules, lights and loads were kept consistent with the calibrated models since these were developed to be representative of typical warehouse configurations. Figures 7 through 10 show the AECOsim Model for the baseline warehouse and Tables 4a and 4b show some of the important building configuration information for each climate zone. Note that only important system characteristics that were changed for each climate zone are shown in the tables.

Air leakage through the walls was addressed using the recommendation in ASHRAE 90.1 and analysis by Lou et-al[6]. This analysis used a general infiltration rate of 0.038 cfm/ft^2 for the exterior walls. There was also a 2000 cfm for damper losses (when the HVAC operated). When the loading dock doors were closed, they were modeled to have an infiltration of 32 cfm per door, and 783 cfm per door when opened and loading (during operating hours). The energy analyses were run with and without the loading doors being in use. Since the closed door configuration would produce the greatest (and thus conservative) effect with changes in the opaque envelope, this configuration was conservatively used for equivalent performance comparisons.

Figure 11 shows a section through both the uninsulated and insulated exterior masonry walls of the baseline warehouse model; the latter being used where the code provisions require insulation.

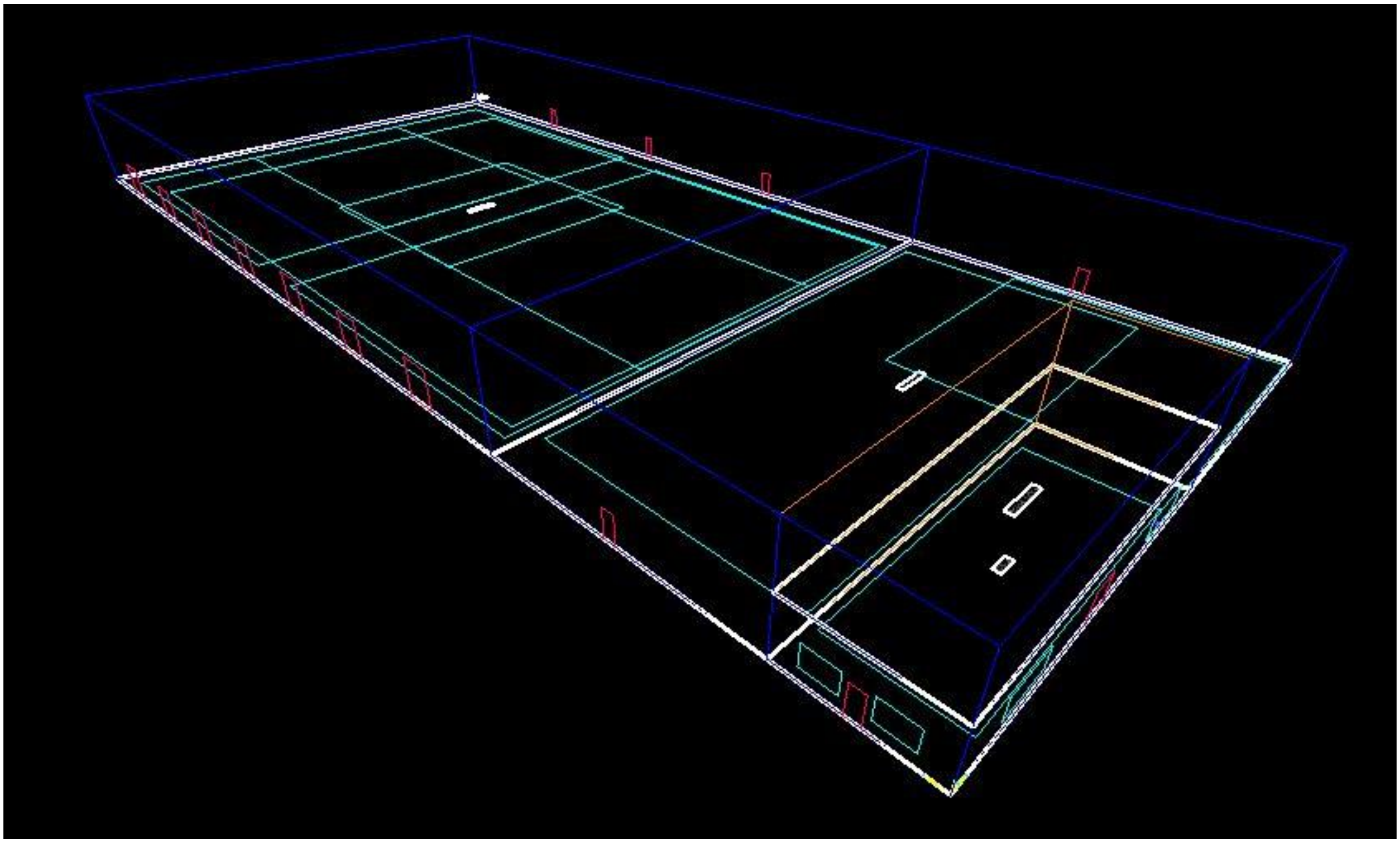

Figure 7. Isometric View of the Baseline Warehouse Model.

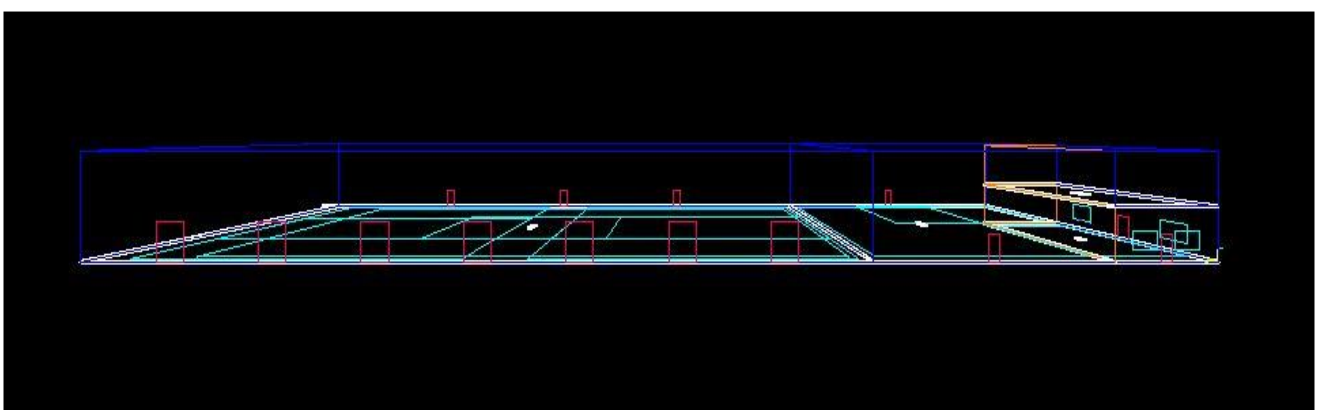

Figure 8. Left Side View of the Baseline Warehouse Model.

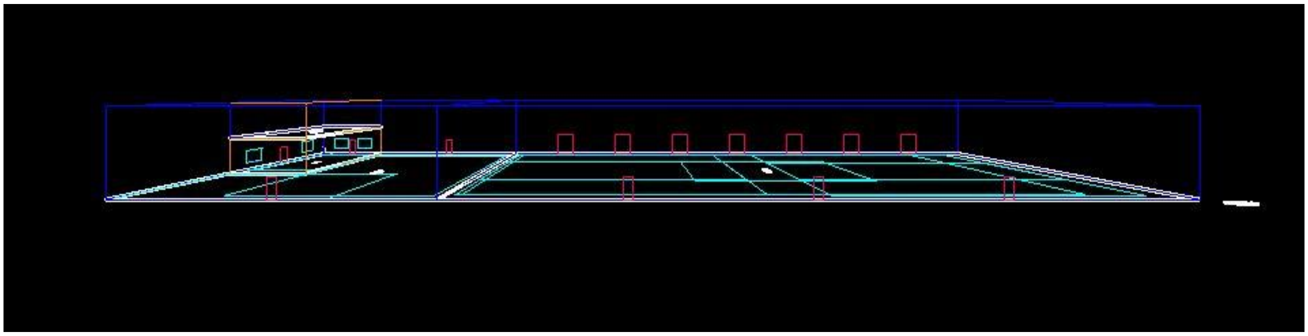

Figure 9. Right Side View of the Baseline Warehouse Model.

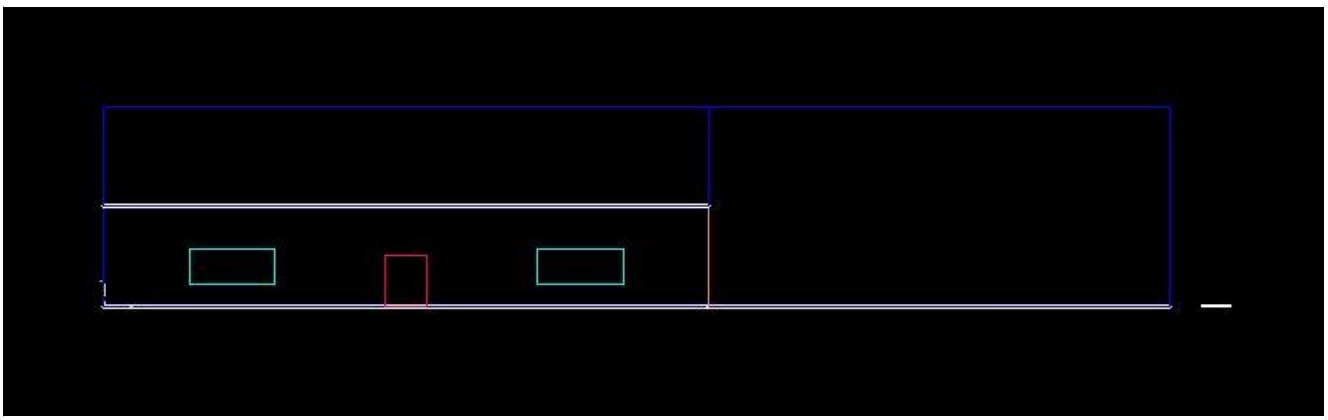

Figure 10. Front View of the Baseline Warehouse Model.

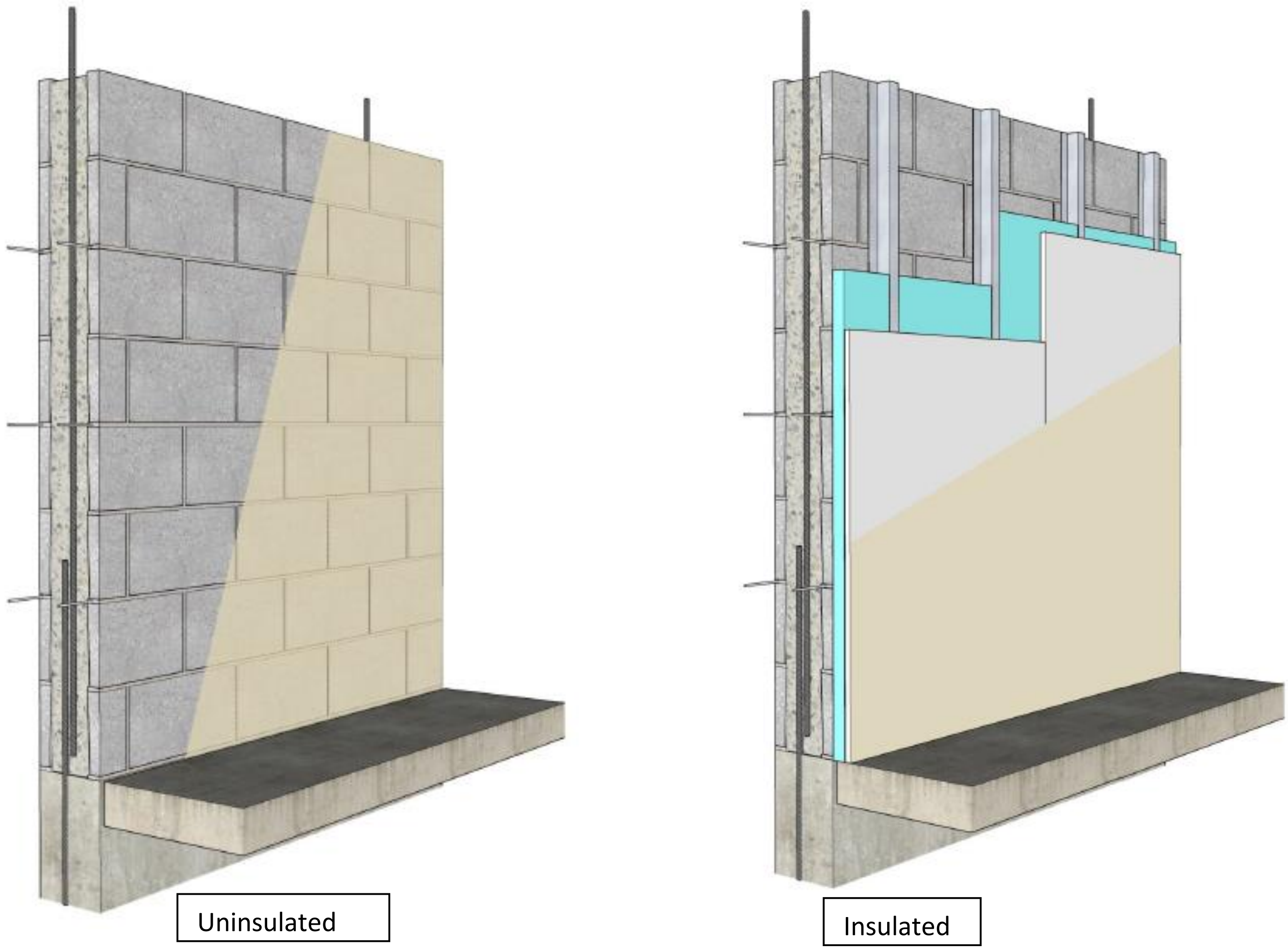

Figure 11. Exterior Masonry Wall Sections, Uninsulated and Insulated.

Table 4a. Baseline Building Envelope Configurations.

Location	Atlanta	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Boulder	Minneapolis	Helena	Duluth
State	Georgia	Nevada	California	Maryland	New Mexico	Washington	Illinois	Colorado	Minnesota	Montana	Minnesota
Climate Zone	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Office/Fine-Storage											
Exterior Walls											
Construction	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)
Insulation Thickness (in.)	1.5	1.5	1.5	2	2	2	2	2	2.5	2.5	2.5
Insulation R-Value (ft^2-h-F/Btu)	7.2	7.2	7.2	9.6	9.6	9.6	9.6	9.6	12	12	12
Required U (Btu/ft^2-h-F)	0.123	0.123	0.123	0.104	0.104	0.104	0.090	0.090	0.078	0.078	0.071
Construction U (Btu/ft^2-h-F)	0.112	0.112	0.112	0.088	0.088	0.088	0.088	0.088	0.070	0.070	0.070
Roof											
Construction	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof
Insulation Thickness (in.)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Insulation R-Value (ft^2-h-F/Btu)	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7
Required U (Btu/ft^2-h-F)	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048
Construction U (Btu/ft^2-h-F)	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	1.045	2.045	3.045
Floor											
Construction	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated
Insulation Thickness (in.)	0	0	0	0	0	0	0	0	0	0	0
Insulation R-Value (ft^2-h-F/Btu)	0	0	0	0	0	0	0	0	0	0	0
Required U (Btu/ft^2-h-F)	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730
Construction U (Btu/ft^2-h-F)	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635
Bulk-Storage											
Exterior Walls											
Construction	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)	Medium Weight CMU (Filled)
Insulation Thickness (in.)	0	0	0	0	0	0	1	1	1	1	1.5
Insulation R-Value (ft^2-h-F/Btu)	0	0	0	0	0	0	4.8	4.8	4.8	4.8	7.2
Required U (Btu/ft^2-h-F)	0.580	0.580	0.580	0.580	0.580	0.580	0.151	0.151	0.151	0.151	0.123
Construction U (Btu/ft^2-h-F)	0.580	0.580	0.580	0.580	0.580	0.580	0.151	0.151	0.151	0.151	0.106
Roof											
Construction	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof	Metal Roof
Insulation Thickness (in.)	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	2.5	2.5
Insulation R-Value (ft^2-h-F/Btu)	7.2	7.2	7.2	7.2	7.2	7.2	9.6	9.6	12	12	12
Required U (Btu/ft^2-h-F)	0.173	0.173	0.173	0.173	0.173	0.173	0.119	0.119	0.093	0.093	0.093
Construction U (Btu/ft^2-h-F)	0.125	0.125	0.125	0.125	0.125	0.125	0.096	0.096	0.070	0.070	0.07
Floor											
Construction	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated	Slab Unheated
Insulation Thickness (in.)	0	0	0	0	0	0	0	0	0	0	0
Insulation R-Value (ft^2-h-F/Btu)	0	0	0	0	0	0	0	0	0	0	0
Required U (Btu/ft^2-h-F)	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730	0.730
Construction U (Btu/ft^2-h-F)	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635

Table 4b. Baseline Building Mechanical System Configurations.

HVAC	Atlanta	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Boulder	Minneapolis	Helena	Duluth
	Georgia	Nevada	California	Maryland	New Mexico	Washington	Illinois	Colorado	Minnesota	Montana	Minnesota
Coils	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
Office Heating (η)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Office Cooling (COP)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
Office Fans (η)	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Fine-storage Heating (η)	0.78	0.78	0.78	0.78	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Fine-storage Cooling (COP)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
Fine-Storage Fans (η)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Bulk-storage Heating (η)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Bulk-storage Fans (η)	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Office Cooling Capacity (tons)	3.8	4.2	3.7	3.7	4.7	3.8	3.9	5.2	4.0	4.5	4.2
Office Heating Capacity (tons)	5.5	4.7	2.9	2.9	3.0	2.7	5.6	3.3	5.7	5.6	5.9
Fine-storage Cooling Capacity (tons)	20.2	11.4	8.9	19.4	21.7	11.8	25.9	17.6	27.7	22.1	26.6
Fine-storage Heating Capacity (tons)	22.1	15.4	13.0	21.1	17.3	17.1	26.8	13.9	29.0	28.2	30.8
Bulk-storage Heating Capacity (tons)	43.3	14.7	3.4	43.3	29.8	24.5	43.8	4.0	51.7	50.0	54.4
Fans											
Office Max Flow Rate (ft^3/min)	1777.3	1991.2	636.6	1753	2230.9	1797.4	1844.8	2470.1	1902.9	2103.4	1999.8
Office Delta Pressure (psi)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.1	0.1
Fine-storage Max Flow Rate (ft^3/min)	5592.6	4194.6	1737.8	5346.4	5285.3	4373.4	6900.1	4286.6	7534.7	1131.0	8174.7
Fine-storage Delta Pressure (psi)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.2
Bulk-storage Max Flow Rate (ft^3/min)	8049.1	2943.4	3271.1	8049.1	6713.4	4607.3	8300.3	906.7	9857.1	10652.4	10607.1
Bulk-storage Delta Pressure (psi)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0

Annual energy use was calculated for each of the baseline buildings using the AECOsim software. The results are summarized in Table 5, and expressed using Energy Usage Intensity (EUI). EUI, the annual energy used per square foot of building foot print, is a convenient way to display energy use in a building and allows easy comparisons. EUI will be used throughout this report to compare building energy consumption.

Only gas heating and electrical cooling were addressed by this study. Yearly average energy costs per kWh of electricity and per thousand square foot of natural gas were calculated for the baseline building in each climate zone (reported in Table 7) using state average unit energy costs for 2012 (shown in Table 6).

The energy analyses clearly show that heating is a large portion of the total energy consumption of the building, especially in the colder climates (Zones 5, 6, and 7). This can be more readily seen in Figure 12.

Table 5. Baseline Building Energy Use Results by Location for Zones 3-7.

City	Climate Zone	Heating (MBtu)	Cooling (MBtu)	Lighting (MBtu)	Equipment (MBtu)	Fans (MBtu)	Total (MBtu)	EUI (kBtu/ft^2)
Atlanta	3A	332.1	7.8	480.0	101.5	66.2	987.6	19.95
Las Vegas	3B	267.2	1.8	480.2	101.5	60.3	926.9	18.72
San Francisco	3C	259.1	8.0	480.1	101.5	48.6	890.0	17.98
Baltimore	4A	541.8	5.4	480.2	101.5	74.3	1203.2	24.31
Albuq-uerque	4B	374.1	5.9	480.0	101.5	76.4	1037.8	20.97
Seattle	4C	407.8	1.3	480.7	101.5	64.0	1055.2	21.32
Chicago	5A	680.8	4.1	480.4	101.5	92.3	1359.0	27.45
Boulder	5B	488.6	3.0	480.3	101.5	72.2	1145.6	23.14
Minnea-polis	6A	868.9	3.5	480.4	101.5	101.9	1556.3	31.44
Helena	6B	656.7	2.2	480.4	101.5	108.0	1348.9	27.25
Duluth	7	1043.0	1.4	480.4	101.5	112.3	1738.6	35.12

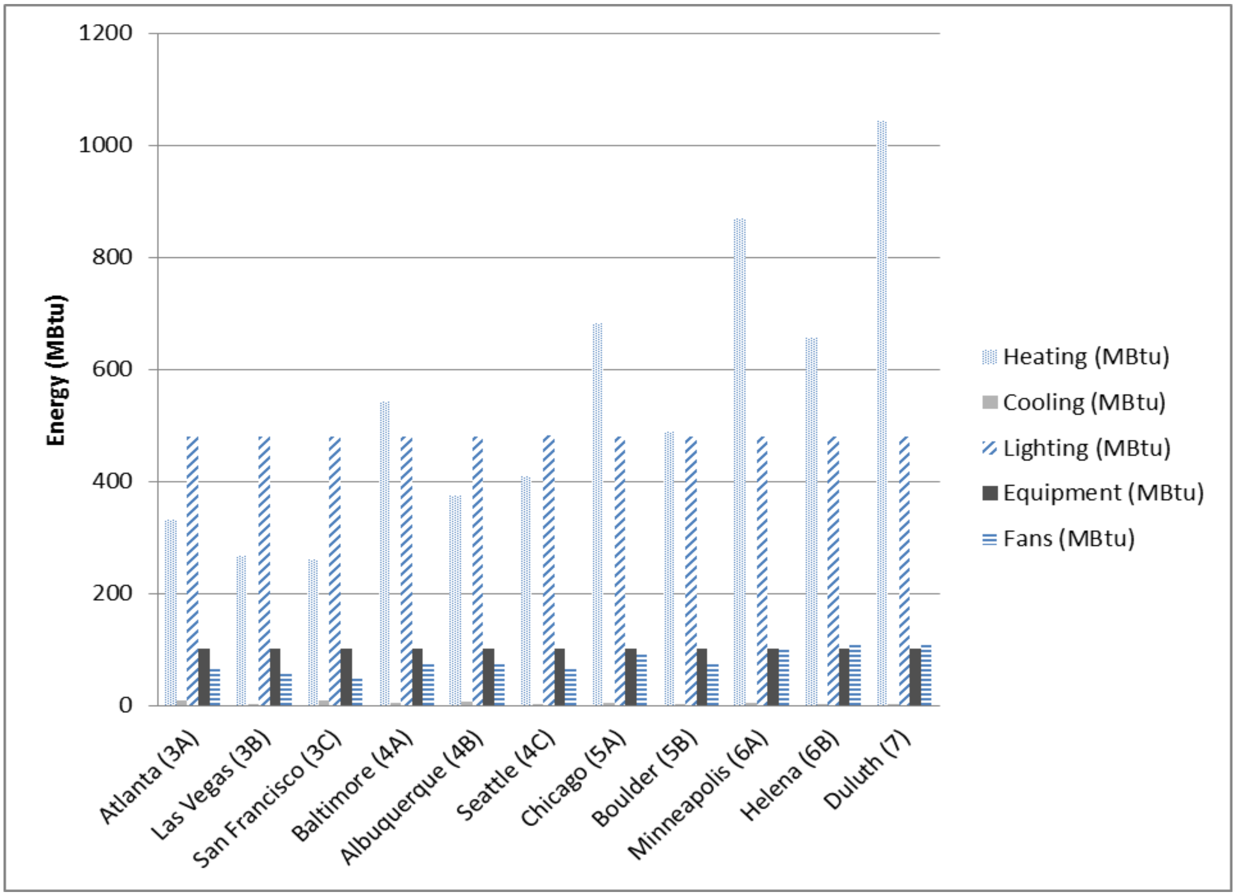

Figure 12. Baseline Building Energy Use Results by Location for Zones 3-7.

Table 6. State Average Unit Energy Costs for 2012[11],[12].

State	Electricity ($/kWh)	Gas ($/1000 ft^3)
Georgia	0.096	4.18
Nevada	0.095	5.13
California	0.129	3.46
Maryland	0.117	5.67
New Mexico	0.086	3.70
Washington	0.075	4.48
Illinois	0.085	4.11
Colorado	0.089	4.26
Minnesota	0.081	4.26
Montana	0.091	5.11

Table 7. Baseline Building Yearly Energy Costs by Location for 2012.

City	Climate Zone	Gas Cost	Electricity Cost	Total Cost
Atlanta	3A	$1,349.12	$1,8443.10	$19,792
Las Vegas	3B	$1,331.94	$18,368.60	$19,700
San Francisco	3C	$871.08	$23,856.80	$24,728
Baltimore	4A	$2,985.35	$22,680.06	$25,665
Albuquerque	4B	$1,345.08	$16,731.41	$18,076
Seattle	4C	$1,775.26	$14,232.86	$16,008
Chicago	5A	$2,719.11	$16,896.78	$19,616
Boulder	5B	$2,022.66	$17,139.81	$19,162
Minneapolis	6A	$3,597.30	$16,318.09	$19,915
Helena	6B	$3,261.22	$18,460.83	$21,722
Duluth	7	$4,317.95	$16,515.06	$20,833

After the baseline building energy use and energy cost analyses were completed, a variety of energy conservation systems/measures (ECMs) were incorporated into the baseline configuration of the prototype building. The effects of each change on the energy used by the building over its life cycle were determined using the AECOsim energy analysis program.

Incremental Analysis

Incremental changes were made to the thermal resistances of building envelope components to establish energy consumption sensitivity to changes in insulation levels, and to determine which changes to the envelope have the greatest effect on yearly building energy use. Multiple configurations were evaluated for each baseline building design, including various roof insulation levels, and higher and lower wall insulation levels in the fine storage area only, bulk storage area only, and for the entire warehouse. Roof insulation levels were adjusted by increasing and decreasing foam board insulation thickness by 1 inch (≈ΔR=6 Btu/(h °F ft^2). The resulting EUI for each incremental change in roof insulation thickness (and associated thermal resistance) can be found in Table 8. Wall insulation levels were adjusted by increasing and decreasing polyurethane foam insulation board thickness by 1/2 inch (≈ΔR=3 Btu/(h °F ft^2) where they were required by code (the bulk storage area walls do not require insulation in all climate zones). A bare masonry wall configuration was also evaluated. The EUI for each variation in wall insulation can be found in Table 9.

Table 8. Energy Use Intensity (kBtu/ft^2) for Variations in Roof Insulation levels.

Fine Storage	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Lower[1]	20.1	18.9	18.1	24.6	21.2	21.5	28.0	23.4	31.9	27.7	35.7
Baseline	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.2	35.1
Higher[2]	20.0	18.6	17.9	24.1	20.8	21.2	27.2	22.9	31.2	27.1	34.7
Bulk Storage	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
Lower[1]	21.1	18.8	18.0	26.5	22.2	21.9	29.2	24.0	33.0	28.4	37.1
Baseline	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.2	35.1
Higher[2]	19.8	18.7	18.0	23.8	20.8	21.2	27.0	22.9	30.8	26.9	34.1

[1] Decreased foam roof insulation 1” below code minimum thickness.
[2] Increased foam roof insulation 1” above code minimum thickness.

Table 9. Energy Use Intensity (kBtu/ft^2) for Variations in Wall Insulation levels.

Fine Storage Only	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
None[1]	39.8	38.3	26.1	58.4	50.1	43.0	84.2	62.5	47.1	39.4	50.8
Lower[2]	20.1	18.9	18.0	24.6	21.1	21.5	28.1	23.4	31.8	36.4	35.6
Baseline	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.2	35.1
Higher[3]	20.3	18.6	18.0	24.1	20.9	21.2	27.1	22.9	31.2	27.1	34.6
Bulk Storage Only	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
None[1]	NA	NA	NA	NA	NA	NA	30.6	25.3	35.9	29.9	43.4
Lower[2]	NA	NA	NA	NA	NA	NA	28.2	23.4	32.6	28.0	35.8
Baseline	NA	NA	NA	NA	NA	NA	27.5	23.1	31.4	27.2	35.1
Higher[3]	NA	NA	NA	NA	NA	NA	27.3	23.0	30.9	27.0	34.6
All	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
Lower[2]	NA	NA	NA	NA	NA	NA	28.8	23.7	33.0	28.3	36.4
Baseline	NA	NA	NA	NA	NA	NA	27.5	23.1	31.4	27.2	35.1
Higher[3]	NA	NA	NA	NA	NA	NA	26.8	22.8	30.7	26.8	34.2

[1] No external wall insulation.
[2] Decreased foam wall insulation 1/2” below code minimum thickness.
[3] Increased foam wall insulation 1/2” above code minimum thickness.

Examination of Tables 8 and 9 shows that there is a diminishing return on energy use as the thermal resistances of building envelope components are increased, but having no insulation in the concrete block masonry mass walls greatly increases the energy use. It is well known that applying additional insulation to the building envelope, especially a masonry wall system, does not produce a linear increase in energy savings[5]. Each successive incremental increase in insulation thickness/R-value above the prescribed code minimum results in comparatively less energy savings. For example, decreasing the wall insulation in the fine storage area by ½ inch thickness increased the energy consumption of the building by an average of 3.24% for the 11 locations evaluated. However, increasing the fine storage wall insulation thickness by ½ inch above prescribed code minimum decreased energy consumption by an average of only 0.72%. Similarly, decreasing the roof insulation thickness by 1 inch in the fine storage area increased the building energy consumption an average of 1.26% for the 11 locations considered, while increasing insulation thickness by 1 inch decreased the building energy consumption by only 0.71%. Clearly, increasing the envelope insulation/R-value above the code prescribed minimums does not have a significant effect on building energy use. This also suggests that the minimum thermal insulation values prescribed by the code for opaque wall systems have been "maximized", and therefore, the designer should seek alternative means to economically improve the energy efficiency of a building other than by increasing the thermal performance of opaque wall systems.

There are large increases in building energy use associated with using low R-value uninsulated concrete block masonry exterior walls (having large envelope surface area), and diminishing returns on energy use offered by incremental increases to the thermal resistances of building envelope components beyond the prescribed code minimums. Together, they identify why the envelope insulation trade-offs allowed under Section 5 of ASHRAE 90.1 are not particularly effective in colder climates when seeking compliance for use of low R-value envelope components (having relatively large envelope areas). Indeed, it is likely that roof and fenestration R-values cannot be increased sufficiently to off-set the heat loss and to compensate for the large increase in building energy consumption caused by the uninsulated walls, even in the warmer Climate Zones 3 and 4. Because these trade-off relationships are based on envelope components only, these being a subset of whole building analyses, this trade-off was not considered during the investigation; it was known beforehand, qualitatively, that simple building envelope trade-off would not be effective in the climate zones addressed in the study.

Cooling energy consumption was relatively low for the building configurations evaluated in this study. Thus, higher efficiency cooling systems were not investigated. However, sensitivity analyses were conducted on the baseline building configurations to determine how increases in the heating efficiency above minimum performance requirements in ASHRAE 90.1 affect yearly energy consumption. Table 10 shows the EUI results for these various improvements. There is no surprise that the data show decreasing energy consumption for increasing heating system efficiency. In all climate zones, using higher efficiency HVAC equipment reduces energy consumption more than increases in wall or roof insulation. Increasing the HVAC efficiencies by 4% to 6% (above the 78 or 80% baseline code minimums) reduces energy consumption more than using 10% to 30% increases in wall and roof insulation (R increases of approximately 3 and 6 from baseline code minimums, respectively). This is shown more clearly in Figure 13. The greater the heating load, the more significant is this effect. Greater energy savings can be realized by focusing on heating system efficiency.

Table 10. Energy Use Intensity (kBtu/ft^2) for Increased Heating System Efficiency.

Heating Efficiency	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Baseline (78 or 80%)	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.3	35.1
84%	19.5	18.3	17.6	23.9	21.1	20.9	27.2	22.6	30.8	26.8	34.3
90%	19.0	18.0	17.3	22.3	20.5	20.8	26.2	22.2	30.0	26.1	34.0

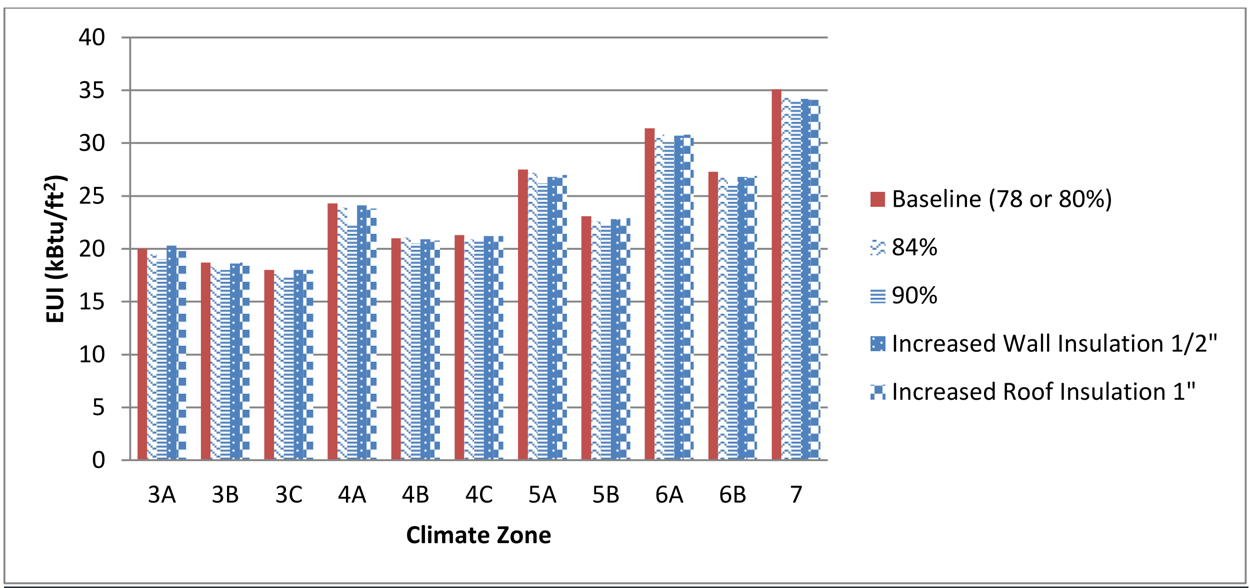

Figure 13. Energy Use Intensities: Wall and Roof Insulation vs. Heating Efficiency.

Foamed in Place Wall

A common alternative to uninsulated concrete block masonry walls is to fill the cores of the units with foam insulation. In practice, concrete block masonry walls used in warehousing are partially reinforced and grouted, and thus, not all cores can be filled with foam resulting in a partially insulated wall. Partially insulated and grouted CMU walls were evaluated in this study to determine the effect of small increases in opaque wall R-value on building energy consumption where opaque wall area accounts for a large area of the building envelope, and where wall insulation values are lower and in some cases significantly lower than the minimum thermal resistances prescribed by ASHRAE 90.1.

Baseline building configurations constructed using an 8 inch CMU wall, partially grouted and reinforced vertically at 48 inches on center with all other cores filled with foam insulation were modeled in AECOsim to evaluate the effects of this wall construction on the building energy use. The procedures described in NCMA TEK Note 6B [14] were used to calculate the effective U- and R-values for this partially grouted/partially foamed wall, these being, 0.287 Btu/ft^2-h-°F and 3.48 ft^2-h-°F/Btu, respectively (assuming 80:20 grouted and ungrouted area ratios with some allowance for horizontal grouting). This is a significant decrease in thermal transmittance when compared to the bare masonry wall (with U-value of 0.580 Btu/ft^2-h-°F- partially grouted). However, it offers a much higher thermal transmittance than does an 8” CMU wall having a continuous insulation of R-7.2 ft^2-h-°F/ Btu (U-value of 0.125 Btu/ft^2-h-°F). The U-values for the exterior CMU walls with insulation are listed in Table 4a. A section through the exterior CMU wall with foamed cores is shown in Figure 14.

Results of whole-building energy analyses conducted on additional prototype warehouse configurations are shown in Table 11. Energy Use Intensities are provided for the baseline building configuration (configured to satisfy the minimum prescriptive requirements of the energy code as defined by ASHRAE 90.1), and four baseline building configurations modified to have 8” partially grouted exterior CMU walls with various thicknesses of roofing insulation. In three of the building configurations, the partially grouted CMU walls were insulated with foam filled cores; in a fourth configuration, no insulation was added to the wall system. Comparing these alternatives to the baseline building EUI values (shown in Table 11 in bold) suggests that the foamed CMU walls have sufficient thermal resistance to significantly reduce the yearly energy use when compared with uninsulated walls. The EUI values, although not equivalent to the baseline values, are much lower than the values for uninsulated CMU walls. Small increases in thermal resistance of the wall have a large effect when the thermal resistance of the exterior walls is low.

Prototype building configurations constructed with foamed in-place partially grouted 8 inch CMU walls and with increasing heating system efficiencies were also modeled. The resulting EUI values can be found in Table 12.

Figure 14. Exterior Masonry Wall Sections with Core Insulation.

Table 11. EUI Values (kBtu/ft²) for Baseline Building Configurations of Partially Grouted, Foamed in Place, 8 inch CMU Wall Construction.

8 in. Foamed CMU Wall	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
ASHRAE Baseline Building	**20.0**	**18.7**	**18.0**	**24.3**	**21.0**	**21.3**	**27.5**	**23.1**	**31.4**	**27.2**	**35.1**
No CMU insulation[1]	39.8	38.3	26.1	58.4	50.1	43.0	84.2	62.5	47.1	39.4	50.8
Baseline[2] Roof	20.6	19.3	18.1	25.6	22.0	23.0	32.2	25.8	38.0	32.6	44.5
1in Inc.[3]	20.8	19.6	18.4	25.5	22.2	23.3	32.0	25.8	37.7	32.5	44.1
2in Inc.[4]	20.3	19.1	18.0	24.6	21.6	22.7	30.9	25.0	36.4	31.4	42.5

[1] No CMU wall insulation (internal or external) - All other building systems at baseline levels.
[2] No external wall insulation – 8" Internally foam insulated CMU walls with grout at 48" o.c. All other building systems at baseline levels including the roof insulation
[3] No external wall insulation – 8" Internally foam insulated CMU walls with grout at 48" o.c. All other building systems at baseline levels, except that the roof insulation is increased 1" above baseline level.
[4] No external wall insulation – 8" Internally foam insulated CMU walls with grout at 48" o.c. All other building systems at baseline levels, except that roof insulation is increased 2" above baseline level.

Table 12. EUI Values (kBtu/ft²) for Base Building Configurations of Partially Grouted, Foamed in Place 8 inch CMU Wall Construction with Increased Heating System Efficiencies.

Heating Efficiency	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
ASHRAE Baseline efficiency[1]	20.6	19.3	18.1	25.6	22.0	23.0	32.2	25.8	38.0	32.6	44.5
84%[2]	20.1	18.9	17.7	25.1	21.6	22.5	31.4	25.2	37.1	30.7	45.4
90%[3]	19.6	18.5	17.5	24.3	21.9	23.0	30.2	24.6	35.8	30.8	44.0

[1] No external wall insulation – 8" Internally foam insulated CMU walls with grout at 48" o.c. All other building systems at baseline levels, including the roof insulation (baseline heating system efficiency 78% and 80%).
[2] No external wall insulation – 8" Internally foam insulated CMU walls with grout at 48" o.c. Heating system efficiency increased to 84%. All other building systems at baseline levels.
[3] No external wall insulation – 8" Internally foam insulated CMU walls with grout at 48" o.c. Heating system efficiency increased to 90%. All other building systems at baseline levels, except that roof insulation is increased 1" above baseline level.

Results from analyses of the higher efficiency heating system/foam CMU wall combinations show a significant reduction in energy consumption with increasing system efficiency. Contrasting EUI in Table 11 with those of Table 12 suggests that improving heating system efficiency may be a more effective option for reducing energy consumption than increasing roof insulation.

Warehouses with taller walls are commonly constructed with 12 in. thick CMU units. As such, two baseline building configurations having all exterior walls constructed with partially grouted (at 48 inches o.c.) foamed in place 12 CMU units were also modeled, these being, with baseline roof insulation and with 2 in. of additional roof insulation. Tables 13 and 14 show the results of these analyses. The U-values used for this wall were 0.209 Btu/ft^2-h-F and 4.77 ft^2-h-F/Btu (assumed 80:20 grouted and ungrouted area ratios with some allowance for horizontal grouting).

Table 13. EUI Values (kBtu/ft^2) for Baseline Building Configuration of Partially Grouted Foamed in Place 12 inch CMU Walls and Baseline Roof Insulation.

12 in. Foamed CMU Wall	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
ASHRAE Baseline Building	**20.0**	**18.7**	**18.0**	**24.3**	**21.0**	**21.3**	**27.5**	**23.1**	**31.4**	**27.2**	**35.1**
Foamed CMU w. Baseline Roof Ins[1].	20.2	19.0	18.0	24.8	22.4	23.5	30.9	25.2	36.3	31.3	44.4

[1] No external wall insulation – 12” Internally foam insulated CMU walls with grout at 48” o.c. All other building systems at baseline levels, including the roof insulation.

Table 14. EUI Values (kBtu/ft^2) for Building Configuration of Partially Grouted Foamed in Place 12 inch CMU Walls and 2 inches Additional Roof Insulation.

12 in. Foamed CMU Wall	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
ASHRAE Baseline Building	**20.0**	**18.7**	**18.0**	**24.3**	**21.0**	**21.3**	**27.5**	**23.1**	**31.4**	**27.2**	**35.1**
Foamed CMU w. 2” Addl. Roof Ins.[1]	19.8	18.7	17.9	24.0	22.0	23.2	29.5	24.6	34.9	30.1	42.1

[1] No external wall insulation – 12” Internally foam insulated CMU walls with grout at 48” o.c. All other building systems at baseline levels, with an additional 2” of the roof insulation.

For Zones 3A-4A, the results show that using a partially grouted 12 in CMU wall with foamed cores will use less energy than the baseline building having prescriptively insulated 8” CMU walls. In Zones 4B through 7, reduced wall thermal resistances produce higher yearly energy use than the baseline configuration. Therefore, for the higher climate zones, simply using foam in cores of exterior CMU walls will not produce a warehouse building having equivalent energy performance to the ASHRAE baseline warehouse; improvements to other building systems will be necessary to get the same or lower energy use.

Lighting Analysis

Since lighting was shown to be a significant portion of the yearly energy used in the model building, these systems were also addressed in the investigation.

As required by the ASHRAE 90.1 standard, the lighting systems of the baseline building model were defined by a maximum watts per unit area. This did not define the actual lighting systems in the building but simply described the basic lighting type and energy use. Thus, to define equivalent alternative systems, an estimate of the baseline lighting configuration first had to be made. Using data gathered from Lighting Design Lab [15], it was reasonably established that the baseline building used fixtures consisting of T8 high performance, 3100 lumen lamps. By using the building layout and an assumed configuration for the light fixtures, and to achieve the lighting power density for the baseline lighting configuration, it was determined that 143 fixtures were required in the bulk storage area and 92 fixtures were required in the fine storage area, with each fixture consisting of six T8 high performance lamps (a total of 217 W per fixture). Similarly, it was determined that 2 fixtures were required in the office area, with each fixture consisting of two T8 high performance lamps (a total of 54.5 W used per fixture). It should be noted that the office lamps have a lower wattage per lamp since the lamps are closer to the working surfaces and thus have a lower ballast factor for a given light output.

Methods of reducing lighting energy consumption, while still meeting minimum lighting standards, were investigated and analyzed for their overall impact on building energy consumption. It should be noted that more efficient lighting also reduces the waste heat provided by the lights and thus increases heating energy requirements. This effect is accounted for by whole building energy analysis programs. Although many options are possible, only two alternative lighting configurations are addressed in this investigation. These two systems involved only minor system changes and were judged to be the simplest and most cost effective.

The first system alternative used a common approach to reduce lighting energy wherein the (baseline) ballast unit is replaced with one having a lower ballast factor. The electrical ballast limits the amount of current allowed into the lighting fixture, and decreases both the light output and the electrical usage. According to Lighting Design Lab [14], lowering the ballast factor would reduce the watts/fixture down to 167 W from 217. Given a set number of lighting fixtures, and by reducing the ballast factor for the light fixtures from 1.15 to 0.88 in the bulk storage and from 0.88 to 0.77 in the office, light power density was reduced in each of these building areas as shown in Table 15.

Note that the reduction of the ballast factor also causes a drop in the effective lumens produced by each fixture. To examine the effect, lighting outputs were also calculated for both the baseline configuration as well as for the configuration using the reduced ballast factor. These are listed in Table 15. In all cases, the light levels for the areas exceeded the minimum illumination levels established by the Illuminating Engineering Society (IES) [14]. These minimum values are also provided in Table 15.

The second alternative for lowering lighting energy consumption makes use of occupancy sensors that allow lighting to be dimmed or turned off when rooms are not in use. Effective occupancy sensors have been utilized in warehouses to produce 20% to 40% in light energy savings. For this study, it was conservatively assumed that the light energy is reduced by 20% when occupancy sensors are used[15].

Energy use was modeled for the baseline building and the building configuration using 8" partially grouted/partially foamed CMU exterior walls, and for each, using both the lower ballast factor lighting systems and the occupancy sensor alternative.

The results for the baseline building and for the baseline building constructed with foamed CMU walls are shown in Table 16 and Table 17, respectively.

Table 15. Lighting Power Density with Lower Ballast Factor.

		Baseline	**Lower BF**	**Occupancy Sensor**
Bulk Storage	LPD (W/ft^2)	0.9	0.69	0.72
	Footcandles	14.05	10.74	-
	Minimum Footcandles	10	10	-
Fine Storage	LPD (W/ft^2)	1.4	1.08	1.12
	Footcandles	21.85	16.76	-
	Minimum Footcandles	10	10	-
Office	LPD (W/ft^2)	1.1	0.96	0.88
	Footcandles	52.31	45.35	-
	Minimum Footcandles	30	30	-

Table 16. EUI Values (kBtu/ft^2) for Lighting Efficiency Improvements to the Baseline Building Configuration.

Lighting	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
ASHRAE Baseline Building	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.2	35.1
Lower BF	18.0	16.7	16.1	22.6	18.9	19.5	25.7	21.3	30.0	25.8	33.4
Occ. Sensor	18.3	16.9	16.3	22.7	19.3	19.7	25.9	21.5	30.3	26.1	32.4

Table 17. EUI Values (kBtu/ft^2) for Lighting Efficiency Improvements to the Baseline Building Configuration Constructed with 8 in. Partially Grouted CMU Foamed Exterior Walls.

Lighting	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Baseline lights	20.6	19.3	18.1	25.6	22.0	23.0	32.2	25.8	38.0	32.6	44.5
Lower BF	18.6	17.2	16.1	24.0	20.1	21.1	30.5	23.9	36.3	30.9	43.0
Occ. Sensor	18.9	17.5	16.4	24.2	20.4	21.4	30.7	24.2	36.5	31.1	43.2

For the various building configurations, Figure 15 plots the EUI values in Tables 16 and 17 against climate zone. The analysis shows that significant energy savings can be gained by implementing energy efficient lighting designs. A reduced ballast factor appears to have a slightly greater effect on the building configurations using the foamed CMU wall, whereas occupancy sensors have a slightly greater effect on the building with the prescriptive wall configuration. Furthermore, building configurations using lighting systems with lower ballast factors and constructed with 8 in. CMU walls with internal foam insulated cores use less energy than the baseline configurations with specified wall configurations up to Climate Zone 4C.

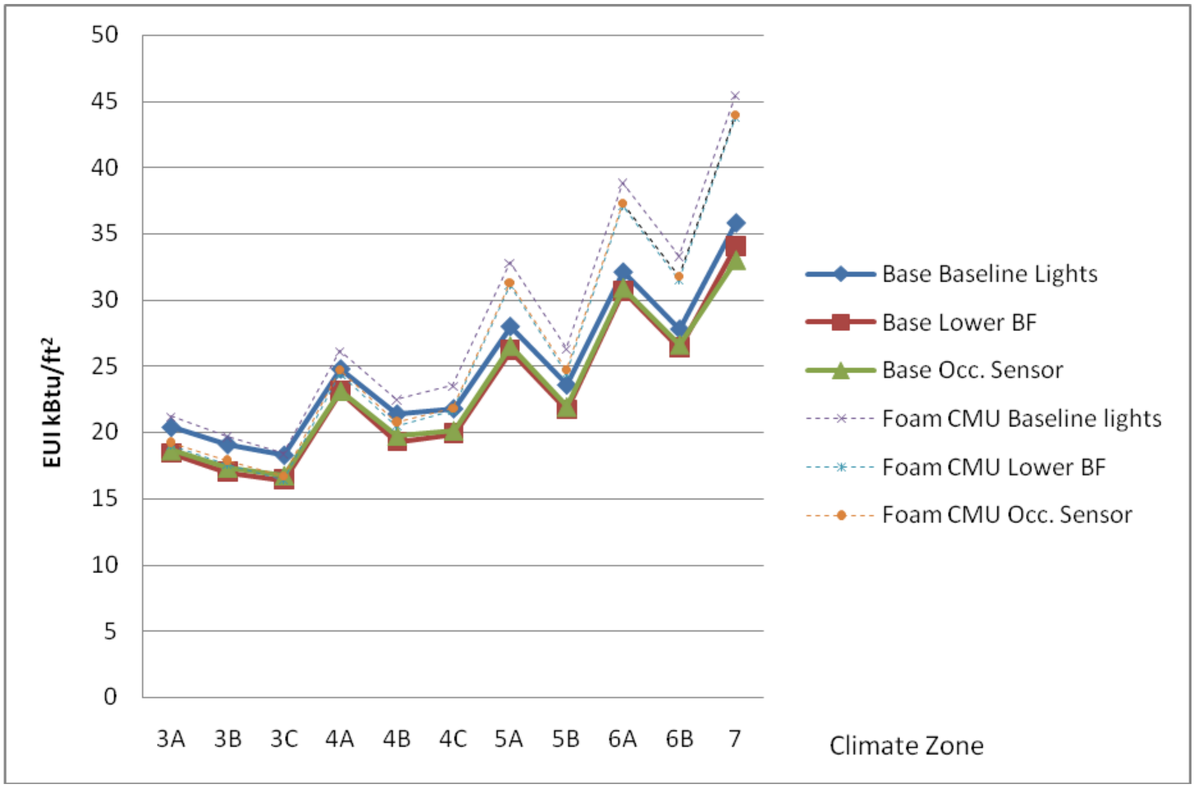

Figure 15. Effects of Lighting System Alternatives on Yearly Energy Use.

The cost effectiveness of implementing energy efficient lighting designs will be discussed in the following section.

Equivalent Performance and Combined Energy Saving Technologies

Energy simulations were conducted on a number of building configurations using a variety of energy saving technologies in an effort to identify those configurations that provided yearly energy usage equivalent to that of the baseline (reference) building. These combined multiple energy saving technologies included: partially grouted 8 in. foam filled CMU walls, partially grouted 12 in. foam filled CMU walls, a reduced ballast factor for T8 Lights (ballast factor changes from 1.15 to 0.88 in the bulk storage and from 0.88 to 0.77 for the office), a 2 in. increase in roof insulation thickness, and an improved heating coil efficiency (from 0.78/0.8 to 0.9). Results from these multiple analyses are shown in Tables 18, 19 and 20. It should be noted that foamed CMU walls were modeled only on those exterior walls that required insulation by the ASHRAE prescriptive requirements. Thus, the exterior walls in the bulk storage area remained with no insulation in Climate Zones 3 and 4. Also shown in these tables, for each climate zone, is the difference between the Energy Use Index of the proposed configuration and the ASHRAE baseline configuration (reference).

Table 18. EUI Values (kBtu/ft^2) for Baseline Configurations Constructed with 8 in. foam filled CMU walls having 0.8 Heat Coil, 2 in. of Insulation Added to Roof, and a Reduced Ballast Factor (0.88 storage and 0.77 office).

	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
EUI	18.1	16.8	15.8	23.3	20.4	21.9	28.5	22.8	34.0	29.2	42.4
Baseline EUI	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.2	35.1
Difference	-1.8	-1.9	-2.2	-1.1	-0.6	0.6	1.1	-0.4	2.6	1.9	7.3

Table 19. EUI Values (kBtu/ft^2) for Baseline Configurations Constructed with 12 in. Foam Filled CMU Walls, having 0.9 Heat Coil and 2 in. of Insulation Added to the Roof.

	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
EUI	19.0	18.0	17.2	22.7	20.9	21.9	27.7	23.1	32.7	28.3	39.5
Baseline EUI	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.2	35.1
Difference	-1.0	-0.7	-0.8	-1.6	-0.1	0.6	0.3	0.0	1.3	1.0	4.3

Table 20. EUI Values (kBtu/ft^2) for Baseline Configurations Constructed with 12 in. Foam filled CMU walls, having 0.8 Heat Coil, 2 in. of Insulation Added to the Roof, and a Reduced Ballast Factor (0.88 storage and 0.77 office).

	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
EUI	17.4	16.3	15.6	21.8	19.5	20.5	27.4	22.4	32.7	28.0	40.1
Baseline EUI	20.0	18.7	18.0	24.3	21.0	21.3	27.5	23.1	31.4	27.2	35.1
Difference	-2.5	-2.4	-2.3	-2.5	-1.5	-0.8	0.0	-0.7	1.3	0.8	4.9

The baseline building configurations constructed with 8 in. foam filled CMU walls, a 0.8 heat coil, an additional 2 in. of insulation added to the roof, and a reduced ballast factor

(0.88 storage and 0.77 office) produced yearly Energy Use Indices less than those for the baseline configurations in Zones 3A through 4B, and 5B.

The baseline building configurations constructed with 8 in. foam filled CMU walls, a 0.9 heat coil, and an additional 2 in. of insulation added to the roof, produced yearly Energy Use Indices equal to or less than those for the baseline configurations in Zones 3A through 4B, and 5B.

The baseline building configurations constructed with 12 in. foam filled CMU walls, a 0.8 heat coil, an additional 2 in. of insulation added to the roof, and a reduced ballast factor (0.88 storage and 0.77 office) produced yearly Energy Usage Indices less than those for the baseline buildings in all zones except 6A, 6B, and 7.

The above information is also presented in graphical form in Figure 16 below.

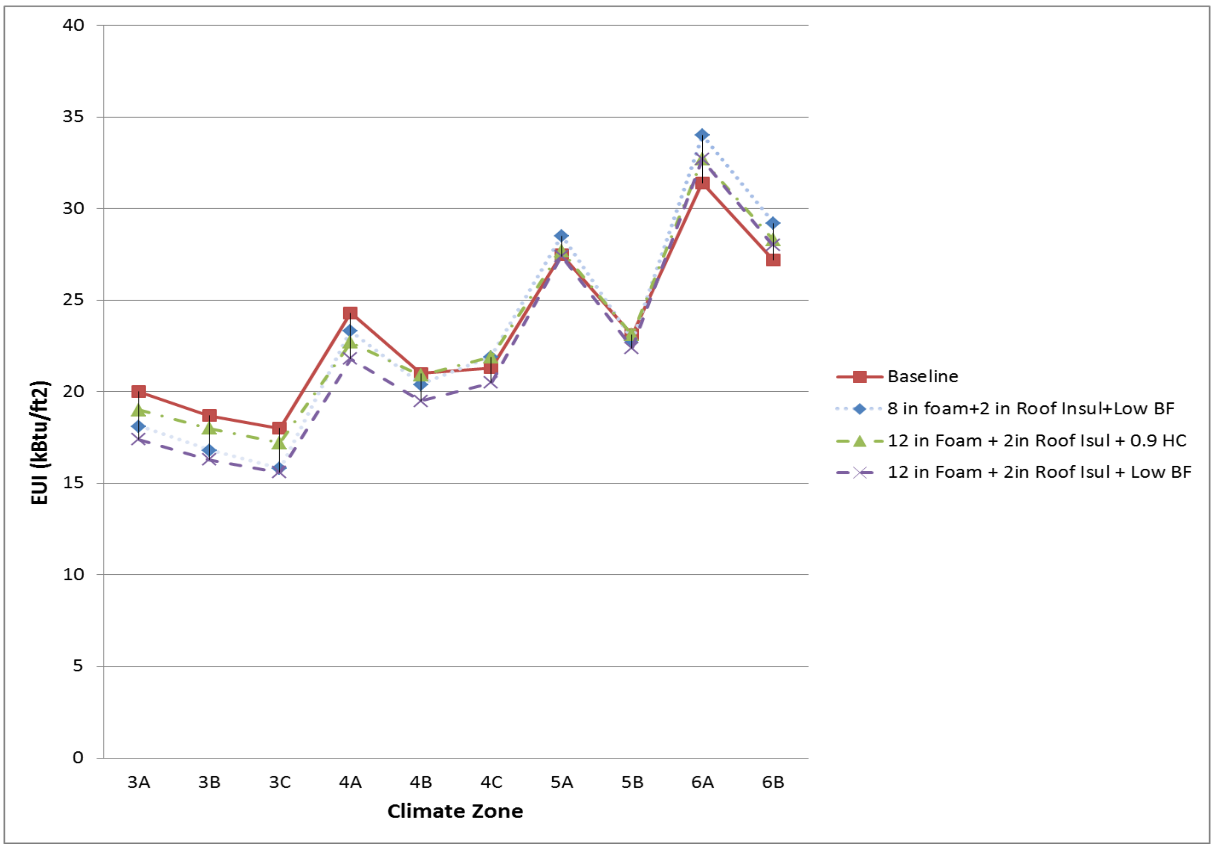

Figure 16. EUI Values for Combined Energy Conservation Measures.

When the baseline building model was described earlier in this report, the operation of the loading docks and the additional air infiltration that this operation allows in the bulk storage area was discussed. When the loading dock doors were closed, they were modeled to have an infiltration of 32 cfm per door, and 783 cfm per door when opened and loading (during operating hours). As the closed door configuration produces the greatest (and thus conservative) effect of changes in the opaque envelope, this configuration was conservatively used for all the previous comparisons. However, select analyses with and without the loading doors operating are shown in Table 21.

Table 21. EUI Values (kBtu/ft^2) for Baseline Configurations and 8 in. Foam filled CMU walls, having 0.8 Heat Coil, and a Reduced Ballast Factor (0.88 storage and 0.77 office), with and without Operating Loading Doors.

	Select Climate Zones			
	Atlanta	**Seattle**	**Minneapolis**	**Duluth**
EUI	**3A**	**4C**	**6A**	**7**
Baseline	20	21.3	31.4	35.1
Baseline Open doors	20.5	22.5	39.2	47.8
8" foam +2 Roof +Low BF	18.1	21.9	34	42.4
8" foam +2 Roof +Low BF+ Open doors	18.8	22.3	47.8	54.8
Difference Doors Closed	1.9	-0.6	-2.6	-7.3
Difference Doors Open	1.6	0.2	-8.6	-7.0

Examining the EUI values in the table shows that the increased infiltration generally increases the yearly energy used, with a more significant effect in colder climates. Also shown in Table 21 are the differences between the baselines and the alternative building configurations for closed doors and open door conditions. The higher infiltration rates appear to lessen the unfavorable effect of lower envelope thermal resistance on the yearly energy used. However, this effect does not appear to be large or consistent and does not affect the results enough to change any of the conclusions presented earlier. All analyses were thus done assuming the loading dock doors were closed.

The relative costs and benefits of including these various energy saving technologies in the baseline building configuration are presented and discussed in the following section.

COST ANALYSES - UNITED STATES

As noted earlier, there are three energy design compliance paths permitted for use in ASHRAE 90.1[3]. The energy cost budget method is the most sophisticated, and for a compliant energy design, this path requires that:

"...the design energy cost [of the proposed design], as calculated in Section 11.3, does not exceed the energy cost budget as calculated by the simulation program described in Section 11.2…".

Thus, to determine if a proposed design is compliant, it must produce the same or lower energy cost as that of the proposed building modeled with the same set points, schedules, etc., but complying with the prescriptive minimum code requirements (baseline or reference building). Using this compliance path, energy cost analyses were run on a variety of building configurations that were expected to give substantially lower construction costs than the baseline building, but which used single wythe exterior wall systems. Results are presented later in the report.

To further evaluate the design variations addressed in the earlier sections of this report (variations in lighting, insulation, HVAC efficiency, and wall construction) and to choose which of these different configurations might be the more cost effective alternatives to explore further, construction costs for the various building configurations were estimated, and their construction cost differences were calculated. To determine the payback time and overall cost savings gained from using these various energy efficient technologies, construction cost differences were then compared to the whole building annual energy cost savings.

Building Costs

The various wall configurations analyzed in this project all have different costs associated with their construction and these costs vary depending on the city in which they are built. These cost variations were necessarily accounted for in each of the cost analyses undertaken.

Wall construction cost data were provided by the International Masonry Institute (IMI) based on the RSMeans data base. The unit prices for the various CMU wall configurations are listed in Tables 22, 23, and 24. These tables provide construction and material costs for the baseline wall configuration (partially grouted, insulated 8 in. CMU), the partially grouted 8 inch foam filled CMU wall, and the partially grouted, 12 inch foam filled wall configurations.

Table 22. Unit Cost Estimate for the Baseline Warehouse Walls.

	Climate Zones										
Wall Profile	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
8" CMU, EXT - reinf alt crs, tool 2 sds, norm wt	8.60	12.05	15.35	9.30	8.80	11.70	14.80	9.00	13.45	10.30	12.90
#7 rebar @ 48" o.c.	0.33	0.40	0.47	0.35	0.31	0.38	0.48	0.33	0.44	0.32	0.41
Grout	0.48	0.54	0.72	0.50	0.46	0.57	0.73	0.50	0.66	0.48	0.54
Bond beam/cmu+rebar+grout	0.15	0.23	0.26	0.18	0.18	0.21	0.27	0.18	0.24	0.19	0.24
Exterior Paint -2 coats, rolled	0.67	0.90	0.83	0.68	0.49	0.71	1.10	0.60	0.96	0.45	0.80
1 5/8" galvmtlfurr @ 24 o.c.	1.46	1.98	2.66	1.62	1.23	1.79	2.92	1.82	1.39	0.79	1.23
Polyurethane Insulation	1.07	1.34	1.47	1.16	1.14	1.25	1.86	1.62	2.40	1.98	2.30
1/2" GWB, taped Fin L4	1.20	1.57	2.1	1.18	1.01	1.45	2.14	1.33	1.82	1.05	1.62
Interior paint, 2 coats, rolled	0.62	0.84	1.04	0.62	0.45	0.63	1.06	0.54	0.89	0.39	0.76
Total $/ SF	**14.58**	**19.85**	**24.90**	**15.59**	**14.07**	**18.69**	**25.36**	**15.92**	**22.25**	**15.95**	**20.80**

Table 23. Unit Cost Estimate for the Partially Grouted, 8 in. Foam Filled CMU Walls.

	Climate Zones										
Wall Profile	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
8" CMU, EXT - reinf alt crs, tool 2 sds, norm wt	8.60	12.05	15.35	9.30	8.80	11.70	14.80	9.00	13.45	10.30	12.90
#7 rebar @ 48" o.c.	0.33	0.40	0.47	0.35	0.31	0.38	0.48	0.33	0.44	0.32	0.41
Grout	0.48	0.54	0.72	0.50	0.46	0.57	0.73	0.50	0.66	0.48	0.54
Bond beam/cmu+rebar+grout	0.15	0.23	0.26	0.18	0.18	0.21	0.27	0.18	0.24	0.19	0.24
Foamed cores / Drill & Patch	0.50	0.59	0.70	0.55	0.52	0.59	0.70	0.56	0.72	0.54	0.69
Exterior Paint -2 coats, rolled	0.67	0.90	0.83	0.68	0.49	0.71	1.10	0.60	0.96	0.45	0.80
Interior Paint, 1 prm-1fin-rolled	0.82	1.12	1.37	0.83	0.58	0.85	1.39	0.73	1.19	0.52	1.02
Total / SF	**11.55**	**15.83**	**19.70**	**12.39**	**11.34**	**15.01**	**19.47**	**11.90**	**17.66**	**12.80**	**16.60**

Table 24. Unit Cost Estimate for the Partially Grouted, 12 in. Foam Filled CMU Walls.

	Climate Zones										
Wall Profile	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
12" CMU, EXT - reinf alt crs, tool 2 sds, norm wt	12.75	18.20	23.50	13.80	12.80	17.60	23.00	13.45	20.50	15.15	19.75
#6 rebar @ 48" o.c.	0.24	0.29	0.35	0.26	0.23	0.28	0.36	0.24	0.32	0.24	0.30
Grout	0.60	0.73	0.86	0.64	0.58	0.70	0.88	0.64	0.80	0.60	0.63
Foamed cores / Drill & Patch	0.80	0.93	1.11	0.89	0.83	0.94	1.12	0.89	1.15	0.86	1.09
Exterior Paint -2 coats, rolled	0.67	0.90	0.83	0.68	0.49	0.71	1.10	0.60	0.96	0.45	0.80
Interior Paint, 1 prm-1fin-rolled	0.82	1.12	1.37	0.83	0.58	0.85	1.39	0.73	1.19	0.52	1.02
Total / SF	**15.88**	**22.17**	**28.02**	**17.10**	**15.51**	**21.08**	**27.85**	**16.55**	**24.92**	**17.82**	**23.59**

Using these wall unit costs, the total exterior wall construction costs for the various warehouse configurations were calculated; these are provided in Table 25 (26,880 sq. ft. wall area). The baseline costs were compiled using bare walls in the bulk storage area for buildings in Climate Zone 4 and lower (and with insulated bulk storage walls for Zones 5 through 7) and insulated walls as required by code for the remainder of the exterior wall areas. All insulated walls were replaced by foamed walls for the other cost determinations. It is clear that the partially grouted 8 inch foamed CMU wall is less costly to construct in all zones than the baseline wall profile. This is perhaps best illustrated by the bar chart in Figure 17. This is not the case for the 12 inch foamed CMU wall where these wall costs exceed those of the baseline configuration. Therefore, where sufficient to meet energy requirements, it is more cost effective to use an 8 inch foamed in place CMU wall because the incremental cost of installing insulation over either the exterior or interior surface of a bare CMU wall is much higher than using foamed cores.

Table 25. Total Wall Cost for Warehouse.

Climate Zones	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
Baseline	$331.6K	$454.8K	$568.5K	$360.7K	$328.4K	$435.4K	$668.2K	$415.5K	$594.7K	$421.0K	$554.8K
8 in. Foam	$301.9K	$415.4K	$517.6K	$323.6K	$295.9K	$393.4K	$523.4K	$319.9K	$474.7K	$344.1K	$446.2K
12 in. Foam	$426.8K	$595.9K	$753.2K	$459.6K	$416.9K	$566.6K	$748.6K	$444.9K	$669.8K	$479.0K	$634.1K

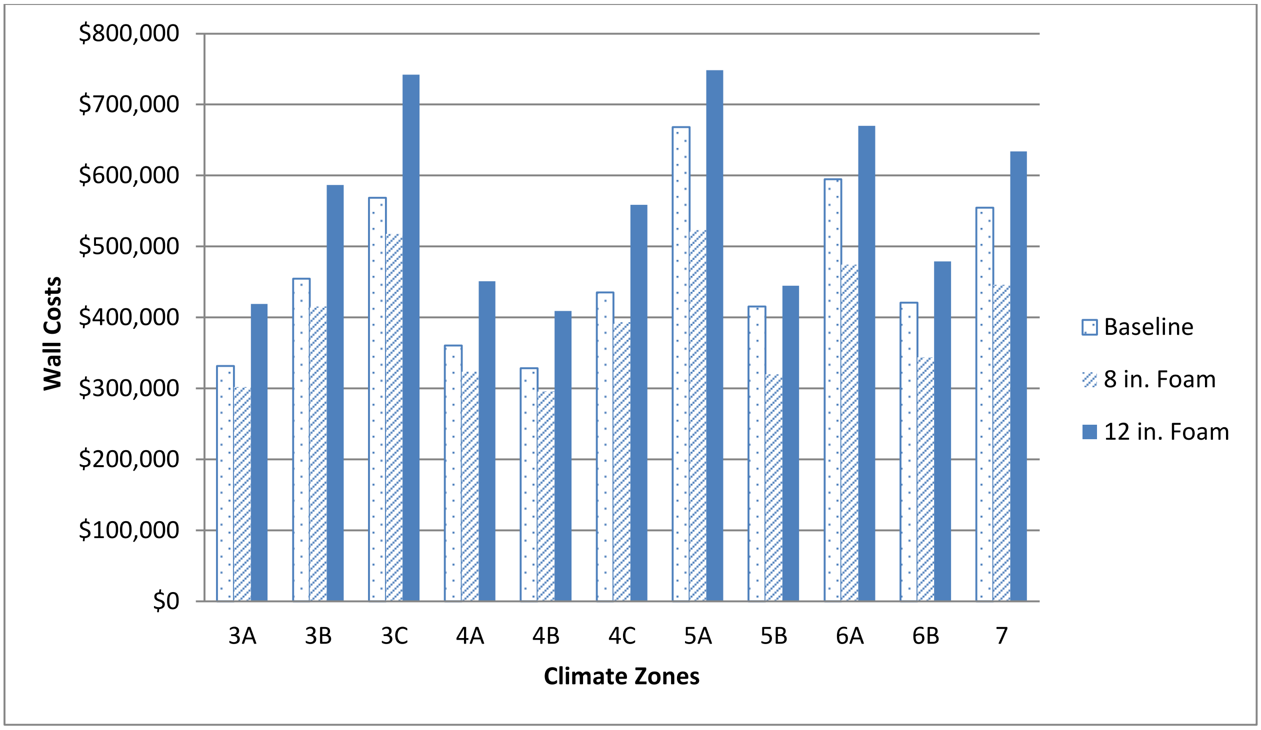

Figure 17. Wall Configuration Costs for the Warehouse Building.

HVAC System Costs

Determining the construction costs for HVAC equipment is dependent upon the size of the units needed to condition the building. Using AECOsim energy simulator, HVAC equipment was auto-sized to meet heating and cooling demands for the climate in each city analyzed and the building construction.

To determine the unit cost for each HVAC variation, unit costs were obtained from Carrier Corp. [18] as an average unit cost for the split unit systems over the range of unit sizes determined by the energy analysis. As was stated earlier, these are roof top units that used DX cooling and gas heating. The unit cost for each range of unit tonnage is shown in Table 26. Using these unit costs and auto-size tonnage values, the construction costs for the different configurations of the HVAC systems were determined. Since these tonnages were held constant within each climate zone, they are not listed unless there was a significant difference in the HVAC efficiency in the configurations addressed in the cost comparisons.

Table 26. Unit HVAC Equipment Costs for Varying Size Ranges [18].

Tons	Standard Gas (80%)	High Efficiency Gas (85%)	Premium Gas (90%)
3	1427	1643	-
4	1267	1487	-
5	1141	1326	-
6	1109	1248	1901
7.5	1154	1293	1903
8.5	1109	1259	1891
10	1039	1175	1686
12.5	1034	1180	1571
15	1028	1144	1534
18	988	1097	1453
20	961	1006	1365
25	932	983	1279
30	903	960	1236
35	874	937	1172
40	845	914	1118
45	816	891	1059
50	787	868	1002
55	758	845	944
60	729	822	887

Lighting

Lighting costs are dependent on the type and the number of lights required in the building. This varies with the building floor plan and the intended use of each of the floor areas. For example, the lighting level required at ground level is higher in the fine storage area than in the bulk storage area. Since these levels changed little between different building configurations, the cost analysis was confined to the cost difference between traditional lighting and any lighting energy conservation measures. It should be noted that most building lighting is designed using the prescriptive method rather than performance trade-off lighting analysis [15].

For the occupancy sensor alternative in the baseline warehouse, switch based occupancy sensors were used in the office space, and ceiling occupancy sensors were used in the fine storage and bulk storage areas. Five sensors costing $101 each were used in the office [17]. Ceiling sensors costing $296 each [17] were used in the other areas, with five needed in the fine storage area and ten needed in the bulk storage area. The occupancy sensor alternative required an additional total construction cost of only $4,945.

Based on RSMeans cost data [17] there is no significant price difference between ballasts having variable ballast factors. Thus, since the number of fixtures used remains fixed and the cost of ballast with lower ballast factors are the same, there is no difference in cost for this alternative design when compared to the baseline configuration.

Building Configuration Analysis and Code Compliance

Using the construction cost estimate data provided in Tables 22 through 26 and the results of the energy analyses undertaken and presented earlier in the report, a number of building configurations were further analyzed to determine which configuration(s) provided the most cost effective means to meet code minimum energy efficiency [essentially, identifying that building configuration having minimum (construction + energy) costs].

To facilitate this comparison and check for code compliance, costs for yearly energy use were determined for the baseline model at each location (that is, for each city) and used as a comparison to determine cost savings on alternative building configurations.

Table 27 shows the yearly energy cost for the baseline building and the warehouse building with partially grouted 8 inch foamed CMU walls, a reduced lighting ballast factor, and an additional 2 inches of roof insulation. Again, note that the foam walls were used only for those walls requiring insulation by the prescriptive code provisions. This information is presented by the bar chart in Figure 18. In all but Zone 7, the yearly energy costs for the alternative building configuration are less than those for the baseline, and thus, these alternatives are code compliant in all but Zone 7. Note that there are significant yearly energy cost savings predicted for the foamed CMU wall configurations over the code prescriptive baseline configurations (as much as $4k/per year in some climate zones).

Table 27. Yearly Energy Costs for Warehouse with 8 in. for Foam Filled CMU Walls, 2 in. Added Roof insulation, and Low Lighting Ballast Factor.

	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Gas Cost	$1,377	$1,336	$865	$3,205	$1,570	$2,319	$3,252	$2,369	$4,435	$4,080	$6,089
Electricity Cost	$15,724	$15,723	$19,834	$19,532	$14,433	$12,105	$14,867	$14,495	$14,574	$16,583	$14,930
Total Cost	$17,100	$17,059	$20,699	$22,737	$16,003	$14,424	$18,119	$16,863	$19,009	$20,663	$21,019
Baseline Total Cost	$19,792	$19,701	$24,728	$25,665	$18,076	$16,008	$19,616	$19,162	$19,915	$21,722	$20,833
Cost Difference	$(2,692)	$(2,642)	$(4,029)	$(2,929)	$(2,074)	$(1,584)	$(1,497)	$(2,299)	$(906)	$(1,059)	$186

noncompliant

A second building configuration was evaluated. This structure was constructed with partially grouted 12 inch foamed CMU walls, with 2 inches added to the roof insulation, and a heating coil efficiency raised to 0.9. The results of these energy cost analyses are shown in Table 28 and presented in a bar chart in Figure 18. This configuration is code compliant to Zone 4A and lower. In the colder (higher) climate zones, it is clear that higher HVAC heating efficiencies alone (certainly for the package units addressed in this study) will not ensure code compliance and that increased lighting efficiencies also must be incorporated into the alternative designs. Moreover, unless 12 inch walls are needed for structural reasons, the building construction cost may be higher than baseline building cost (see the discussion in the following section).

Table 28. Yearly Energy Costs for the Warehouse with 12 in. Partially Grouted Foam Filled CMU Walls, 2 in. Added Roof Insulation, and Heating Coil Efficiency of 0.9.

	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Gas Cost	$1,127	$1,126	$740	$2,480	$1,293	$1,863	$2,696	$2,002	$3,751	$3,375	$5,082
Electricity Cost	$18,650	$18,550	$23,888	$23,060	$17,034	$14,405	$17,366	$17,242	$16,936	$19,198	$17,231
Total Cost	$ 19,777	$ 19,676	$ 24,629	$ 25,540	$ 18,327	$ 16,267	$ 20,062	$19,244	$ 20,687	$ 22,573	$ 22,313
Baseline Total Cost	$19,792	$19,701	$24,728	$25,665	$18,076	$16,008	$19,616	$19,162	$19,915	$21,722	$20,833
Cost Difference	$(15)	$(25)	$(99)	$(125)	$251	$259	$446	$81	$771	$851	$1,480

Noncompliant

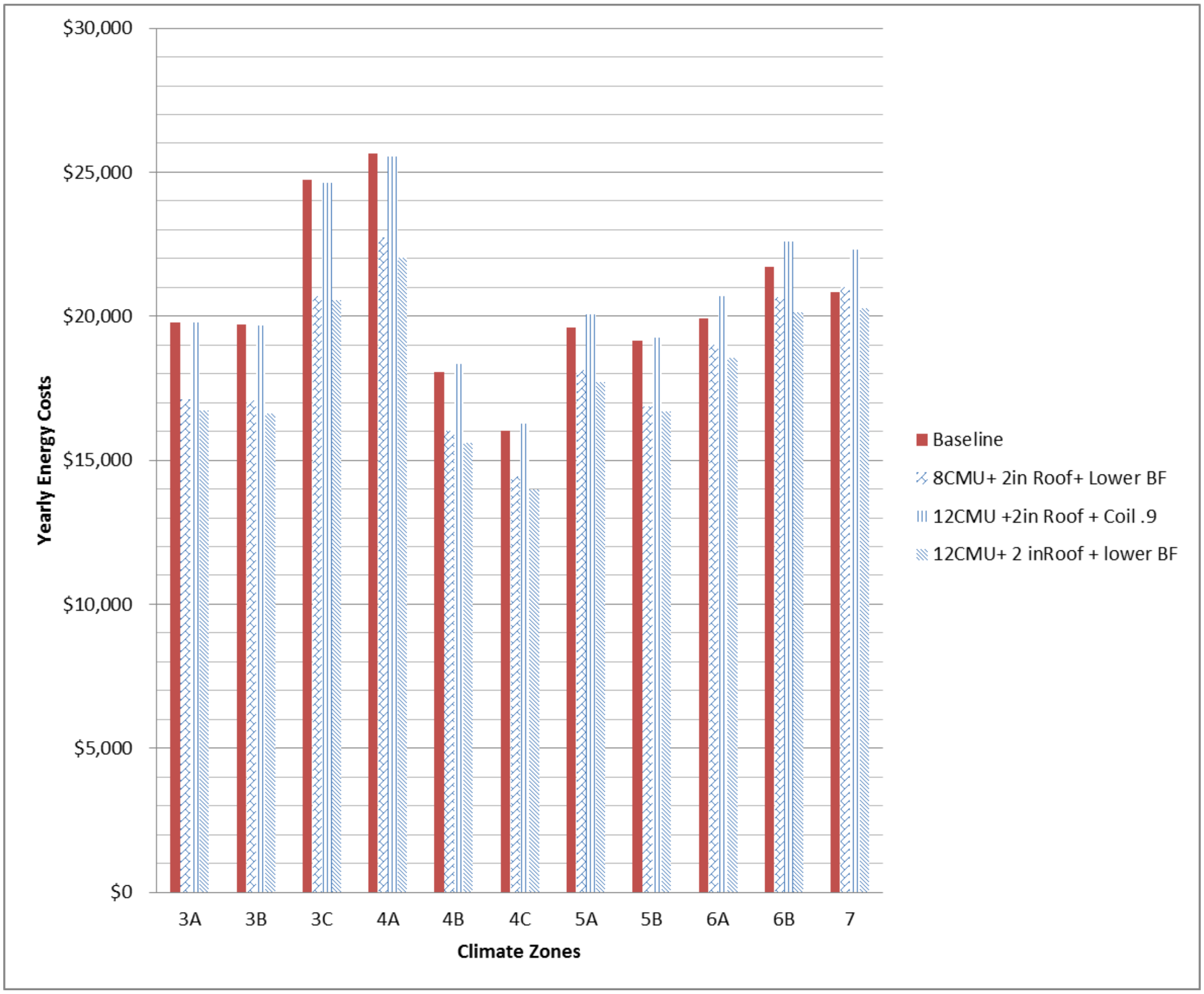

Figure 18. Yearly Warehouse Energy Costs.

A third building configuration was evaluated using a partially grouted 12 inch foamed in place CMU wall with 2 inches added to the roof insulation and a low lighting ballast factor. The results of these energy cost analyses are shown in Table 29 and presented in a bar chart in Figure 18. Examination of this data reveals that this configuration is code compliant in Climate Zones 3 through 7.

Clearly, bare (but core insulated) CMU walls provide yearly energy cost savings when compared to the code prescriptive baseline configurations where 8 inch CMU walls are used for construction in Climate Zones 6 and less, and where 12 in. CMU walls are used in Climate Zones 7 and less (and thus, 12 in. CMU construction can be used to meet the energy code in all climate zones). However in both these cases, these walls must be coupled with improved energy efficiencies in other building systems (lower lighting energy use and more roof insulation).

Table 29. Yearly Energy Costs for the Warehouse with a Partially Grouted 12 in. Foam CMU Wall, 2 in. Added to the Roof Insulation, and Low Lighting Ballast Factor.

	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Gas Cost	$1,271	$1,276	$853	$2,880	$1,448	$2,063	$3,078	$2,315	$4,213	$3,859	$5,659
Electricity Cost	$15,437	$15,350	$19,686	$19,147	$14,155	$11,924	$14,621	$14,368	$14,316	$16,267	$14,625
Total Cost	$16,708	$16,626	$20,540	$22,027	$15,603	$13,986	$17,699	$16,682	$18,530	$20,126	$20,284
Baseline Total Cost	$19,792	$19,701	$24,728	$25,665	$18,076	$16,008	$19,616	$19,162	$19,915	$21,722	$20,833
Cost Difference	$(3,084)	$(3,074)	$(4,188)	$(3,638)	$(2,473)	$(2,022)	$(1,917)	$(2,480)	$(1,386)	$(1,596)	$(549)

As a further comparison between alternative configurations and baselines, the differential construction costs for the various building configurations were compiled (see Tables 30 through 32). As shown in Table 30, the warehouse configuration constructed with an 8 inch foam filled CMU wall, 2 in. added roof insulation and a low lighting ballast factor generally has a lower wall construction cost than the respective code baseline configurations. However, when the cost of the added roof insulation is included, the net construction cost savings are much lower, and in Climate Zone 3A, the alternative configuration actually has a higher initial construction cost than the code prescriptive configuration (baselines). In general, because the lower ballast factor lighting fixtures are not expected to cost significantly more than the conventional lighting systems, these costs represent the total differential construction costs for each building configuration. As well, note that the yearly energy savings predicted in the Climate Zones 3 and 4 for the alternative design are substantial (ranging from $1584 to $4,029 – Table 27). In Climate Zone 3A, the yearly energy savings of $2692 (Table 27) would offset the initial construction cost upcharge of 1,951 (Table 30) in Zone 3A, with less than a year payback.

Recognizing that there is a substantial yearly energy cost savings in Zones 3 through 4, the alternative warehouse configuration was modified to use only foamed 8 in. CMU walls in the fine storage and office areas (the bulk storage had bare walls) with code prescriptive roof insulation levels and a low lighting ballast factor. This building configuration was analyzed for both construction costs and energy costs in climate Zones 3A through 4A, and the results are shown in Table 31. Because there is no additional roof insulation cost, and no incremental costs for the lower ballast factor lighting, the total construction cost differential is given only by the difference in wall construction costs. Both entries, “Wall Construction Cost Differential” and “Total Construction Savings” are shown in the table to make this point clear. Examination of these data shows that there is a substantial yearly energy cost savings as well as significant construction cost savings in Zones 3A through 4A, where additional roof insulation is not needed to achieve code compliance. Importantly, these savings could not be identified and used to demonstrate code compliance without conducting a holistic energy analysis on the warehouse building.

Table 30. Initial Construction Cost Savings for 8 inch Foam Filled CMU Wall with 2 in. Added Roof Insulation and a low Lighting Ballast Factor (In Contrast to Code Prescriptive Baseline Configurations).

	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Wall	($29,694)	($39,396)	($50,960)	($37,044)	($32,438)	($42,042)	($144,830)	($95,589)	($119,963)	($76,986)	($108,626)
Roof	$31,645	$38,039	$41,415	$33,262	$31,717	$37,716	$42,098	$32,974	$40,410	$32,112	$38,003
Lighting	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Total Savings	$1,951	($1,357)	($9,545)	($3,782)	($721)	($4,326)	($102,732)	($62,615)	($79,554)	($44,874)	($70,623)

Noncompliant   () Denotes a net savings in construction costs

Table 31. Energy Use (EUI-kBtu/ft^2), Energy Costs and Construction Cost Savings for 8 inch Foam Filled CMU Walls and a Low Lighting Ballast Factor for Climate Zones 3 and 4 (In Contrast to Code Prescriptive Baseline Configurations).

	3A	3B	3C	4A
EUI	18.5	17.0	15.9	24.5
Baseline EUI	20.0	18.7	18.0	24.3
Gas Cost	$ 1,443	$ 1,366	$ 878	$ 3,514
Electric Cost	$ 5,818	$ 15,831	$ 19,894	$ 19,662
Total Energy Cost	$ 17,261	$ 17,197	$ 20,771	$ 23,176
Total Energy Cost Savings	$(2,532)	$(2,504)	$(3,957)	$(2,490)
Wall Const. Cost Differential	($29,694)	($39,396)	($50,960)	($37,044)
Total Constr. Savings	($29,694)	($39,396)	($50,960)	($37,044)

() Denotes a net savings in construction costs

Differential cost analyses were also conducted on the warehouse configurations that used the 12 inch foam filled CMU wall with 2 in. added roof insulation and a low lighting ballast factor. As shown in Table 29, this building configuration had a yearly energy cost lower than the baseline building in all zones, including Zone 7 (and thus, was compliant for all climate zones). The 12 in. foamed CMU wall system is energy code compliant in Climate Zone 7, however, as shown in Table 32, the initial construction cost for this configuration in Zone 7 is higher than the initial construction cost for the baseline warehouse. In fact, Table 32 shows that the warehouse configuration constructed with 12 inch Foam + 2 inch Roof Insul + Low Lighting Ballast Factor does not have an acceptable payback period when compared to the baseline warehouse configuration constructed with an 8 inch wall. The payback period of 213 years is calculated by dividing the total differential construction cost ($117,268.00) by the yearly energy savings ($549/year). Unless the 12 inch CMU wall is needed for structural reasons, this wall configuration is not a cost effective building configuration.

Table 32. Initial Cost Differentials and Payback Period for the Warehouse with Partially Grouted 12 in Foam Filled CMU Wall, 2 in, added Roof Insulation, and Low Lighting Ballast Factor.

Zone 7	**Differential Costs**
Wall	$79,265
Roof	$38,003
Lighting	-
Total	$117,268
Payback (years)	**213**

The 12 inch CMU wall configuration was shown to be not cost effective for Climate Zone 7 unless increased wall thickness (greater than 8 in.) was needed for other reasons (such as increased structural demand). Thus, an additional energy analysis was conducted on a building configuration that used a partially grouted 8 inch foam filled CMU wall, 2 in. added roof insulation, a low lighting ballast factor, and occupancy sensors. This analysis was restricted to Climate Zone 7 and produced a yearly electrical energy cost of $6,398 and a gas cost of 13,148, for a total of $19,546 ($1,286 below the prescriptive baseline configuration). Thus, the proposed building configuration is code compliant. Note that the EUI for the proposed configuration was 43.3 kBtu/ft^2, which is higher than the baseline configuration, but the configuration produced lower energy costs because gas is much less expensive than electricity. This result will vary with changes in the relative cost of electricity and gas, but nevertheless, should prove true even for large changes in their relative prices. Further, the additional $4,945 cost for the Occupancy Sensors does not appreciably change the cost savings values stated in Table 30 for Climate Zone 7 for the 8 inch foamed CMU wall configuration ($70k).

US Study Summary

The results of this study of the energy performance of single wythe masonry warehouse archetype buildings showed that holistic energy analyses can be used effectively to demonstrate US energy code compliance for warehouses constructed with single wythe masonry walls without continuous external insulation. Moreover, when compared to the US code prescriptive configurations (externally insulated walls), benefits of the single wythe masonry wall configurations with integral foam insulation include both substantial construction cost savings, and in most cases, significant yearly energy costs savings (see Figure 18, and Tables 29, 30, and 31). The predicted construction cost savings for the alternative configurations ranged from $1000 to $65,000 and the predicted yearly energy cost savings ranged from $1,400 to $4,000.

PROTOTYPE BUILDING DESIGN AND ANALYSIS – CANADA

The prototype building design and analyses described in the previous sections were extended to examine alternative energy solutions for warehousing in a number of Canadian cities using the energy requirements of the 2011 edition of the National Energy Code for Buildings (NECB)[19]. The climates investigated were restricted to Climate Zones 4 through 7B since these zones cover the vast majority of the climates in Canada and also represent those geographical areas for nearly all construction activity. The Canadian cities investigated, and basic climate data obtained from the NECB, are shown in Table 33[19].

Table 33. Canadian Cities for Climate Zones 4 through 7B.

City	Climate Zone	Heating Degree Days (HDD)
Victoria, BC	4 (<3000 HDD)	2650
Windsor, ON	5 (3000 to 3999)	3400
Montreal (City Hall), QC	6 (4000 to 4999)	4200
Edmonton, AB	7A (5000 to 5999)	5120
Ft. McMurray, AB	7B (6000 to 6999)	6250

Changes to Prototype Warehouse

The prescriptive requirements of NECB 2011 [19] differ from those in the ASHRAE 90.1 standard, and thus, changes to the prototype warehouse building baseline configurations were needed for many of the climate zones. For instance, under the prescriptive requirements of the NECB, for a given climate zone, the various components of the building envelope such as walls, floors, roofs, or fenestrations, are each prescribed a maximum overall thermal transmittance (minimum thermal resistance) that does not vary with construction type. Thus, both mass walls and light frame walls are required to meet the same maximum thermal transmittance. Furthermore, for all climate zones, the prescribed maximum thermal transmittances for the various building envelope components (walls, roofs, floors, fenestrations) are generally lower in the NECB-11 than in ASHRAE 90.1. The differing prescriptive baselines required significant changes to the reference building configurations.

In addition, unlike ASHRAE 90.1, the holistic energy analysis option for code compliance (Part 8, Building Energy Performance Compliance) requires that the yearly energy use (not energy *cost*) of the proposed building not exceed that of the reference building designed to meet the prescriptive requirements. This is a more stringent requirement than the ASHRAE Standard.

Tables 34 through 36 list the changes made to the ASHRAE baseline prototype warehouse configuration in order to meet minimum requirements set forth in NECB 2011[19]. There were increases in wall thermal resistances, reductions in lighting system energy budgets, and a slight increase in HVAC system efficiencies. Where applicable, the tables also show US standard units for comparison to the previous analyses.

Table 34. Building Envelope Component Prescribed Maximum Thermal Transmittances (U-value) (NECB 2011)[19].

Climate Zone	4	5	6	7A	7B
(SI Units)					
Wall (W/m²K)	0.315	0.278	0.247	0.210	0.210
Roof (W/m²K)	0.227	0.183	0.183	0.162	0.162
Floor (W/m²K)	0.227	0.183	0.183	0.162	0.162
Floors in contract with ground (W/m²K)	0.757 for 1.2 m	0.757 for 1.2 m	0.757 for 1.2 m	0.757 for 1.2 m	0.757 for 1.2 m
Windows (W/m²K)	2.4	2.2	2.2	2.2	2.2
Doors (W/m²K)	2.4	2.2	2.2	2.2	2.2
(US Standard Units)					
Wall (Btu/ft²-h-°F)	0.055	0.049	0.043	0.037	0.037
Roof (Btu/ft²-h-°F)	0.040	0.032	0.032	0.028	0.028
Floor (Btu/ft²-h-°F)	0.040	0.032	0.032	0.028	0.028
Floors in contract with ground (Btu/ft²-h-°F)	0.133 for 4 ft.	0.133 for 4 ft.	0.133 for 4 ft.	0.133 for 4 ft.	0.133 for 4 ft.
Windows (Btu/ft²-h-°F)	0.422	0.387	0.387	0.387	0.387
Doors (Btu/ft²-h-°F)	0.422	0.387	0.387	0.387	0.387

Table 35. Lighting Energy Minimum Requirements (Lighting Power Densities) in NECB 2011[19].

Space Type	W/ft²	W/m²
Fine Storage	0.95	10.2
Bulk Storage	0.59	6.3
Office	1.02	11.0

Table 36. HVAC Minimum Efficiency Requirements in NECB 2011.

	Coefficient of Performance (COP)
Heat Pump	3.1

Energy Analysis

To produce the Canadian prototype baseline warehouse building, for each climate zone, the US-based ASHRAE 90.1 prototype was modified to comply with the NECB minimum performance levels prescribed for the building envelope components, lighting, and HVAC systems. These Canadian baseline building configurations were otherwise identical to those described for the US analyses, and were maintained with the same fenestration areas. As will be discussed later in this report, the NECB permits the reference building fenestration area to vary with HDD to permit energy performance trade-offs. In the first series of analyses, the FDWR (Fenestration+Door area to gross Wall area Ratio) was not changed to facilitate direct comparison with the results of the ASHRAE 90.1 analyses. Thus, (using the terminology of the NECB), the FDWR was not adjusted, and the FDWR of the reference building equaled that of the proposed building. Subsequent analyses explored the effects of changing the FDWR of the reference building on energy use and compliance. EnergyPlus analyses were conducted on each building prototype using hourly weather data [9] for the Canadian cities listed in Table 33. The results of the Canadian prototype baseline warehouse building analyses are shown in Table 37. Both SI and US standard units are shown in this table to allow comparison to the previous analyses.

Comparing the EUI values for the Canadian NECB baseline configurations (Table 37) with those of the U.S. ASHRAE 90.1 baseline configurations (Table 5), suggests that they are lower than ASHRAE 90.1 baseline values for the corresponding climate zones (Seattle has an EUI of 21.3 kBtu/ft^2 and Victoria has an EUI of 19.3 kBtu/ft^2 – both have similar climates), although direct comparison of the subzone values is difficult. In addition, it appears that the much lower building envelope thermal transmittances required in the Canadian Code do not appear to have a large effect on the building energy performance.

As shown in Figures 19 and 20, the majority of the energy used in the Canadian prototype configurations is for heating, fans, equipment and lighting. Thus, alternative designs focused on the HVAC and lighting systems.

Table 37. Yearly Energy Consumption and EUI Values for NECB 2011 Baseline Configurations of the Warehouse Prototype (No FDWR Adjustments).

Location	Victoria	Windsor	Montreal	Edmonton	Ft. McMurray
Province	BC	ON	QC	AB	AB
Climate Zone	4	5	6	7A	7B
SI Units					
Heating (GJ)	494.7	632.5	704.3	875.5	1187.5
Cooling (GJ)	0.8	2.4	1.5	1.0	1.1
Interior Lighting (GJ)	338.5	337.9	338.5	338.3	338.7
Interior Equipment (GJ)	107.1	107.1	107.1	107.1	107.1
Fans (GJ)	64.6	82.7	60.9	114.0	122.9
Total (GJ)	**1005.7**	**1162.6**	**1212.2**	**1435.9**	**1757.4**
EUI (GJ/m^2)	**0.220**	**0.254**	**0.264**	**0.314**	**0.383**
US Standard Units					
Heating (kBtu)	468876	599480	667520	829803	1125563
Cooling (kBtu)	799	2249	1404	979	1077
Interior Lighting (kBtu)	320870	320289	320826	320671	321020
Interior Equipment (kBtu)	101469	101469	101469	101469	101469
Fans (kBtu)	61212	78420	57719	108031	116524
Total (kBtu)	**953226**	**1101907**	**1148938**	**1360953**	**1665653**
EUI (kBtu/ft^2)	**19.3**	**22.3**	**23.2**	**27.5**	**33.6**

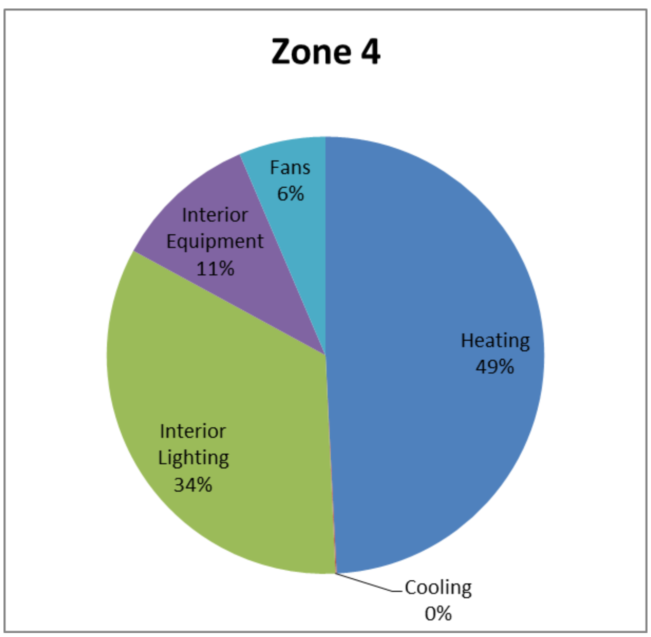

Figure 19. Annual Energy Use of the Canadian Baseline Warehouse (NECB-11 Prescriptive Configuration – No FDWR Adjustments) Zone 4.

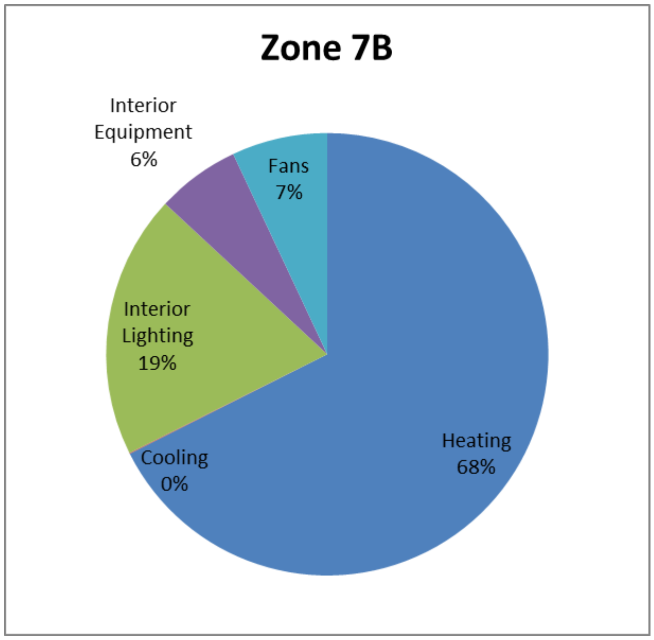

Figure 20 Annual Energy Use of the Canadian Baseline Warehouse (NECB-11 Prescriptive Configuration- No FDWR Adjustments) Zone 7B.

When using the whole building analysis compliance path, one notable difference between NECB-11 and ASHRAE 90.1 is the NECB provision that allows the FDWR of the reference building to be increased under certain conditions independent of the FDWR of the proposed building configuration. The FDWR of the reference building is not required to "track" the FDWR of the proposed building where the FDWR of the proposed building is below a prescribed maximum value. Thus, for the purposes of analyses and compliance, the reference building may be assigned the maximum FDWR permissible even though the proposed building uses its design FDWR. The FDWR limit varies with HDD, and is equal to 40% where HDD < 4000, 20% where HDD > 7000, and varies linearly between these HDD limits. Because fenestration and doors typically have higher U-values compared to opaque envelope components, this code provision aids in qualifying proposed buildings where the FDWR is low, such as a warehouse. This effect is particularly pronounced in buildings where the opaque wall thermal transmittance is higher than prescribed by the code. These provisions also allow the reference building to be assigned a total skylight area of 5% of the gross roof area, and like FDWR, may be used where the proposed building has less than a 5% skylight area, however this effect is much smaller.

The FDWR for the proposed warehouse configuration is below 7%, and because this is below the maximum allowable FDWR for the HDD of all climate zones, the reference buildings used for holistic energy analysis comparisons were adjusted so that the fenestrations in each area (office, fine storage and bulk storage) met the percentages shown in Table 38 (these became “revised baseline building configurations” for each climate zone). The fenestrations were assumed to be uniformly distributed in each area. Because a skylight is unlikely to be used in a warehouse and its effect on energy use is small due to its small area (5% of the roof area), a skylight was not added to the reference building configurations. The yearly energy use indices produced by the energy simulations for each of the revised baseline building configurations are shown in Table 39. By comparison with the EUIs stated in Table 37 (for the baseline building configurations without permitted higher FDWR), it is clear that the increased fenestrations have a significant effect on energy use particularly for the higher climate zones (producing up to a 45% increase in EUI).

Table 38. Adjusted FDWR Values for the Reference Warehouse Configuration.

City	Climate Zone	FDWR (%)
Victoria	4	40%
Windsor	5	40%
Montreal	6	38.6%
Edmonton	7A	32.5%
Fort McMurray	7B	25%

Table 39. Yearly Energy Consumption and EUI Values for NECB 2011 Revised Baseline Configurations (Reference Building with Maximum Allowable Fenestration Areas).

Location	Victoria	Windsor	Montreal	Edmonton	Ft. McMurray
Province	**BC**	**ON**	**QC**	**AB**	**AB**
Climate Zone	**4**	**5**	**6**	**7A**	**7B**
SI Units					
EUI (GJ/m^2)	0.236	0.319	0.349	0.454	0.557
US Standard Units					
EUI ($kBtu/ft^2$)	20.71	28.02	30.62	39.83	48.83

It should be noted that the NECB also allows semi-heated space, such as a bulk storage area used in the prototype warehouse, to be compared against a reference building configuration that is held to a heating set point of 18° C. Because the proposed building has set points lower than this, using this provision will produce greater differences between the energy use of the proposed building and the reference building, and thus, facilitate the use of building envelope components in the proposed building having thermal transmittances greater than the prescribed maximums used by the reference building. However, for all climate zones, code compliance was obtained without this adjustment by using opaque wall thermal transmittances typically produced by the single wythe masonry wall systems. Furthermore, set points are user defined and can be quite variable. Thus, this allowance was not addressed by the analyses performed in this study.

The revised reference buildings (with maximum permissible FDWRs) were used as the baseline for the holistic energy compliance path (using the requirements of Part 8 of the NECB, "Building Energy Performance Compliance"). A number of energy conservation measures were investigated for the proposed buildings. To keep the construction cost of the alternative opaque wall system low, 8" (20 cm) exterior CMU walls with foamed cores were used [with vertical reinforcement at 48 inches on centre (1200 mm) to satisfy structural demand]. Overall thermal transmittance was calculated accordingly. In response to the comparatively more stringent HVAC systems and lighting requirements in the NECB, more efficient LED lights were expected to provide significant improvements in building energy performance and were investigated as an alternative lighting configuration.

LED lighting technology produces low energy consumption with high lumen output. GE's IP series LED lighting systems were chosen for the simulation and GE's lighting design tool was used to obtain the light output of specific IP series lamp configurations. This information was used to determine how many fixtures would be required to reach the IES minimum lumen level in each of the areas of the warehouse [21]. This revised lighting design resulted in light power densities of 0.1 W/ft^2 (1.07 W/m^2) in the bulk storage area and 0.3 W/ft^2 (3.2W/m^2) in the office area.

Table 40 shows the yearly energy use for the prototype warehouse configuration (the proposed building) with 20 cm (8") core insulated exterior CMU walls and energy efficient LED lights, in Climate Zones 4 through 7. This table also shows the EUI index of the proposed building for each climate zone, and the difference between this EUI and that of the revised baseline building configuration (this being the reference building having maximum permissible FDWR). Both SI and US standard units are shown in this table to allow comparison to the previous analyses.

As shown in Table 40, the proposed building configuration meets or exceeds the NECB 2011 requirements for Climate Zones 4 through 7B. The yearly energy use predicted for the proposed building is less than the energy use of the reference building (having maximum permissible FDWR) in all climate zones.

Table 40. Yearly Energy Consumption for the Proposed Buildings [Having Foamed in Place 8" (20 cm) CMU Walls, and LED Lighting].

Location	**Victoria**	**Windsor**	**Montreal**	**Edmonton**	**Ft. McMurray**
Province	**BC**	**ON**	**QC**	**AB**	**AB**
Climate Zone	**4**	**5**	**6**	**7A**	**7B**
SI Units					
Heating (GJ)	663.4	965.2	1150.7	1532.2	2040.1
Cooling (GJ)	0.6	2.3	1.3	0.7	1.0
Interior Lighting (GJ)	49.1	49.0	49.1	49.1	49.1
Interior Equipment (GJ)	107.1	107.1	107.1	107.1	107.1
Fans (GJ)	85.1	119.2	83.2	177.4	189.3
Total (GJ)	**905.3**	**1242.7**	**1391.4**	**1866.5**	**2386.5**
EUI (GJ/m^2) (Proposed Building)	**0.198**	**0.271**	**0.304**	**0.407**	**0.521**
EUI (GJ/m^2) (Reference building with max FDWR)	**0.236**	**0.319**	**0.349**	**0.454**	**0.557**
Difference	**-0.038**	**-0.048**	**-0.045**	**-0.047**	**-0.036**
US Standard Units					
Heating (kBtu)	628766	914813	1090643	1452275	1933638
Cooling (kBtu)	606	2144	1279	708	912
Interior Lighting (kBtu)	46512	46452	46515	46493	46533
Interior Equipment (kBtu)	101469	101469	101469	101469	101469
Fans (kBtu)	80688	113001	78857	168188	179399
Total (kBtu)	**858041**	**1177879**	**1318763**	**1769133**	**2261951**
EUI (kBtu/ft^2) (Proposed Building)	**17.33**	**23.80**	**26.64**	**35.74**	**45.70**
EUI (kBtu/ft^2) (Reference building with max FDWR)	**20.71**	**28.02**	**30.62**	**39.83**	**48.83**
Difference	**-3.38**	**-4.22**	**-3.98**	**-4.09**	**-3.13**

In summary, the NECB provision that permits the areas of fenestration and doors of the reference building to be increased above the FDWR of the proposed building facilitates trade-offs between the energy effects of increased fenestration (in the reference building) and the reduced thermal resistance of the opaque building envelope components (in the proposed building). Clearly, this provision is very effective in facilitating compliance in all climate zones of warehouse buildings having low FDWR.

Heat flow through a component is inversely proportional to its thermal resistance (R) but the thermal resistance of a component generally increases linearly with thickness. As a consequence, the rate at which conductive heat flow is reduced by increasing the insulation thickness (or R) of an assembly, decreases at a lower rate at higher R values. Given this relationship, the relatively high prescriptive thermal resistances (low thermal transmittances) required by the NECB for all building envelope components greatly diminishes any effects that large increases or decreases in their thermal resistances have on the thermal performance of the assembly. For example, thermal resistance trade-offs between opaque wall systems and the roof is not particularly effective because the prescriptive thermal resistance required for a roof by the NECB is high enough that large increases in thermal resistance above this minimum have little effect on building energy use. This greatly limits the ability of the designer to obtain whole building compliance using only building envelope trade-offs.

For each climate zone, yearly energy cost for the proposed building configuration was then calculated using natural gas prices from the Canadian Natural Gas Association (yearly average) and electricity rates for Canadian cities from hydroquebec.com. These yearly costs are listed in Table 41. Note that the 500 kW-200,000 kWh electrical rates were used. As not all the cities were listed, the unit cost for Vancouver was used for Victoria, Edmonton rates were used for Fort McMurray, and Toronto rates were used for Windsor. This was judged to be reasonable since this is for comparison purposes only (not for compliance under the NECB) and because actual energy prices vary with demand and location. Also calculated are the yearly energy costs for the Canadian baseline warehouse prototype (the reference building without increased FDWR).

As shown in Table 41, yearly energy use predictions show significant energy cost savings for the proposed building configuration in all climate zones. Zone 5 had yearly energy cost savings of over $5,600 compared to the reference (baseline) building prototype configuration. For all climate zones, the analyses results show that much of the yearly energy cost savings are a result of a reduction in lighting electrical energy cost. Even though the increase in thermal transmittance of the alternative building configuration increases the heat heating energy demand and costs, this increase is heavily mitigated by the relatively low cost of natural gas.

Table 41. Yearly Energy Costs for the Proposed Building Warehouse Prototype [Having Foamed in Place 8" (20 cm) CMU wall and LED lighting].

Location	**Victoria**	**Windsor**	**Montreal**	**Edmonton**	**Ft. McMurray**
Province	**BC**	**ON**	**QC**	**AB**	**AB**
Climate Zone	**4**	**5**	**6**	**7A**	**7B**
Gas Cost	$ 2,295	$ 3,339	$ 3,981	$ 5,301	$ 7,058
Electricity Cost	$ 4,757	$ 7,510	$ 4,807	$ 10,280	$10,652
Total Energy Cost Proposed Building	$7,052	$10,849	$ 8,788	$ 15,581	$ 17,710
Baseline Cost Reference Building[a]	$ 11,762	$ 16,531	$ 12,581	$ 20,262	$ 21,631
Cost Difference	($4,709)	($5,682)	($3,793)	($4,681)	($3,921)

() indicates net cost savings

[a]The Canadian baseline reference building compliant with the minimum prescriptive requirements of the NECB, and without FDWR increased to the permissible limits.

Construction cost analyses were conducted using IMI construction estimating software (based on the RSMeans database). The costs of the baseline buildings are based on using 3" to 5" (76 mm to 127 mm) of XPS insulation (as required to meet NECB climate zone requirements) on the interior surface of the exterior masonry walls, with 25 gauge studs at 24" centers (610 mm) used as furring. A cost analysis was conducted as described in the previous section, with the unit wall costs adjusted for each Canadian city using the applicable city cost index in RSMeans. Similar results to those shown for the alternative ASHRAE 90.1 building modelled earlier were observed, with wall costs for the proposed building [using 8" (20 cm) foamed in place concrete block masonry walls] being much lower than those for the baseline reference building configuration [internally strapped and insulated 8" (20 cm) concrete block masonry walls, Figure 11]. The wall cost differentials are shown in Table 42 for the various climate zones.

The lighting analysis for the LED design resulted in fewer light fixtures required for the proposed building configurations than for the baseline design. The baseline design (used for the reference building) required 146 fixtures and the LED design (used for the proposed building) produced 123 fixtures. The per fixture cost of the baseline fluorescent lamps were obtained from RSMeans [17] at $220 per fixture. The LED fixture material costs were obtained from the Granger product catalog [23] and the labour cost obtained from RSMeans [17] for a similar fixture. The total cost for the LED fixture was $720. These values were also adjusted for (city) location using the MEANS procedures. Differential lighting costs are shown in Table 42.

Table 42. Differential Construction Costs, (Proposed Building Cost – Baseline Warehouse Prototype Cost).

City	Victoria	Windsor	Montreal	Edmonton	Ft. McMurray
Climate Zone	**4**	**5**	**6**	**7A**	**7B**
Walls‡	($114,345)	($100,150)	($106,989)	($109,963)	($106,098)
Lighting§	$59,375	$58,303	$61,689	$64,849	$59,375
Total	($54,971)	($41,848)	($45,300)	($45,113)	($46,723)

() indicates net cost savings

‡ 8” (20 cm) CMU foam filled wall (proposed building) vs. 8” (20 cm) internally insulated wall (baseline building)

§ LED lighting (proposed building) vs. fluorescent lamp (baseline building)

The differential construction cost analyses show that the alternative designs proposed for the Canadian prototype warehouse are less costly to construct than the code prescriptive configurations.

Clearly, holistic energy analyses can be used to show that warehouses constructed with single wythe core insulated masonry walls can be code compliant, built at lower cost than other constructions meeting code prescriptive configurations, and can produce significant yearly energy savings when compared to other compliant constructions.

Canadian Study Summary

The results of this study showed that holistic energy analyses can be used effectively to demonstrate Canadian energy code (NECB) compliance in Climate Zones 4 through 7B for warehouses constructed with single wythe masonry walls having core foam insulation only (without continuous external insulation), and by trading out traditional fluorescent lights for more efficient LED fixtures. Moreover, when compared to the NECB prescriptive configurations (externally insulated walls), benefits of the single wythe masonry wall configurations with integral foam insulation include both substantial construction cost savings, and in most cases, significant yearly energy costs savings (see Tables 41 and 42). The predicted construction cost savings for the alternative configurations ranged from $41,000 to $55,000 and the predicted yearly energy cost savings ranged from $3,800 to $5,700.

CONCLUSIONS

The following conclusions can be made based on the model warehouse archetype used in this energy study:

1. There are a number of warehouse building configurations which use exterior single wythe concrete masonry unit (CMU) wall systems (without external insulation) that can be readily shown to comply with ASHRAE 90.1 and NECB-11 when modelled using the whole building analysis compliance path.
2. Warehousing constructed with CMU walls (without external insulation) cannot be easily designed for code compliance using only the simple building envelope trade-offs permitted by ASHRAE 90.1 and NECB-11.
3. Under ASHRAE 90.1 in the U.S., for Climate Zones 3 through 6, the whole building energy analysis path shows code compliance (wherein yearly energy cost of the proposed building is not greater than the energy cost for a building designed to code prescriptive requirements) for a warehouse archetype model constructed with (a) exterior 8 in. CMU walls (partially grouted, with the ungrouted cores filled with foam insulation), (b) additional insulation on the roof (that is, in addition to the code prescriptive minimum), and (c) lighting ballasts having low ballast factors.
4. Under ASHRAE 90.1 in the U.S, for Climate Zone 7, the whole building energy analysis compliance path shows code compliance for a warehouse archetype model constructed with (a) 8 inch CMU walls (partially grouted, with the ungrouted cores foamed filled), (b) additional insulation on the roof (that is, in addition to the code prescriptive minimum), (c) lighting ballasts having low ballast factors, and (d) occupancy sensors.
5. For the building configurations and climate zones studied, yearly energy cost was able to show code compliance under ASHRAE 90.1. In many cases the proposed building configurations used more energy (had higher EUI values) than code prescriptive building configurations, but the trade-off of higher cost electricity with low cost natural gas produced lower overall energy costs and thus code compliance.
6. Lighting and HVAC efficiency have a greater effect on energy use than envelope insulation, provided some increase in thermal resistance over bare CMU walls is realized.
7. The whole building analysis methodology is effective at producing warehouse building design alternatives that have significantly lower capital costs than the code prescriptive building configurations, as well as producing significant yearly energy cost savings.
8. Compliant warehouse buildings can be designed under the Canadian energy code (NECB 2011) in Climate Zones 4 to 7B by using only foamed-in-place 8” CMU walls and LED lighting systems. These alternative designs offer significant

construction and yearly energy cost savings over code prescriptive building configurations.

9. The comparatively low prescriptive envelope thermal transmittances required under the NECB render building envelope trade-offs less effective because further decreases have little, and progressively less effect, on the overall energy used by the buildings.
10. The NECB provision that allows the fenestration+door area to gross wall area ratio (FDWR) of the reference building to be increased to a maximum permissible value, independent of the proposed building configurations, significantly aids in qualifying proposed buildings (having a higher opaque wall thermal transmittance than that prescribed by the code). This is particularly true where the FDWR is low, such as in a warehouse building.

RECOMMENDATIONS

The results of whole building energy analyses show that typical warehouse buildings constructed using single wythe masonry walls without external insulation can be energy code compliant in cost effective construction configurations for most US climate zones and for Canadian Climate Zones 4 through 7B. This methodology should be applied to other building archetypes using single wythe masonry walls systems to determine if similar results can be obtained. Furthermore, additional building systems (such as variable refrigeration systems, passive solar systems and others) appropriate for application to warehouse use should be investigated to determine if they might produce more cost effective designs.

An effort must be made to encourage holistic energy analysis in building design (use of the “Energy Cost Budget Method” of ASHRAE 90.1, and of “Building Energy Performance Compliance” of the NECB). This will allow the designer and building owner to focus on the building systems that meaningfully affect the energy use of the building and help eliminate any tendency to needlessly increase the thermal insulation levels of mass exterior wall systems beyond those where they have no significant effect on the building performance yet significantly increase the cost of construction.

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