STRUCTURAL, BUILDING SCIENCE, SUSTAINABILITY, 
AND CONSTRUCTABILITY STUDY OF A TRANSPARENT RESIDENTIAL 
WALL SYSTEM 

A Thesis in 
Architectural Engineering 

by 
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Submitted in Partial Fulfillment 
of the Requirements 
for the Degree of 

Master of Science 

August 2016
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ABSTRACT

The depletion of available resources, growing world population, and rising cost of available resources have brought greater emphasis on the adoption of sustainable practices, materials, and technologies. Even though sustainability is beneficial its adoption in the residential sector is currently much less than that of the commercial sector (Center for Climate and Energy Solutions, 2013).

Originally, the Residential Glazed Wall Panel System (RGWPS) was formulated to improve sustainability for residences. More specifically, permitting daylighting to penetrate into a residence’s interior and generate electricity – through embedded photovoltaic (PV) cells. RGWPS is a system that combines two traditionally separate systems. In doing so, the constraint of window size and structural requirements are reduced; because the entire system is load bearing. Traditional window glazing systems do not carry gravity or in-plane lateral loads.

Structural steel is commonly used in commercial construction, however it is less used in residential construction (Jellen, 2012). The fact that structural material for framing systems can vary opens the opportunity to explore the use of cold formed steel (CFS) and structural aluminum frame in-lieu of the structural steel sections. The design of the mentioned systems were evaluated for building science performance, structural performance, as well as constructability. Building science performance were based on thermal bridging potential, potential for condensation, visible transmission, acoustical attenuation, estimated environmental impact – using both ATHENA Impact Estimator and a quantitative method. Using these evaluation points, the designs were compared with the original wall system (RGWPS) and the typical residential wood frame system to determine if further development is warranted.
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ACKNOWLEDGEMENTS

Before continuing any further, I would like to mention and extend my gratitude to the individuals for their support in completing this thesis project, this thesis report:

First I’d like to express my gratitude to my thesis advisor Professor Ali M. Memari. I greatly appreciated your patience, intuitive inputs, and guidance through the difficult thesis process. Also I’d like to show my appreciation towards Professors Treado and Iulo, my thesis committee members for their time and insights.

To Dong Do and his family’s support to complete my thesis. I would also like to thank the AE staff, especially Corey Wilkinson, for their technical support.

Though these individuals may mean nothing to those reading this thesis report; they have gained my gratitude, my respect – which I can in no way convey them completely and often enough.
1.1 Original System

The original transparent PC sheathing wall system – more formally known as Residential Glazed Wall Panel System (RGWPS) – aimed to reduce energy consumption in artificial interior illumination. It does so by increasing natural lighting into the interior spaces. This was achieved through using transparent polycarbonate (PC) sheathing, in lieu of the more traditional plywood or orientated strand board (OSB) sheathing.

Most residential buildings are constructed using opaque walls. These walls typically employ wood studs and wood structural sheathing material – like plywood and orientated strand board (OSB). The wood studs are nailed together into a frame, whose main purpose is to resist gravity loads. Structural sheathing on the other hand, handles the lateral loads – like wind and seismic –, and is nailed to the wood stud frame.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Fenestration R-Value</th>
<th>Wood Frame Wall R-Value</th>
<th>Mass Wall R-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not Required</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>2.9</td>
<td>20 or 13 + 5</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>20 or 13 + 5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>3.1</td>
<td>20 or 13 + 5</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>3.1</td>
<td>20 + 5 or 13 + 10</td>
<td>15</td>
</tr>
<tr>
<td>7, 8</td>
<td>3.1</td>
<td>20 + 5 or 13 + 10</td>
<td>19</td>
</tr>
</tbody>
</table>

In most residential buildings windows are employed to permit natural lighting penetration into the interior spaces. Greater amounts of natural lighting can be achieved by using large
windows. Since most windows do not carry gravity and in-plane lateral loads, there is a size limit. As windows become larger, there is less room for the structural frame and structural sheathing, which translates to less gravity and lateral load capacity for the wall. Other than structural disadvantages, walls with large windows experience greater energy loss and glare. Greater energy loss arises from the low thermal resistance of window glazing – when compared to walls. Table 1-1 shows the thermal resistance required by the 2012 International Residential Code (IRC) (ICC, 2012). Rectifying these disadvantages can be done through using materials less used in the residential sector, window treatments, and specialized glazing; but is financially costly.

![Figure 1-1: Components of IGU](source: Lapella (2013))

![Figure 1-2: Thermal Performance of Multi-Pane Glazing](source: Ander (2010))

<table>
<thead>
<tr>
<th>Number of Glazing Panes</th>
<th>R-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>0.917</td>
</tr>
<tr>
<td>Double</td>
<td>2.083</td>
</tr>
<tr>
<td>Triple</td>
<td>2.778</td>
</tr>
</tbody>
</table>
Insulating Glazing Units (IGU), as shown in Figure 1-1, were used in the RGWPS to provide thermal insulation. Figure 1-2 shows the general thermal performance of IGU, based on the number of glazing panes. IGU relies on still air between multiple glass panes as insulation. The spacers separating the glass panes are made of low conductivity materials – varies by manufacturer – to reduce thermal bridging. Greater thermal resistance can typically be achieved with increasing the number of panes, replacing still air with dense gases – argon –, or any combination of the two ideas. In doing so, the IGU will become costly and heavy. The main reasons that IGUs were used in the RGWPS is that it allows maximum daylighting and reduces noise mitigation (Lingnell, 2011) – when compared to other conventional insulation.

RGWPS combines the traditionally separate structural system and window glazing systems. The conceptual result was a more simple and compact structural system, where independent gravity and lateral force resisting systems are not necessary. Figure 1-3 shows a cross-section of the initial RGWPS design. Functioning as equivalent of structural sheathing, the transparent PC sheathing is used to resist lateral loads. To handle the gravity loads, RGWPS relies on structural
steel tube sections. Using structural steel sections reduces the number of structural members in the field of view – through its high load capacity when compared to wood and cold formed steel (CFS). The high load capacity of the structural steel sections also resulted in excessive overdesign (Standley, 2009). An additional problem arising from the use of structural steel sections include: lack of laborer’s knowledge in structural steel sections and implementation rarity in the residential sector (Standley, 2009). The result is high cost of the RGWPS, as shown in Figure 1-4, nearly twice the cost of the proposed Transparent PC Sheathing Wall System w/ CFS structure. Structural steel sections are generally more expensive than CFS and wood in the residential sector because residential construction typically gravitates around wood and to a lesser extent light gage metal sections (Jellen, 2012).

![Figure 1-4: Cost of Various Wall Systems](source: 2014 R.S. Means)

The original study also briefly explored the use of embedded/building integrated solar photovoltaic systems in the transparent sheathing wall system – with the intent to further improve sustainability in the residential sector. The primary benefit is reduced cost; where the embedded solar photovoltaic cells – building integrated photovoltaic (BIPV) – create electricity for the occupants to use and directly replaces traditional building materials – instead of behaving merely as a building add-on (Standley, 2009). The initial RGWPS design considered only enough solar
photovoltaic cells to meet energy demands. It would appear that cladding a building in more solar photovoltaic cells is advantageous, but is not the case. If a building is cladded in PV elements (e.g., 95%) then the cost reduction turns into cost increases (Ordenes et al., 2007). Cost increase arising from excessive solar photovoltaic cells arises from significant increases in the solar heat gain (Fung and Yang, 2008).

1.2 Transparent PC

Transparent PC is a glazing product and marketed as such but it has been shown (Standley, 2009) that it can also be used as a structural sheathing product capable of transferring lateral loads to the structural framing through attachment to the individual studs, which then resist loads as an integrated wall system. Figure 1-5 shows a sample of transparent PC. Structural sheathing in walls also has a secondary function that is to prevent exterior environmental conditions from severely impacting the controlled interior environment (Memari, 2013). Some exterior environmental conditions that are kept out by the structural sheathing in walls are: wind driven rain (Straub, 2006) and airborne debris.

Figure 1-5, Transparent PC used as Wall Sheathing
Source: Tetlow (2012)
Polycarbonate (PC) itself is not a new material but the application as a structural sheathing is more recent. PC is used in a variety of other applications like in Figure 1-5 and Figure 1-6. PC is a thermal plastic that can experience large deformations before failure – meaning that there is little risk of catastrophic failure should an object impact it. Since transparent PC sheathing is a type of plastic, it has a greater thermal expansion rate than the respective structural frame – the potential for buckling is far greater than plywood and oriented strand board (OSB) sheathing. An example of thermal induced buckling is shown in Figure 1-7. §2606.6 of the 2012 International Building Code states that fasteners shall have proper allowance for expansion and contraction. Furthermore, the transparent PC sheathing should be exposed to minimal temperature changes and gradients.
In terms of aesthetics, there are some precautions when using PC. One precaution is poor ultraviolet (UV) resistance. PC will degrade and turn yellow over time when exposed to UV rays, as shown in Figure 1-8. This problem is primarily a long term aesthetic issue. However, additive compounds can be added to PC to improve UV resistance (Polymer Technology & Services, 2012). The second precaution is potentially detracting scratches. PC is not scratch resistant as glass (TAP Plastics, 2014). To counter the low abrasion resistance, PC sheathing should be protected during construction or abrasion resistant PC should be used. As a note, abrasion resistant PC is less common and is not available in certain thicknesses (TAP Plastics, 2014).
1.3 Sustainability

Sustainability is an important consideration when designing and retrofitting buildings. Sustainability strives to preserve finite available resources for future use and reduce detrimental human impacts on the natural environment (BDC, 2003). To achieve this, there is emphasis on the efficient use and consumption of available resources. A few ways to incorporate sustainability into building design and retrofit are listed below:

1. Energy consumption reduction through using renewable and local resources – like daylighting, solar heating –, mechanical equipment selection, as well as eliminating the air leaks and thermal bridging occurrences
2. Material selection based on locality, energy and environmental impact of extraction, and durability (BDC, 2003)
3. Building Information Modeling (BIM) usage to reduce material waste during design, construction, occupancy, and decommissioning/demolition (Messner, 2013)

![Figure 1-9, Breakdown of the Reason to Adopt Sustainable Practices and Technologies](source.png)

Recently, sustainable design has become more assertive. Figure 1-9 shows that lower operating cost – a category that energy efficiency is associated with – is a growing concern and is
a significant contributor to adopt sustainable practices and technologies. The growing demand for sustainable design also leads to the creation of guidelines evaluating sustainability – like Leadership in Energy and Environmental Design (LEED), National Green Building Standard (NGBS), and International Green Construction Code (IGCC). Typically, each guideline uses a point system where points are awarded for implementing certain defined sustainable requirements. The main obstacles do not rest on the lack of innovation, instead it rest on solving practical issues, one of which is the high upfront costs associated with implementing sustainable practices and technologies (BDC, 2003). The other is the general limited knowledge – on both the part of the designer, contractor, and owner – on current sustainable practices and technologies.

1.4 Research Intent

The purpose of this study is to create a more practical transparent PC sheathing wall system that will promote viable adoption of sustainable technologies and practices in residences. The boost will help the residential sector reduce the disparity with the commercial sector – when it comes to adoption and use of new viable sustainable technologies and practices – and traditional inefficiencies (Center for Climate and Energy Solutions, 2013). By showing that the transparent PC sheathing wall system is viable, it will spur further development and make the system easier to adapt – through code modifications, simplified design tables, and marketability to owners and contractors. Let it be noted that this study is a follow-on to the previous study – designing and evaluating the RGWPS – by Standley in 2009.

It is the study’s objectives that will govern the study’s success. The three objectives for the study are: building science design, structural design, along with constructability and cost assessment.
Three design configurations were explored for the four prevalent climate zones in the continental U.S. The three design configurations are light gauge CFS, heavy gauge CFS, and structural aluminum frame. The four prevalent climate zones are: hot-humid, mixed-humid, cold, and mixed-dry. As shown in Figure 1-10, maritime and very cold climate zones are also present in the continental U.S. but will not be included in this study. The reason for not studying these climate zones is that only a few areas in the continental U.S. are classified to be in the maritime and very cold climate zones. Innovative materials were used to better suit prevalent local environmental conditions and hazards. Specifically, this meant exploring the use of various transparent and translucent insulation materials – aerogel, cellular PC, and fiberglass. Each of the three design configurations were developed, studied, and revised; in the end the effort yielded seven final designs.
Chapter 2

Development of the Transparent Wall Systems and Building Science Evaluation

2.1 Introduction to Building Science

Building science is a generally broad field of study. Building science studies physical impacts on the built environment. Naming each and all of these impacts is exhaustive; therefore only a few of these impacts are listed: humidity, freeze-thaw cycle, climate, soil and underground conditions, material properties, energy consumption, and comfort. This study only focused on a few important aspects for design. These include: maintaining generally acceptable light transmission through the wall system, improve thermal performance, adequately drain moisture – penetrating the wall assembly – to the exterior, and sustainability of the designs – gauged by the respective embodied energy. A set of guidelines were formulated to reach the defined objectives, and are tabulated in Table 2-1.

<table>
<thead>
<tr>
<th>Table 2-1, Design Objectives and Respective Guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
</tr>
<tr>
<td>Maintain generally acceptable light transmission through the wall system</td>
</tr>
<tr>
<td>Improve thermal performance when compared to original system</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Permit penetrating moisture to drain to the exterior</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Thermal insulation, acoustical performance, and defined limits were acquired through 2012 International Building Code (IBC), International Residential Code (IRC), and International
Energy Conservation Code (IECC). The general design used published research and literature material as aid and guidance.

2.1.1 Literature Review

2.1.1.1 Climate Impacts

Climate conditions vary by location; the impact on building envelope design is paramount. Climate conditions are important because they dictate the placement of vapor retarders and specify the envelope thermal performance. Figure 2-1 shows the various regions with similar and different climates in the continental U.S.

![Figure 2-1, General Climate Zones in North America](image)

According to the 2012 IRC, each climate zone is defined by the amount of precipitation, temperature, as well as annual cooling and heating degree days (CDD and HDD, respectively). The CDD measures the number of degrees above a set temperature, the set temperature is typically 72°F (IRC, 2012). Likewise, HDD measures the number of degrees below a set
temperature – where heating is required. For the HDD, the set temperature is lower than the CDD; usually at 65°F. The exact quantities defining each climate zone can be found in the 2012 IRC §N1101.10.2(1). The unique characteristics defining each climate zone, prevents direct building transplant from one zone to another. Therefore there are climate dependent thermal and moisture control strategies for each idealized climate as shown in Table 2-2.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Cold</th>
<th>Hot</th>
<th>Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°Install vapor retarders and air barriers towards the warm (interior) surface</td>
<td>°Generally opposite of cold climates</td>
<td>°Protect the wall from getting wet from interior and exterior</td>
</tr>
<tr>
<td></td>
<td>- Vapor flows from hot (interior) to cold (exterior)</td>
<td>°Protect walls from exterior wetting</td>
<td>°Compensate for vapor flow in both directions w/ air pressure and moisture control</td>
</tr>
<tr>
<td></td>
<td>°Maintain low RH in spaces conditioned</td>
<td>°Use permeable interiors to permit drying walls from the interior</td>
<td>°May allow moisture and air to “Flow-Through” to aid drying</td>
</tr>
<tr>
<td></td>
<td>°Don’t use impermeable or semi-impermeable insulating sheathings, so that drying can occur</td>
<td>°Pressurization of spaces conditioned to reduce infiltration</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-3, 2012 IRC Defined Thermal Resistance per Climate Zone for Fenestration and Opaque Walls

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Fenestration R-Value</th>
<th>Wood Frame Wall R-Value</th>
<th>Mass Wall R-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not Required</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>2.9</td>
<td>20 or 13 + 5</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>20 or 13 + 5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>3.1</td>
<td>20 or 13 + 5</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>3.1</td>
<td>20 + 5 or 13 + 10</td>
<td>15</td>
</tr>
<tr>
<td>7, 8</td>
<td>3.1</td>
<td>20 + 5 or 13 + 10</td>
<td>19</td>
</tr>
</tbody>
</table>

Each climate zone has unique building science requirements, where a building in one region cannot be transplanted to another without changes. Table 2-3, shows the code required
general thermal resistance for both windows and opaque walls. It may be noticed that there are multiple values for the recommended thermal insulation used in wood frame walls, values with a plus sign signify the use of both continuous insulation and insulation between the studs.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Fenestration R-Value</th>
<th>Frame Wall R-Value</th>
<th>Mass Wall R-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>12.2</td>
<td>5.1</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>12.2</td>
<td>6.1</td>
</tr>
<tr>
<td>3</td>
<td>2.9</td>
<td>17.5</td>
<td>10.2</td>
</tr>
<tr>
<td>4 except Marine</td>
<td>2.9</td>
<td>17.5</td>
<td>10.2</td>
</tr>
<tr>
<td>5 and Marine 4</td>
<td>3.1</td>
<td>17.5</td>
<td>12.2</td>
</tr>
<tr>
<td>6</td>
<td>3.1</td>
<td>20.8</td>
<td>16.7</td>
</tr>
<tr>
<td>7 and 8</td>
<td>3.1</td>
<td>20.8</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Another table exists in the 2012 IRC that defines an alternate required thermal resistance. Table 2-4 converts the U-Value of the alternate design table, to R-Value. The R-Value is derived by taking the inverse of the U-Value. This was the table used in designing for building science aspects. What can be said about both tables is that the fenestration – includes windows and doors – thermal resistance is less stringent than those of walls as glazing cannot inherently offer high thermal resistance.

Though the climate conditions vary by location, the interior conditions are generally kept constant and designed as such. §N1101.11 of the 2012 IRC dictates that the interior temperatures be no greater than 72°F for heating and no less than 75°F for cooling.
2.1.1.2 Thermal Insulation and Visible Light Transmission

Thermal insulation is used to impede the flow of heat, between spaces. Only when a thermal gradient exists does heat flow occur. Thermal gradients exist in objects and assemblies experiencing temperature differences at two or more interfaces. Impeding heat flow depends on controlling its three mechanisms, specifically: conduction, convection, and radiation.

Conduction involves direct contact between relatively immobile molecules to propagate heat flow. If direct molecular contact is prevented, then conduction cannot occur, which can be achieved by preventing the interior and the exterior interfaces from touching or coming into contact through a shared intermediate conductive molecular medium. Typically, a low conductivity material – like still air – is used between the interior and exterior interfaces to impede heat flow.

Heat flow can also be propagated through moving gas and liquid molecules – flowing fluids. The phenomenon is known as convection. Fluids flow occurs in two ways: naturally and forced. Under natural convection, temperature differences in the fluid causes it to flow – where higher temperature molecules rise above lower temperature molecules. Once the higher temperature molecules transfer their energy – in the form of heat – to lower temperature molecules, they begin to sink. The process continues until all molecules reach an equilibrium temperature. To keep convection down to a minimum, it is desired to stop fluid flow through compartmentalizing the envelope system into small cells to prevent more fluid volume from flowing.

The third way that heat is transferred is through radiation. The radiation heat flow mechanism doesn’t require a medium to occur, because it revolves around the movement of electromagnetic waves. Radiation works by electromagnetic waves striking molecules – the
energy from the electromagnetic waves are transferred to the molecules struck – causing the molecules struck to vibrate and rub against adjacent molecules. The movement and friction between the molecules are converted to heat – same principle behind the workings of microwaves. Heat flow by radiation can be mitigated by electromagnetic wave absorbing coatings – like low emissivity (e) coatings.

In buildings, thermal insulation serves to moderate temperature cycles in the interior environment caused by the exterior environment. Moderating the number of temperature cycles reduces HVAC system use – reduces energy consumption and improves sustainability. However, problems will arise with improper use: moisture damage, health hazards – mold and mildew. Thermal insulation affects the location of condensation within the wall assembly. Based on Lstiburek’s recommendations, the desired location of condensation is at layers that are least susceptible to moisture induced damage and does not foster health hazards. Also the location of condensation should make it easily dried for penetrating moisture to drain to the exterior.

![Figure 2-2, Visible Light Transmission for Transparent and Translucent Insulation Materials](Source: Buratti and Moretti (2011), Polygal (2010), Ander (2010))
<table>
<thead>
<tr>
<th></th>
<th>Single Glazing</th>
<th>Double Glazing</th>
<th>BRAGC</th>
<th>Clear</th>
<th>Tinted</th>
<th>Clear</th>
<th>Tinted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SHGC</strong></td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td><strong>Visible Transmission</strong></td>
<td>0.6</td>
<td>0.3</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

One attribute of the transparent PC sheathing wall system is permitting interior illumination by natural daylighting from the sun. Using natural daylighting improves sustainability by primarily decreasing artificial light and respective energy use. Preserving visible light transmission through the wall assembly is difficult, not because there is a shortage of translucent insulation materials; but because visible light transmission is degraded once the translucent insulation material is thickened to meet thermal performance requirements. Visible light transmission of transparent and translucent insulations are shown in Figure 2-2. The building code publishes visible transmission requirements, and are tabulated in Table 2-5. Three different types of innovative translucent insulation described subsequently were explored and their respective impact on wall assembly transparency analyzed.
Cellular PC is a lightweight insulation with internal voids. The internal voids usually contain still air, which is the major contributor of thermal resistance. Figure 2-3 shows internal voids present in samples of cellular PC. The internal voids also dissipate thermal energy and diffuse natural sun light – through the reflective properties of the void’s walls – to prevent overheating. Akin to the PC sheathing, the cellular PC requires large tolerances to allow for thermal expansion and contraction.

Increasing the system’s thermal resistance is achieved by increasing the number of void layers. Some manufacturers go a step further by injecting granular aerogel into the voids. Adding additional void layers does have downsides. For one, there is greater potential for condensation to occur in the voids. As a result, it is essential to drain penetrating moisture out of the assembly else temporary clouding/fogging occurs – reduces natural daylight penetration into interior spaces. Anti-condensation coating can be applied to spread the condensation to reduce clouding – have been successfully implemented in greenhouses. Additional void layers also reduce light transmission through the system.

Figure 2-4, FRP Insulation
Source: Ridout Plastics (2014)
The second type of applicable insulation is fiberglass reinforced polyester (FRP), a composite. On the aesthetic front, FRP is cloudy and milky – like frosted glass, as shown in Figure 2-4. This characteristic improves occupant privacy, but at the cost of light transmission. Light transmission is affected by the tightness the glass fibers are placed in the plastic and whether color additives were added. The glass fibers function as reinforcement to the plastic, thus giving the insulation significantly greater stiffness and structural properties when compared to comparative applicable insulations (Bakis, 2011). Like cellular PC, extended exposure to moisture is detrimental because the glass fiber strength degrades and results in clouding (Bakis, 2011). To date, FRP is primarily used as glass glazing substitute and structural thermal breaks (Modern Steel Construction, 2012). FRP’s structural properties depends on fiber and matrix volume percentages, most strength comes from fibers (Bakis, 2011). Matrix only keeps the material fibers together, like cement bonding the aggregate (East Coast Fiberglass Supplies, 2013).

Figure 2-5, Monolithic Aerogel
Source: Aerogel Technologies (2014)

Figure 2-6, Granular Aerogel
Source: Gibson (2012)
Aerogel is another applicable insulation that may be implemented. It is a relatively new material and therefore more difficult to acquire and more expensive than the previously mentioned insulations – cellular PC and FRP. Insulation properties stem from self-contained pores – with compositions of 80% to 99% air – for relatively robust thermal insulation properties (Aerogel Technologies, 2014). The material itself is brittle and degrades when in contact with water when waterproofing is not applied during the manufacturing process. Figure 2-5 and Figure 2-6 show the two major types of aerogel.

Granular aerogel as its name implies, is made up of many small grains, which are clumped together to create an insulation interface. The multiple small grains and spaces between them affect light transmissibility and thermal performance. Random grains and respective spaces between them diffuse light and result in reduced light transmission – up to 66% reduction in light transmission when compared to conventional double glazing with low-e coatings (Buratti and Moretti, 2011). When comparing thermal performance, granular aerogel’s performance falls behind monolithic aerogel and vacuum insulated panels. The advantage of granular aerogel lies with the relative ease to manufacture and maintain consistent quality when compared to monolithic aerogel (Buratti and Moretti, 2011), where large and uniform grains are not required.

Figure 2-7, Monolithic Aerogel Encased Glazing Unit
Source: Schultz and Jensen (2007)
Monolithic aerogel is a high performance insulation and is relatively transparent. Greater transparency stems from the lack of grains and respective spaces between them, thus relatively less light diffusion. High level of light transmission through monolithic aerogel can be seen in Figure 2-7. Only vacuum insulation panels offer thermal insulation in the same league, Table 2-6. To date, only small samples are sold commercially because it is difficult to manufacture and maintain consistent quality of the larger samples (Schultz and Jensen, 2007). The difficulty primarily stems from the aging and drying processes. In the aging process, the gel solution is purified and strengthened (Husing and Schubert, 2005). The aging process is crucial in preventing the cells in the gel from collapsing once the liquid is removed in the next step – drying.

### 2.1.1.3 Moisture Control

Moisture and water vapor flow through the wall assembly must to be tackled. If moisture and water vapor flow are not controlled, the wall water drainage system will become overwhelmed. The result is damage to the wall system – like spalling caused by the freeze-and-thaw cycle, and corrosion (Lstiburek, 2006; Straube, 2011).

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m-k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>1.05</td>
</tr>
<tr>
<td>Fiberglass Reinforced Polyester</td>
<td>0.40</td>
</tr>
<tr>
<td>PC</td>
<td>0.22</td>
</tr>
<tr>
<td>Still Air</td>
<td>0.024</td>
</tr>
<tr>
<td>Granular Aerogel</td>
<td>0.018</td>
</tr>
<tr>
<td>Vacuum Insulated Panel</td>
<td>0.006</td>
</tr>
<tr>
<td>Monolithic Aerogel</td>
<td>0.004</td>
</tr>
</tbody>
</table>
There are two mindsets to controlling moisture and water vapor. One way of thinking is water vapor should be kept out of wall assemblies. The other is, if any water vapor penetrates the wall assembly, then there must be a way to get the water vapor out. These two mindsets may appear simple but many times a compromise between the two are required, because the best ways to keep water vapor out also traps water vapor (Lstiburek, 2011). The most effective materials to keep water out are either impermeable or semi-impermeable, thus pre-existing moisture or moisture that had penetrated through imperfect joints cannot freely dry out.

Moisture and water vapor can be tamed by either or both vapor diffusion and air transport of vapor. Two potential wall components can control these vapor transport modes: vapor retarders and air barriers. Vapor retarders slow down and control water vapor flow due to diffusion through a wall assembly. The vapor retardation capacity is measured by vapor permeability. Vapor permeability is the ease with which water vapor can move through a material and is usually measured in perms. According to the 2012 International Building Code (IBC), a vapor retarder should have a permeability \( \leq 1 \) perm under the dry cup testing method. The dry cup testing method is just one method to measure a material’s permeability, whereby one side is exposed to 0% relative humidity (RH) and the other side of the test sample is exposed to 50% RH. The second method is the wet cup, where one side of the test sample is exposed to 50% RH and the other side is exposed to 100% RH. In non-hygroscopic materials the dry cup and wet cup permeability values coincide, but in hygroscopic materials (varying permeability when exposed to various RH levels) like plywood this is not so.

Air barriers can be used to resist the air pressure differences but must be continuous. Air barriers reduce and stop air transport of vapor. Continuity is essential because holes, openings, and penetrations will reduce the air barriers ability to stop air transport of vapor. Thus it is
necessary to install air barriers such that small holes, openings, and penetrations are eliminated. When the air barrier is continuous and results in a tight building then it is easier to pressurize and depressurize a building, as well as control interior moisture levels through ventilation and dehumidification.

One of the most critical areas is at joints. Here the air barrier and vapor retarder is necessary. Without these here, the moisture will quickly penetrate through the wall assembly – causing high humidity levels and uncontrolled condensation.

2.1.1.4 Joints

Generally overlooked are the sealants and expansion joints – which retard water penetration at the wall’s many joints and prevent thermal induced buckling, respectively. In a wall system – especially cavity walls – each component has a specific function, should one of them fail the entire wall system’s performance is significantly reduced.

Table 2-7, shows the types of sealants currently available on the market. What can be said is that high performance sealants – like urethanes are sensitive to bonding surface preparation (ASC, 2010). Based on sealant characteristics, silicone sealants were selected for use in the redesigns. The deciding factors were UV resistance and generous permissible joint movement.

Non-continuous elements of water-resisting barriers also pose potential moisture intrusion problems when installed improperly. The main problem is joining two water-resisting elements. By code – §1404.2 of the 2012 IRC – all water resistive barriers are required to be continuous. At joint interface, problems such as lack of tolerance and incompatible materials can arise. In order to prevent discontinuity and material rupture due to expansion and contraction, the 2012 IRC dictates that water-resisting elements be lapped a minimum 2 inches, but whenever control or expansion joints exist the lap is a 6 inch minimum. There also exist best practice
recommendations, to ensure joint and sealant durability and longevity. The recommendations are listed in Table 2-8.

<table>
<thead>
<tr>
<th>Sealant Type</th>
<th>Sealant Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butyl</td>
<td>- Good adhesion, water resistance, and color stability</td>
</tr>
<tr>
<td></td>
<td>- Minimal surface preparation</td>
</tr>
<tr>
<td></td>
<td>- Cures slowly</td>
</tr>
<tr>
<td></td>
<td>- High shrinkage and low shape recovery</td>
</tr>
<tr>
<td>Neoprene</td>
<td>- Good adhesion and water resistance</td>
</tr>
<tr>
<td></td>
<td>- Compatible with bitumen and asphalt surfaces</td>
</tr>
<tr>
<td></td>
<td>- Relatively inexpensive</td>
</tr>
<tr>
<td></td>
<td>- Cures slowly</td>
</tr>
<tr>
<td></td>
<td>- Typically available in dark colors only</td>
</tr>
<tr>
<td></td>
<td>- Stains surrounding materials</td>
</tr>
<tr>
<td></td>
<td>- High shrinkage</td>
</tr>
<tr>
<td>Solvent-Based</td>
<td>- Good adhesion, UV resistance, and chemical resistance</td>
</tr>
<tr>
<td>Acrylics</td>
<td>- Minimal surface preparation</td>
</tr>
<tr>
<td></td>
<td>- Does not stain surrounding material</td>
</tr>
<tr>
<td></td>
<td>- Cures slowly</td>
</tr>
<tr>
<td></td>
<td>- Only for joints ( \leq 3/4'' ) wide</td>
</tr>
<tr>
<td></td>
<td>- Low shape recovery</td>
</tr>
<tr>
<td></td>
<td>- Poor water resistance</td>
</tr>
<tr>
<td>Urethanes</td>
<td>- Good tear resistance, UV resistance, chemical resistance, and shape recovery</td>
</tr>
<tr>
<td></td>
<td>- 20 to 30 year mean life</td>
</tr>
<tr>
<td></td>
<td>- Joints can be sized ( \leq 6'' ) wide</td>
</tr>
<tr>
<td></td>
<td>- Surface preparation is required</td>
</tr>
<tr>
<td></td>
<td>- Poor water immersion resistance</td>
</tr>
<tr>
<td>Silicones</td>
<td>- Good heat resistance, UV resistance, and shape recovery</td>
</tr>
<tr>
<td></td>
<td>- 25% to 50% movement capacity</td>
</tr>
<tr>
<td></td>
<td>- 20 to 30 year mean life</td>
</tr>
<tr>
<td></td>
<td>- Does not stain surrounding material</td>
</tr>
<tr>
<td></td>
<td>- Surface preparation is required</td>
</tr>
</tbody>
</table>
Table 2-8, Recommended Sealant Depth  
Source: ASC (2010), The Adhesive and Sealant Council (2008)

- Joints shall be a minimum 1/4" in width
- Bond with only moving substrates
- Width-to-depth ratio should be 2:1, for joints no more than 1" wide
- Joints should not exceed 2" in width
- Compatibility with surrounding materials

2.1.1.5 Fire Resistance and Safety

<table>
<thead>
<tr>
<th>Building Element</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
<th>Type V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary structural frame</td>
<td>A 3</td>
<td>B 2</td>
<td>A 1</td>
<td>B 0</td>
<td>HT HT</td>
</tr>
<tr>
<td>Bearing walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior</td>
<td>3 1</td>
<td>2 0</td>
<td>2 2</td>
<td>2 0</td>
<td>1 0</td>
</tr>
<tr>
<td>Interior</td>
<td>3 1</td>
<td>2 0</td>
<td>1 0</td>
<td>1 0</td>
<td>1/HT 1</td>
</tr>
<tr>
<td>Floor construction and associated secondary members</td>
<td>2 2</td>
<td>1 0</td>
<td>1 0</td>
<td>1 0</td>
<td>HT 1</td>
</tr>
<tr>
<td>Roof construction and associated secondary members</td>
<td>1 1/2</td>
<td>1 1</td>
<td>1 0</td>
<td>1 0</td>
<td>HT 1</td>
</tr>
</tbody>
</table>

Fire is a major concern for most buildings and its structure. Its importance is exemplified by the code concerning fire. The primary impact will be on the transparent PC sheathing and potential use of sprinklers. To start off, it will be said that a building’s occupancy and building component combustibility dictates the fire protection level, as can be seen in Table 2-9.

Before going into depth with the fire protection provisions in the 2012 IBC and 2012 IRC, relevant occupancies and building component combustibility will be briefly reviewed. Straight off, the intended application of the practical transparent sheathing wall system is residential; as a result, the fire protection will be based on occupancy R – per 2012 IBC §310. In addition, structural metals and wood structural elements are required to be covered with fire resistant material and meet minimum fire resistance requirements (2012 IBC §722). Table 2-10 shows the
various sub-categories of occupancy R. Building component combustibility – also classified as construction type in the 2012 IBC – is divided into five categories. The five construction types are defined in Table 2-11. When it comes to the use of non-traditional materials, prescriptive fire resistance tables cannot be used – per 2012 IBC §721. The result is that plastic sheathing – like transparent PC – cannot be used structurally – with the exception of Type V construction – until there are revisions to the code.

<table>
<thead>
<tr>
<th>Occupancy Sub-Category</th>
<th>Defining Characteristics</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>- Contains sleeping units</td>
<td>- Boarding house</td>
</tr>
<tr>
<td></td>
<td>- Occupants are transient/non-permanent in nature</td>
<td>- Hotels</td>
</tr>
<tr>
<td>R-2</td>
<td>- Contains sleeping units or more than two dwelling units</td>
<td>- Apartments</td>
</tr>
<tr>
<td></td>
<td>- Occupants are usually permanent</td>
<td>- Dormitories</td>
</tr>
<tr>
<td></td>
<td>- Not classified as R-1, R-2, R-4, or I occupancy</td>
<td>- Timeshare properties</td>
</tr>
<tr>
<td>R-3</td>
<td>- Occupants are usually permanent</td>
<td>- Single family homes</td>
</tr>
<tr>
<td></td>
<td>- No more than 16 occupants, excluding supervision staff</td>
<td>- Duplex</td>
</tr>
<tr>
<td>R-4</td>
<td>- 24 hour supervised residence</td>
<td>- Assisted living facilities</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Construction Type</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>Noncombustible building elements</td>
</tr>
<tr>
<td>Type II</td>
<td>Noncombustible building elements but less than Type I</td>
</tr>
<tr>
<td>Type III</td>
<td>Only exterior walls are noncombustible</td>
</tr>
<tr>
<td>Type IV</td>
<td>Heavy timber construction</td>
</tr>
<tr>
<td>Type V</td>
<td>Exterior and interior walls are made of any material</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>FSI</th>
<th>SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Transparent PC</td>
<td>5</td>
<td>30</td>
</tr>
</tbody>
</table>
If transparent PC is used as a non-structural wall sheathing, only a few changes are required to be made to the building code. Transparent PC’s fire characteristics is categorically similar to gypsum board. Fire characteristics are based on two numbers – smoke index and flame spread index. The smoke index is a metric that measures the quantity of smoke produced when a material is burned. As for the flame spread index, it measures the speed which fire engulfs the material (ASTM E84). Both transparent PC and gypsum boards have a smoke index less than the code limit of 450, and flame spread index as Class A (Sundance Supply, 2015). Table 2-12 shows both the flame spread index and smoke density indices for both transparent PC sheathing and gypsum wall boards. What can be said is that the transparent PC sheathing is more resistant to fire, but produces greater light hindering smoke. Though the smoke generated by the transparent PC sheathing obscures light to a greater extent, it is still within acceptable limits defined in the 2012 IBC §2606.4 – for use. This means that the design tables for gypsum boards can be used – with little change – for transparent PC sheathing. However tests should be done to determine whether moisture, UV degradation degrades the fire resistance.

Based on occupancy and combustibility, the 2012 IBC – shown in Table 2-13 – defines the area and height limit of the perspective building. Greater areas and heights can be attained with the addition of automatic sprinklers ((2012 IBC §503.1). Specific details concerning permissible area and height increases will not be covered in this literature review but can found in §504.2, §506.2, and §506.3 of the 2012 IBC.

Next, glass glazing requirements will be discussed. Due to the danger arising from glazing failure, the area of glazing for each panel is limited. Should the glazing be used as a veneer material, then the panel shall be limited to no more than 10 ft² of glazing (2012 IBC §2406.4.3). Any sizes greater than the limit requires the use of safety glazing – sometimes known as impact
resistant glazing. Safety glazing is also required if there are walking surfaces less than 36” from the glazing (2012 IBC §2406.4.3).

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Height Limit (ft)</th>
<th>Type of Construction</th>
<th>Maximum Allowable Stories and Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type I A</td>
<td>B</td>
</tr>
<tr>
<td>M</td>
<td>Non 160</td>
<td>65</td>
<td>55</td>
</tr>
<tr>
<td>R-1</td>
<td>Non 24,000</td>
<td>4</td>
<td>12,500</td>
</tr>
<tr>
<td>R-2</td>
<td>Non 24,000</td>
<td>4</td>
<td>16,000</td>
</tr>
<tr>
<td>R-3</td>
<td>Non 24,000</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>R-4</td>
<td>Non 24,000</td>
<td>4</td>
<td>16,000</td>
</tr>
<tr>
<td>S-1</td>
<td>Non 24,000</td>
<td>4</td>
<td>16,000</td>
</tr>
<tr>
<td>S-2</td>
<td>Non 24,000</td>
<td>4</td>
<td>39,000</td>
</tr>
<tr>
<td>U</td>
<td>Non 35,500</td>
<td>4</td>
<td>19,000</td>
</tr>
</tbody>
</table>

2.1.2 Methodology

<table>
<thead>
<tr>
<th>City</th>
<th>Temperature (°F)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>70</td>
<td>52</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>43</td>
<td>29</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>47</td>
<td>26</td>
</tr>
</tbody>
</table>
Table 2-15, Properties of Potential Wall Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity, K (W/m-K)</th>
<th>Permeance (Perm)/BTU-in/(hr-ft²°F)</th>
<th>ρ (lb/in³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic Float Glass</td>
<td>0.63</td>
<td>4.36</td>
<td>0.10127</td>
</tr>
<tr>
<td>IGU</td>
<td></td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>16.20</td>
<td>112.40</td>
<td>0.29000</td>
</tr>
<tr>
<td>Aluminum</td>
<td>200.00</td>
<td>1388.00</td>
<td>0.09700</td>
</tr>
<tr>
<td>Cellular PC</td>
<td>0.04</td>
<td>0.26</td>
<td>0.00450</td>
</tr>
<tr>
<td>Fiber-Glass Reinforced Polyester</td>
<td>0.40</td>
<td>2.78</td>
<td>0.09400</td>
</tr>
<tr>
<td>Granular Aerogel</td>
<td>0.02</td>
<td>0.12</td>
<td>0.00330</td>
</tr>
<tr>
<td>Monolithic Aerogel</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00720</td>
</tr>
<tr>
<td>Polyurethane Foam</td>
<td>0.03</td>
<td>0.21</td>
<td>0.00145</td>
</tr>
<tr>
<td>Batt Insulation (R-13)</td>
<td>0.04</td>
<td>0.27</td>
<td>0.00044</td>
</tr>
<tr>
<td>Batt Insulation (R-21)</td>
<td>0.04</td>
<td>0.26</td>
<td>0.00025</td>
</tr>
<tr>
<td>PC</td>
<td>0.22</td>
<td>1.53</td>
<td>0.04300</td>
</tr>
<tr>
<td>Gypsum Wall Board</td>
<td>0.17</td>
<td>1.18</td>
<td>0.08333</td>
</tr>
<tr>
<td>Vinyl Siding</td>
<td>0.19</td>
<td>1.32</td>
<td>0.05019</td>
</tr>
<tr>
<td>Still Air</td>
<td>0.02</td>
<td>0.17</td>
<td>0.00004</td>
</tr>
<tr>
<td>Steel Web w/ 50% Openings</td>
<td>1.02</td>
<td>225.08</td>
<td>0.14502</td>
</tr>
<tr>
<td>Steel</td>
<td>64.84</td>
<td>450.00</td>
<td>0.29000</td>
</tr>
<tr>
<td>Brick</td>
<td>1.00</td>
<td>6.94</td>
<td>0.05787</td>
</tr>
</tbody>
</table>

In the study here, design was achieved by multiple structured tasks. The first task was to acquire the relevant characteristics of the climates for the four cities – exemplifying the four hygro-thermal climate zones – and potential materials for the wall system. Tables 2-14 and 2-15 show the climate and potential wall materials, respectively. It was determined that for the design condition the exterior relative humidity (RH) should be 100%, which occurs when it is raining and the wall assembly becomes wet. In doing so, the potential for condensation in the wall assemblies is maximized – proven in the preliminary design and analysis. The design interior RH is maintained a constant 50%, which is based on ASHRAE recommendations to prevent bacterial and mold growth – 60% maximum –, HVAC control accuracy, as well as door and window openings by the residence’s occupants. Next, the required thermal insulation thickness was
determined from the previously acquired material thermal resistance and code required thermal resistance. Thickness required of the various thermal insulation materials are shown in Table 2-16, while the hand calculations can be referenced in Appendix A§1.

Table 2-16, Minimum Thickness of Various Thermal Insulation Materials for Analyzed Cities (Based on 2012 IRC Table N1102.1.3)

<table>
<thead>
<tr>
<th>City</th>
<th>Minimum Thickness (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cellular PC</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>3.18</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>4.57</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>5.43</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>4.57</td>
</tr>
</tbody>
</table>

Table 2-17, R-Value of Wall Components

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>R_i = 1/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m²-K/W</td>
<td>h-ft²-°F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.13</td>
<td>34.88</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>IGU</td>
<td></td>
<td>0.300</td>
<td>2.083</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.50</td>
<td>2776.00</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>3.25</td>
<td>0.08</td>
<td>1.776</td>
</tr>
<tr>
<td></td>
<td>Granular Aerogel</td>
<td>1.63</td>
<td>0.08</td>
<td>1.874</td>
</tr>
<tr>
<td></td>
<td>Monolithic Aerogel</td>
<td>0.38</td>
<td>0.07</td>
<td>1.946</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>2.00</td>
<td>694.00</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
<td>4</td>
<td>Still Air</td>
<td>3.63</td>
<td>0.05</td>
<td>3.136</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>3.63</td>
<td>124.14</td>
<td>0.001</td>
</tr>
</tbody>
</table>
### Table 2-18, $R_v$-Value of Wall Components

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_v = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.13</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>IGU</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.50</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>3.25</td>
<td>0.43</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>Granular Aerogel</td>
<td>1.63</td>
<td>0.94</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>Monolithic Aerogel</td>
<td>0.38</td>
<td>4.05</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>2.00</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>3</td>
<td>PC</td>
<td>0.50</td>
<td>2.80</td>
<td>0.36</td>
</tr>
<tr>
<td>4</td>
<td>Still Air</td>
<td>3.63</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>3.63</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2.1.2.1 Determine Condensation Location

The next phase was preliminary design. The location of condensation in the wall assemblies were determined by hand calculations for the various designs drawn up. Tables 2-17 and 2-18, details the thermal resistance ($R$) and moisture resistance ($R_v$) of each wall element of the CFS preliminary design, respectively. These resistances are derived from the element thickness and material thermal and vapor resistance properties. When a layer has more than one material, then the layer is assigned an average thermal resistance of the materials. To determine the location of condensation in a wall assembly, one needs to determine the temperature at each layer, which is proportional to thermal resistance of the layer, shown in Appendix A§2.1.1. Modifications were made to ensure that condensation only occurs in a moisture resistant layer where the condensation can easily drain out of the system. The next task of this phase was inputting the preliminary designs into THERM to determine potential thermal bridges. One of
the greatest concerns regarding thermal bridging is that it reduces thermal performance of wall systems, by bypassing thermal insulation materials when heat can flow through more conductive materials in the assembly, e.g., that penetrates through insulation, – similar to short-circuits (Ander, 2010). To determine thermal bridges, the thermal gradient and thermal resistance of the frame was acquired from the THERM simulation. Large thermal gradient between the frame and the center of the wall assembly indicates potential thermal bridging, which occurs where there is large thermal gradient and low intrinsic frame thermal resistance. The THERM simulation showed trends in the preliminary design and served as a guide – along with the literature review – in what design strategies would work and what would not. Figure 2-8 and Table 2-19 show the types and characteristics of the air films applied to the THERM simulations.

Figure 2-8, Air-Film Applications on Wall Designs
<table>
<thead>
<tr>
<th>Air Film</th>
<th>Temperature (°F) (Tampa, FL/Other)</th>
<th>Thermal Resistance (Btu/(h-ft²·°F))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exterior</td>
<td>Interior</td>
</tr>
<tr>
<td>SHGC</td>
<td>52/19</td>
<td>75/72</td>
</tr>
<tr>
<td>Frame</td>
<td>52/19</td>
<td>75/72</td>
</tr>
<tr>
<td>Edge</td>
<td>52/19</td>
<td>75/72</td>
</tr>
</tbody>
</table>

2.1.3 Design and Configuration of the Transparent Wall Systems Studied

From this point onwards, the final designs were formulated and revised to reduce thermal bridging, minimize physical dimensions, and achieve adequate visible light transmission through the wall assemblies. The design process was aided and simplified by certain assumptions made, including the following:

1. Required thermal performance defined in the 2012 IBC and 2012 IRC may guide the design
2. Thermal and moisture resistance properties of various materials were acquired from manufacturers and Whole Building Design Guide (WBDG)
3. Imperfect seals and lack of maintenance can be accounted for by approximating impermeable materials as permeable
4. Vapor retarders are continuous
2.1.4 Preliminary Design and Analysis

The purpose of the preliminary design and analysis is to determine which thermal breaking strategies work. Only then will the final design be drawn up and further evaluated.
VERTICAL ELEMENTS
CLOSED CELLED FOAM THERMAL BREAK
ALUMINUM PRESSURE PLATE
WEEP HOLE
MTL FLASHING W/ DRIP EDGE

SIDING W/ RIGID INSULATION

VAPOR RETARDER

MTL FLASHING W/ DRIP EDGE
ALUMINUM PRESSURE PLATE
WEEP HOLE WEATHER SEALANT
CLOSED CELLED FOAM THERMAL BREAK
VERTICAL ELEMENTS

b) Side Section

Figure 2-9, Frame with Thermal Decoupling Opening
Figure 2-10, Frame with Screw Connections and Structural Composite Thermal Breaks
a) Top Section

- STR. ALUMINUM FRAME
- SCREW
- SELF DRILLING SCREWS
- STR. COMPOSITE THERMAL BREAKS W/ ALUMINUM PLATES
- WEATHER SEALANT
- WEATHER SEALANT

- SIDE SECTION
- STR. PC SHEATHING
- CELLULAR PC INSULATION
- FOAM INSULATION IN CORE
- GLASS GLAZING
- THERMAL BREAK CAP
- STEEL PRESSURE PLATE
The preliminary designs – shown in Figures 2-9 to 2-11 – and analysis were based on insulation requirements defined in the 2012 IBC, 2012 IRC, as well as recommendations from published works. The preliminary design phase serves as a launching pad to eventual final design, here the trends and lessons learned from the thermal and moisture performance of
various configurations were explored. Therefore, the preliminary designs were primarily
designed towards the Tampa, FL climate. Only the location of condensation was determined for
all four cities.

| Table 2-20, Relative Humidity Distribution During Rains (100% Exterior RH) in Tampa, FL. |
|---------------------------------------------|---------------------------------------------|
| Layer | Relative Humidity (%) |          | Notes |
|       | Winter               | Summer    |       |
|       | High     | Low     | High  | Low  |
| Outside | 100%    | 100%    | 100%  | 100% |
| 1      | 92%      | 96%     | 89%   | 92%  |
| 2      | 74%      | 57%     | 96%   | 74%  |
| 3      | 80%      | 57%     | 109%  | 80%  |
| Inside  | 50%      | 50%     | 50%   | 50%  |
|         |          |          | Condensation Occurs |

| Table 2-21, Relative Humidity Distribution During Rains (100% Exterior RH) in Washington D.C. |
|---------------------------------------------|---------------------------------------------|
| Layer | Relative Humidity (%) |          | Notes |
|       | Winter               | Summer    |       |
|       | High     | Low     | High  | Low  |
| Outside | 100%    | 100%    | 100%  | 100% |
| 1      | 100%     | 107%    | 89%   | 91%  |
|         |          |          | Condensation occurs |
| 2      | 97%      | 74%     | 95%   | 73%  |
| 3      | 96%      | 69%     | 108%  | 79%  |
| Inside  | 50%      | 50%     | 50%   | 50%  |
|         |          |          | Condensation occurs |

| Table 2-22, Relative Humidity Distribution During Rains (100% Exterior RH) in Detroit, MI. |
|---------------------------------------------|---------------------------------------------|
| Layer | Relative Humidity (%) |          | Notes |
|       | Winter               | Summer    |       |
|       | High     | Low     | High  | Low  |
| Outside | 100%    | 100%    | 100%  | 100% |
| 1      | 107%     | 116%    | 90%   | 93%  |
|         |          |          | Condensation occurs |
| 2      | 112%     | 87%     | 98%   | 78%  |
|         |          |          | Condensation occurs |
| 3      | 107%     | 77%     | 111%  | 82%  |
| Inside  | 50%      | 50%     | 50%   | 50%  |
|         |          |          | Condensation occurs |
### Table 2-23, Relative Humidity Distribution During Rains (100% Exterior RH) in Albuquerque, NM

<table>
<thead>
<tr>
<th>Layer</th>
<th>Relative Humidity (%)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Winter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Outside</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>99%</td>
<td>110%</td>
</tr>
<tr>
<td>2</td>
<td>92%</td>
<td>78%</td>
</tr>
<tr>
<td>3</td>
<td>93%</td>
<td>71%</td>
</tr>
<tr>
<td>Inside</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Most preliminary designs and analyses showed that condensation only occurs when the wall assembly is wet or whenever it rains – 100% relative humidity. Tables 2-20 to 2-23 detail the condensation location for preliminary design in each of the four. Before preliminary design, a decision was made to avoid condensation occurrence in the interior portion of the wall assembly. More specifically, the condensation was not to occur beyond the exterior face of the transparent PC sheathing, partly because it can foster health hazards like mold and that the mechanical equipment will have to work harder to handle the latent load. The additional latent load on the mechanical equipment will increase general energy consumption. As a result, the majority of the thermal insulation is placed towards the exterior portion of the wall system. The practice is based on placement of insulation in commercial applications.

First, the preliminary design with a CFS structural frame and thermal decoupling openings will be discussed. Figure 2-12 shows the thermal characteristics of the wall system. The purpose of the thermal decoupling openings in the aluminum glazing frame is to reduce thermal bridging arising from conduction. THERM simulation showed improved thermal performance. It can also be said that sections with conductive elements experience greater thermal impact of exterior and interior temperatures. At the interface of the thermal decoupling openings, there are significant
temperature changes – become more pronounced if close to highly conductive elements. Significant temperature changes are directly proportionate to the occurrence of condensation.

![Diagram of thermal characteristics](image)

**a) Thermal Gradient of Top Section**

**b) U-Value of Wall**

Figure 2-12, Thermal Characteristics of Wall w/ CFS Structural Frame and Thermal Decoupling Openings
Another preliminary design uses a structural composite thermal break – secured with screws – and thermal break caps for the glazing. Like the previously mentioned predesign, it also
uses CFS structure. However, the second preliminary design uses structural composite thermal breaks – as shown in Figure 2-13. In doing so, it permits decoupling of the exterior and interior components, thereby reducing thermal bridging from conduction and convection. As for the thermal break caps, they are made of high thermal resistance material (FRP) and serve to prevent the thermal bridging tendency at the edges – have less thermal resistance. It was determined that the thermal break caps extend beyond conductive elements, like the aluminum glazing frame. If the thermal break caps do not extend that far, then the benefit is no more. In addition, THERM showed that thick thermal breaks and significantly large connections increase potential for thermal bridging. The third lesson of the second preliminary design involves deep bolted and screwed connections, that attach the exterior components to those deeper in the assembly and act as thermal bridges, negating any thermal break influence.

The third preliminary design used a structural aluminum frame with structural composite thermal breaks. This preliminary design is based on some of the lessons learned from the previous two. Here the conductive aluminum web is minimized to reduce thermal bridging. Even so, the conductive aluminum still had significant effect on the surrounding thermal performance. Structural thermal breaks were used to reduce the thermal bridging and decouple the exterior and interior components. In the end, the third preliminary design achieved better thermal performance than the second preliminary design, and the thermal performance can be seen in Figure 2-14.
ALUMINUM IS VERY CONDUCTIVE AND NEGATES ANY INSULATIVE CORE MATERIAL.

THERMAL GRADIENT PROVES THAT THERMAL BREAK IS WORKING.

(a) Thermal Gradient of Top Section

(b) U-Value of Wall

Figure 2-14, Thermal Characteristics of Wall w/ Structural Aluminum Frame
2.1.5 Design and Results

More accurate designs were formulated once the preliminary designs were analyzed and lessons were learned. A total of seven designs were drawn up and evaluated for condensation potential, thermal performance, acoustical attenuation, thickness, and weight. The seven designs were based on two general categories – more specifically cities – Tampa, FL; and Detroit, MI – designated as other. The rationale behind the decision will be covered in the constructability section. Other cities like Washington D.C. and Albuquerque, NM – exemplifying other climate zones – were based on the same template for Detroit, MI. The main difference for these cities are the thermal insulation. These designs were revised if the moisture and thermal performances were deemed inadequate.

2.1.5.1 Designs for Tampa, FL

Four designs were formulated for Tampa, FL. The underlying load bearing structures are either: light gauge CFS, heavy gauge CFS, or aluminum frame. Aerogel thermal insulation was not used in any of the designs in this location because it reduces the walls depth to a point that the structural composite thermal breaks no longer work. The composite thermal breaks stop working when the conductive interfaces – separated – get closer than 1/4 inch. The only seeable way that aerogel can be used is if a more insulating structural composite thermal break material is formulated. Couple this with the current high manufacturing cost of aerogel, are the reasons why aerogel was not used. Additional details like hand calculations can be found in Appendix B§2.1.
Figure 2-15, Top View Section of Light Gauge (1) Design

1/2” PC SHEATHING

POLYURETHANE FOAM INSULATION

CARBON STEEL CFS STUD
S. STEEL SELF DRILLING SCREW
THERMAL BREAK
THERMAL INSULATION
IMPACT RESISTANT GLAZING
S. STEEL PRESSURE PLATE

THERMAL BREAK CAP
GASKET
ALUMINUM GLAZING FRAME
THERMAL BREAK
Figure 2-16, Side View Section of Light Gauge (1) Design

- Insulated Siding
- Flashing
- S. Steel Screw
- Composite Securing Angle
- S. Steel Pressure Plate
- Aluminum Glazing Frame
- Thermal Break Cap
- Gasket
- Composite Track
- Thermal Insulation
- Bolt Connection
- Wood Base Plate
- Wood Top Plate
- 1/2" PC Sheathing
- Polyurethane Foam Insulation
- Wood Floor System
- Bolt Connection
- Top Section
a) Thermal Gradient of Top Section

b) U-Value of Top Section
c) Thermal Gradient of Side Section

Light Gauge (1) design for the climate in Tampa, FL involves placing light gauge CFS studs in the middle of the wall assembly, shown in Figures 2-15 and 2-16. This strategy reduces the wall assembly’s depth. The catch is that there is a slight reduction in thermal performance at the frame and regions adjacent to it, as shown in Figures 2-17a and c. Effects on adjacent regions to the frame arises primarily from the CFS stud’s flanges. The reason for this is insufficient quantity of thermal decoupling openings in the CFS stud’s webs. As a result, there is greater thermal resistance demand on the thermal breaks. If the thermal resistance demand is greater –

<table>
<thead>
<tr>
<th>U-Factors</th>
<th>U-factor</th>
<th>delta T</th>
<th>Length</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHC Exterior</td>
<td>0.2476</td>
<td>16.0</td>
<td>1.625</td>
<td>N/A</td>
</tr>
<tr>
<td>Frame</td>
<td>0.1269</td>
<td>16.0</td>
<td>3.0000</td>
<td>N/A</td>
</tr>
<tr>
<td>Edge</td>
<td>0.0792</td>
<td>16.0</td>
<td>2.5000</td>
<td>N/A</td>
</tr>
<tr>
<td>% Error Energy Norm</td>
<td>9.84%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-17, Thermal Performance of Light Gauge (1) Design
like in colder climates – thermal bridges can form across the previous thermal breaks. Overall, the thermal performance of light gauge (1) at the frame – shown in Figures 2-17b and d – is at least three times better than those required by the 2012 IECC. The 2012 IECC thermal performance requirement for exterior glazing is shown in Table 2-24.

<table>
<thead>
<tr>
<th>Frame Type</th>
<th>Single Pane</th>
<th>Double Pane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Metal w/ Thermal Break</td>
<td>1.1</td>
<td>0.65</td>
</tr>
<tr>
<td>Nonmetal or Metal Clad</td>
<td>0.95</td>
<td>0.55</td>
</tr>
<tr>
<td>Glazed Block</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 2-24, Exterior Glazing Thermal Requirements (U-Value)
Source: 2012 International Energy Conservation Code (IECC) §303.1.3

Figure 2-18, Top View Section of Light Gauge (2) Design
Figure 2-19, Side View Section of Light Gauge (2) Design
a) Thermal Gradient of Top Section

b) U-Value of Top Section

INTERIOR CFS STUD HAS NO IMPACT ON THERMAL RESISTANCE AND NEED NOT BE MODELED

INCREASING THE DISTANCE BETWEEN CONDUCTIVE SURFACES REDUCES THERMAL BRIDGING
c) Thermal Gradient of Side Section

Light Gauge (2) design differs from Light Gauge (1) design by placing the CFS in the interior. Furthermore, the Light Gauge (2) design incorporates thermal breaks in the aluminum glazing frame. The design is a more direct evolution of the preliminary designs than Light Gauge (1). By placing the light gauge CFS structure on the interior side, thermal performance at the frame and adjacent regions yielded better thermal performance (Figure 2-20). The lack of thermal gradation in the CFS stud in Figure 2-20 shows that the light gauge CFS structure has no
impact on thermal resistance – when not placed in the wall cavity – therefore, need not be modeled in THERM. Furthermore, it was learned to increase distance between conductive surfaces to reduce thermal bridging. Also thermal resistance of the entire wall system can be increased if the adjacent frame and edge regions have similar R-values. If not, then the thermal resistance gravitates close to the lesser R-value. Unlike Light Gauge (1), the top and bottom tracks remained light gauge CFS. Light Gauge (2) is not without its downsides, where significant quantity of structural composite thermal breaks were used. The entire wall assembly is quite deep, nearly 9in. verses the more typical 5in. – light gauge CFS located in the wall cavity. This depth is evident from Figures 2-18 and 2-19. If this system was used in colder climates, Light Gauge (2) will not be advantageous because the system would reach close to 1ft thickness. Replacing the cellular PC thermal insulation with aerogel was explored. Unfortunately, thermal bridging at the frame increased; primarily due to greater thermal bridging at the frame location. This arises because the conductive elements are too close together and that a more thermally insulating structural material is not readily available.
Figure 2-21, Top View Section of Heavy Gauge (1) Design
Figure 2-22, Side View Section of Heavy Gauge (1) Design
a) Thermal Gradient of Top Section

b) U-Value of Top Section
Another design for the Tampa, FL category is replacing the light gauge CFS in Light Gauge (1) design with heavy gauge CFS. Here the heavy gauge CFS is spaced further apart, because of greater strength. Figures 2-21 and 2-22 show the wall design. Akin to its light gauge counterpart, the large airspace in the cavity has no contribution to overall thermal resistance, as can be seen in the relatively constant temperature in Figure 2-23. One explanation is the highly thermally conductive light gauge CFS structure, acts as a thermal bridge across the cavity.
Breaking the bridge is hard if the light gauge CFS studs are located in the cavity, however, additional holes can be cut into the stud’s web to better reduce the thermal bridging area. It is a limited solution because it will weaken the structure. Greater spacing between the structural members improves the overall average thermal performance. Since there is less conductive material.

Figure 2-24, Top View of Aluminum Frame Design
Figure 2-25, Side View of Aluminum Frame Design
a) Thermal Gradient of Top Section

SLIGHT R-VALUE INCREASES ARE POSSIBLE IF THERMAL BREAK IS LENGTHENED

b) U-Value of Top Section
c) Thermal Gradient of Side Section

d) U-Value of Side Section

Figure 2-26, Thermal Performance of Aluminum Frame Design

The fourth design for Tampa, FL is the structural aluminum frame design. Here the aluminum frame was used to bear structural loads, therefore the CFS studs and tracks were eliminated. Figures 2-24 to 2-26 detail the wall design and thermal performance. The structural members were also spaced further, at 4’ apart – reducing the total thermal loss through the wall assembly. From the lesson learned in the preliminary design, the structural aluminum frame incorporates structural thermal breaks made of FRP. When compared to the previously
mentioned designs, the structural aluminum frame design performs better with respect to thermal performance at the frame. Most of the wall’s thermal resistance rests on the thermal breaks joining the aluminum frame together. Also adjacent material and components to the wall systems – like the insulating siding and wood headers – influence the wall’s thermal performance. However there is weakness, the thermal performance of the surrounding region is less than that of Light Gauge (2). The reason is greater concentration of more conductive material – aluminum – at the edges of the structural frame. Though the wall system is deep in Tampa, FL – due to high lateral loads – the system will be more slender in other regions with less lateral loads.

2.1.5.2 Designs for Other Regions

![Diagram of Light Gauge Design](image)

Figure 2-27, Top View Section of Light Gauge (1) Design
Figure 2-28, Side View Section of Light Gauge (1) Design
a) Thermal Gradient of Top Section

b) U-Value of Top Section
The first design for other regions uses light gauge CFS, placed in the insulation cavity. This is similar to traditional residential construction. Here the thermal insulation is scaled to meet code requirements. Unfortunately, the thermal performance at the frame remains similar to those designs for Tampa, FL. There is only a slight improvement in thermal performance of the surrounding regions, short of the thermal performance between the studs. The reason is the thermally conductive light gauge CFS studs, which act as a thermal bridge across the cavity.
Originally the top and bottom tracks were light gauge CFS, however the THERM simulation revealed significant thermal bridging. As a result, the light gauge CFS track was replaced with structural FRP thermal break. Significant thermal bridging was tamed by the track material switch. The design and thermal performance of Light Gauge (1) is shown in Figures 2-27 to 2-29.
Figure 2-31, Side View Section of Heavy Gauge (1) Design
a) Thermal Gradient of Top Section

b) U-Value of Top Section

R-VALUE INCREASES PRIMARILY POSSIBLE IF WEB IS MADE MORE INSULATIVE
c) Thermal Gradient of Side Section

The next design for other regions replaces the light gauge CFS with heavy gauge CFS spaced further apart – at 24”. Figures 2-30 and 2-31 shows that still the track remains FRP – to reduce thermal bridging. Its effect is similar to the system in Tampa, FL and can be seen in Figure 2-32; overall the system’s performance is better than the light gauge CFS, due to fewer studs. Greater improvements to the CFS systems is possible if the thermal breaking material is deepened near the exterior face of the CFS structure, or increasing the number of openings in the
stud’s web – to reduce thermal bridging. However, only significant thermal resistance improvement is only possible if the stud’s web is made more insulative.
Figure 2-34, Side View of Aluminum Frame Design
a) Thermal Gradient of Top Section

INCREASING THE DISTANCE BETWEEN CONDUCTIVE SURFACES INCREASES SYSTEMS THERMAL RESISTANCE

b) U-Value of Top Section
c) Thermal Gradient of Side Section

Figure 2-35, Thermal Performance of Aluminum Frame Design

Structural aluminum design for other regions is also based on those for Tampa, FL. Here the thermal insulation is scaled to meet code requirements. The thermal performance of the frame is similar, but with slightly less thermal performance degradation at locations close to the frame (Figure 2-35). Total depth of the system is the selling point of the structural aluminum frame design – Figures 2-33 and 2-34, which is the most slender of all redesigns and the original system (RGWPS).
2.1.6 Light Transmission and Acoustical Attenuation

<table>
<thead>
<tr>
<th>Wall Systems</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>50%</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>50%</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td>50%</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>50%</td>
</tr>
</tbody>
</table>

Light transmission through the original wall system (RGWPS) and the redesigns is paramount, as the purpose of the mentioned systems is to reduce energy consumption primarily associated with illumination. To achieve this, visible light must penetrate through the wall assemblies to illuminate the interior environment. Light transmission through the redesign wall assemblies were determined from a literature review of available data and research findings in the literature. Therefore, the light transmission through the redesign wall assemblies are estimates. More accurate determination of light transmission through the redesign wall assemblies is possible with lab verification following ASTM D1003. However, such experimentation and physical verification was not implemented because it is beyond the scope of the thesis.

Based on estimates in Table 2-25, granular aerogel significantly reduces the light transmission through the redesign wall assemblies – in colder climates. The reduced natural light transmission will warrant either separate or a combination of supplemental interior lighting and standalone window systems. Though the wall assemblies using granular aerogel do not satisfy code defined light transmission levels for window glazing (2012 IECC §303.1.3), those which use only cellular PC did not fare better – even though the light transmission is greater than those
with granular aerogel. The only time where the systems using cellular PC satisfies the 2012 IECC is if the cellular PC can be considered as a form of tint (30% light transmittance threshold). The redesign wall systems are combinations of traditionally separate window and wall systems. When coupled with the significant size of the redesign wall systems – when compared to a typical window glazing unit – there should be evaluation of how much light transmission is necessary. The end result of the evaluation is codified light transmission levels for unique wall systems like the redesigns.

Another important building science consideration for walls is acoustical attenuation, which reduces external noise and provide better comfort for occupants of a building. Noise attenuation is also important through interior walls separating rooms or units. The metric for acoustical attenuation are transmission loss (TL) and sound transmission coefficient (STC). TL measures the amount of noise remaining – after it has passed through a barrier. The TL value is frequency dependent, and to make comparisons simpler, a single composite value must be derived. STC is a single value that reflects the TL across the range of frequencies which can be heard by humans. Table 2-26 shows the TL of walls systems, which were used to derive the STC of the designed walls. To attain the STC rating of a wall, the TL and respective frequency must be plotted, only then can the STC contour be imposed onto the plot. The requirements for the STC contour are shown in Table 2-27. As an example to derive the STC rating, Table 2-28 and Figure 2-36 details the plot, as well as the maximum deviation between the STC contour and TL. In the final step, the STC rating is the TL value on the STC contour at 500Hz. Table 2-29 shows the STC rating of the wall redesigns and a typical wood frame system. Additional STC rating derivations for the other designed wall systems can be found in Appendix C. The STC values of all the wall systems in the table fall short of recommended STC 50 for kitchens and bedrooms (Egan, 1989).
<table>
<thead>
<tr>
<th>Designation</th>
<th>125Hz</th>
<th>250Hz</th>
<th>500Hz</th>
<th>1000Hz</th>
<th>2000Hz</th>
<th>4000Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>8&quot; Concrete</td>
<td>34</td>
<td>40</td>
<td>44</td>
<td>49</td>
<td>59</td>
<td>64</td>
</tr>
<tr>
<td>Face Brick</td>
<td>32</td>
<td>34</td>
<td>40</td>
<td>47</td>
<td>55</td>
<td>61</td>
</tr>
<tr>
<td>2x4 Studs at 16&quot; O.C. w/ Sheathing on Both Sides</td>
<td>17</td>
<td>31</td>
<td>33</td>
<td>40</td>
<td>38</td>
<td>36</td>
</tr>
<tr>
<td>3-5/8&quot; Metal Studs at 16&quot; O.C. w/ Sheathing on Both Sides</td>
<td>26</td>
<td>36</td>
<td>43</td>
<td>51</td>
<td>48</td>
<td>43</td>
</tr>
<tr>
<td>2-1/2&quot; Steel Channels at 24&quot; O.C. w/ Sheathing</td>
<td>22</td>
<td>27</td>
<td>43</td>
<td>47</td>
<td>37</td>
<td>46</td>
</tr>
<tr>
<td>Face Brick and 2x4 Studs at 16&quot; O.C. w/ Sheathing on Both Sides</td>
<td>32</td>
<td>36</td>
<td>41</td>
<td>48</td>
<td>55</td>
<td>61</td>
</tr>
<tr>
<td>Face Brick and 3-5/8&quot; Metal Studs at 16&quot; O.C. w/ Sheathing on Both Sides</td>
<td>33</td>
<td>38</td>
<td>45</td>
<td>53</td>
<td>56</td>
<td>62</td>
</tr>
<tr>
<td>1/8&quot; Monolithic Glazing, PC, and 2-1/2&quot; Steel Channels at 24&quot; O.C.</td>
<td>23</td>
<td>28</td>
<td>43</td>
<td>47</td>
<td>38</td>
<td>46</td>
</tr>
<tr>
<td>1/4&quot; Monolithic Glazing, PC, and 2-1/2&quot; Steel Channels at 24&quot; O.C.</td>
<td>24</td>
<td>30</td>
<td>43</td>
<td>47</td>
<td>38</td>
<td>46</td>
</tr>
<tr>
<td>IGU, PC, and 2-1/2&quot; Steel Channels at 24&quot; O.C.</td>
<td>25</td>
<td>30</td>
<td>43</td>
<td>47</td>
<td>38</td>
<td>46</td>
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Table 2-27, STC Contour Criteria
Source: Egan (1989)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Maximum Allowable Deviation at Each Frequency</th>
<th>Maximum Allowable Sum of Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
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</tr>
<tr>
<td>250</td>
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<td>2000</td>
<td></td>
<td></td>
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<tr>
<td>4000</td>
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<td>8</td>
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</tbody>
</table>

Figure 2-36, STC Contour for Wall Assembly w/ Face Brick and 2x4 Studs at 16" O.C. w/ Sheathing on Both Sides

Table 2-28, Face Brick and 2x4 Studs at 16" O.C. w/ Sheathing on Both Sides

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Deviation at Each Frequency</th>
<th>Sum of Deviation</th>
<th>Note</th>
</tr>
</thead>
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<tr>
<td>125</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>250</td>
<td>4</td>
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<td>500</td>
<td>8</td>
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<td>1000</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>8</td>
<td></td>
<td></td>
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</tbody>
</table>

Maximum allowable deviation at each frequency and maximum allowable sum of deviation are satisfied.
<table>
<thead>
<tr>
<th>Wall Systems</th>
<th>Location</th>
<th>Location</th>
<th>Location</th>
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<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
<td>Washington D.C.;</td>
<td>Detroit, MI</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>Wood Frame</td>
<td>49</td>
<td>49</td>
<td>49</td>
</tr>
</tbody>
</table>

The STC was also determined for the traditional wood frame wall system, because it serves as a standard that the acoustical attenuation of the redesigns should aim for. In addition, the second reason for including the traditional wood frame wall system is that the previous study (designing and studying the RGWPS) – by Standley – incorporated it, this study is a follow-up of that Standley’s study. When comparing the STC of the wall redesigns to wood frame system, it is fairly similar. This does not mean that the wall systems are failures, instead there is room for improvement. As a note, the thermal insulation was not included in the acoustical attenuation calculations. The reason is the lack of complete acoustical data on cellular PC and aerogel. When comparing the STC of the wall redesigns to wood frame system, it is fairly similar. There is no doubt that the actual acoustical attenuation of the redesigns is equivalent to that of the wood wall system – main competitor in residences – when the thermal insulation is included.

2.1.7 Conclusions

Based on building science criteria evaluations, all the redesigns surpass the thermal performance of original system (RGWPS) – at least five times the R-Value. Of all the redesigns, the aluminum frame system has the better thermal performance – particularly less thermal bridging and its respective impact on surrounding thermal resistance. The result is 50% greater
R-Value than the CFS systems. On the subject of thermal bridges, the majority occur through the edges of the window glazing close to the thermally conductive glazing frame. Better thermal bridging resistance will require the use of less traditional thermal insulation materials at the mentioned location. In addition the less traditional thermal insulation materials should have structural properties, to reduce the use of thermally conductive structural metals. The other significance that the designs revealed is cut-outs in the structural frame’s web can reduce the thermal bridging potential.

In terms of thermal insulation, adding additional thermal insulation or material with greater thermal resistance does not meaningfully reduce thermal bridging, if it is adjacent to a conductive element – like a CFS stud. This was the reason why using only aerogel – whether monolithic or granular – for the thermal insulation was not implemented. High thermal resistance materials like aerogel are only effective and advantageous if the adjacent frame is less thermally conductive than metals; an example would be FRP and thermal plastics. The described strategy is expensive due to fabrication difficulty and tediousness, as well as lack of trained laborer in handling and installing them. It should be noted that proper assembly of the wall systems and quality control is paramount to achieving calculated thermal and moisture performance. Prefabrication was studied in the constructability section of this report, because to reduce field assembly errors and maintain continuous quality control.

Though the redesigns surpass the code requirements for windows and RGWPS, it is still nowhere as good as traditional wood frame structure. Mainly due to wood’s greater thermal resistance than those of the metal frames. In addition, if the redesigns are treated as walls then they do not necessarily satisfy wall thermal performance criterion and thus remains an objective for further refinement of the design.
3.1 Introduction to Sustainability

Sustainability is currently gaining greater attention and has become an important consideration when designing and retrofitting buildings. The sustainability concept deals with the efficient use and consumption of available resources. Sustainability, in the end, aims to preserve finite available resources for future use and reduce detrimental human impacts on the natural environment (BDC, 2003). There are a multitude of ways to incorporate sustainability into building design and retrofit, some of which are listed below:

1. Energy use reduction through using renewable and local resources – like daylighting, solar heating –, mechanical equipment selection, as well as eliminating the air leaks and thermal bridging occurrences
2. Material selection based on locality, energy and environmental impact of extraction, and durability (BDC, 2003)
3. Building Information Modeling (BIM) usage to reduce material waste during design, construction, occupancy, and decommissioning/demolition (Messner, 2013)

The growing assertiveness of sustainability arises from rising energy costs and growing scarcity of materials. This has prompted the creation of guidelines evaluating sustainability – like Leadership in Energy and Environmental Design (LEED), National Green Building Standard (NGBS), and International Green Construction Code (IGCC). Typically, each guideline uses a point system where points are awarded for implementing certain defined sustainable requirements. The second leg for sustainability’s assertiveness is growing demand by owners. Figure 3-1 shows
the adoption of various technologies in residential buildings. What can be accessed from the figure is that energy efficiency and generation are in greater demand. Greater energy efficiency was aided by many factors. One is the gradual transition to light emitting diode (LED) – which has longer life before failure and uses significantly less electricity (Tinder, 2015). The second factor is using extra insulation to improve thermal performance and reduce long term costs. Thirdly, there is increased automation to manage energy use like smart home systems (Baker, 2014). Other factors affecting energy efficiency include: reducing waste, healthier construction components, and more durable components (Baker, 2013)

![Bar Chart](Figure 3-1, Home Technologies which Owners Prefer)

One obstacle towards sustainability in the building industry is the high upfront costs (BDC, 2003). The other obstacle is the general limited knowledge – on both the part of the designer, contractor, and owner – of current sustainable practices and technologies.
3.2 Methodology for Assessing Sustainability

Two methods will be used in this study to assess sustainability, one is using ATHENA Impact Estimator and the other is a quantitative process. Assessing sustainability was done for all of the potential wall designs. The baseline that they were compared to are the original wall system (RGWPS) and a typical wood frame wall. All wall systems accessed had a face dimension of 4’ by 8’.

ATHENA Impact Estimator software assesses the environmental impact of building assemblies over various periods of time. The software permits multiple building systems to be compared simultaneously. It was developed by the Athena Institute and Morrison Hershfield Consulting Engineers (Athena Sustainable Materials Institute, 2009). Since the materials in ATHENA Impact Estimator are predefined and cannot easily be modified, certain assumptions were made. Elements like sealant and rubber gaskets were omitted because the quantity was negligible and was not available in the material database of the software. Material substitutions were also made, and the reason behind it was lack of availability in the software’s material database. These substitutions include replacing polycarbonate with polypropylene – a similar petroleum based thermoplastic –, as well as polyurethane foam insulation with expanded polystyrene. Designs using silica aerogel insulation were analyzed without them because of the lack of long-term environmental impact data on silica aerogel. Below, Tables 3-1 to 3-12 detail the modeling inputs for each wall system compared.
### Table 3-1, Material Input Quantities for RGWPS

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Glazing Frame</td>
<td>0.0126</td>
<td>Ton</td>
</tr>
<tr>
<td>Hard Coated Double Glazing Argon</td>
<td>Cladding</td>
<td>9.1515</td>
<td>m²</td>
</tr>
<tr>
<td>EPDM Membrane</td>
<td>Vapor Retarder</td>
<td>2.4298</td>
<td>kg</td>
</tr>
<tr>
<td>Single Glazing</td>
<td>Cladding</td>
<td>0.0316</td>
<td>Ton</td>
</tr>
<tr>
<td>HSS</td>
<td>Structural Frame</td>
<td>0.1203</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Used in lieu of polycarbonate</td>
<td>0.0281</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts</td>
<td>Fasteners</td>
<td>0.0013</td>
<td>Ton</td>
</tr>
</tbody>
</table>

### Table 3-2, Material Input Quantities for Traditional Wood Frame

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>#15 Organic Felt</td>
<td>Vapor Retarder</td>
<td>3.3892</td>
<td>m²</td>
</tr>
<tr>
<td>½” Regular Gypsum Board</td>
<td>Interior Cladding</td>
<td>3.2702</td>
<td>m²</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Siding Brackets</td>
<td>0.0004</td>
<td>Ton</td>
</tr>
<tr>
<td>Fiberglass Batt R-20</td>
<td>Thermal Insulation</td>
<td>12.2675</td>
<td>m²</td>
</tr>
<tr>
<td>Joint Compound</td>
<td></td>
<td>0.0033</td>
<td>Ton</td>
</tr>
<tr>
<td>Nails</td>
<td>Fastener</td>
<td>0.0006</td>
<td>Ton</td>
</tr>
<tr>
<td>OSB</td>
<td>Structural Sheathing</td>
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<td>m²</td>
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<tr>
<td>Dimensional Lumber (Kiln-Dried)</td>
<td>Structural Frame</td>
<td>0.0641</td>
<td>m³</td>
</tr>
<tr>
<td>Vinyl Siding</td>
<td>Exterior Cladding</td>
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<td>m²</td>
</tr>
<tr>
<td>Latex Paint</td>
<td>Finish</td>
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<td>L</td>
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Table 3-3, Material Input Quantities for Light Gauge (1) CFS in Tampa, FL

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>0.0037</td>
<td>Ton</td>
</tr>
<tr>
<td>Expanded Polystyrene (25mm Thk) Foam Insulation</td>
<td>1.7466</td>
<td>m²</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>8.6636</td>
<td>kg</td>
</tr>
<tr>
<td>Galvanized Studs Structural System</td>
<td>0.0123</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>0.0497</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0750</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td>0.0020</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0030</td>
<td>Ton</td>
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</tbody>
</table>

Table 3-4, Material Input Quantities for Light Gauge (2) CFS in Tampa, FL

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
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<tr>
<td>Aluminum Glazing Frame</td>
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<td>Expanded Polystyrene (25mm Thk) Foam Insulation</td>
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<tr>
<td>Fiberglass Structural thermal breaks</td>
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</tr>
<tr>
<td>Galvanized Studs Structural System</td>
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<td>Ton</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>0.0497</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0758</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td>0.0020</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0030</td>
<td>Ton</td>
</tr>
</tbody>
</table>
### Table 3-5, Material Input Quantities for Heavy Gauge (1) CFS in Tampa, FL

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>0.0037</td>
<td>Ton</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td>2.3783</td>
<td>m²</td>
</tr>
<tr>
<td>(25mm Thk) Foam Insulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>8.6636</td>
<td>kg</td>
</tr>
<tr>
<td>Galvanized Studs Structural System</td>
<td>0.0179</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>0.0497</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0752</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td>0.0018</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0030</td>
<td>Ton</td>
</tr>
</tbody>
</table>

### Table 3-6, Material Input Quantities for Aluminum Frame in Tampa, FL

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Structural frame and brackets</td>
<td>0.0170</td>
<td>m²</td>
</tr>
<tr>
<td>Expanded Polystyrene Foam Insulation (25mm Thk)</td>
<td>0.3066</td>
<td>kg</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>6.5317</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing Cladding Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0500</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td>0.0009</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0032</td>
<td>m²</td>
</tr>
</tbody>
</table>

### Table 3-7, Material Input Quantities for Light Gauge (1) CFS in Washington D.C.

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>0.0037</td>
<td>Ton</td>
</tr>
<tr>
<td>Expanded Polystyrene Foam Insulation (25mm Thk)</td>
<td>2.9543</td>
<td>m²</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>8.6636</td>
<td>kg</td>
</tr>
<tr>
<td>Galvanized Studs Structural System</td>
<td>0.0169</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing Cladding Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0497</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td>0.0016</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0030</td>
<td>Ton</td>
</tr>
</tbody>
</table>
### Table 3-8, Material Input Quantities for Heavy Gauge (1) CFS in Washington D.C.

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Glazing Frame</td>
<td>0.0037</td>
<td>Ton</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td>Expanded Polystyrene (25mm Thk) Foam Insulation</td>
<td>1.4121</td>
<td>m²</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>Structural thermal breaks</td>
<td>8.6636</td>
<td>kg</td>
</tr>
<tr>
<td>Galvanized Studs</td>
<td>Structural System</td>
<td>0.0133</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing</td>
<td>Cladding</td>
<td>0.0497</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Used in lieu of polycarbonate</td>
<td>0.0690</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts</td>
<td>Fasteners</td>
<td>0.0014</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate</td>
<td>Pressure Plate</td>
<td>0.0030</td>
<td>Ton</td>
</tr>
</tbody>
</table>

### Table 3-9, Material Input Quantities for Aluminum Frame in Washington D.C.

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Structural frame and brackets</td>
<td>0.0143</td>
<td>m²</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td>Expanded Polystyrene (25mm Thk) Foam Insulation</td>
<td>0.3066</td>
<td>kg</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>Structural thermal breaks</td>
<td>6.5317</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing</td>
<td>Cladding</td>
<td>0.0500</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Used in lieu of polycarbonate</td>
<td>0.0688</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts</td>
<td>Fasteners</td>
<td>0.0009</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate</td>
<td>Pressure Plate</td>
<td>0.0032</td>
<td>m²</td>
</tr>
</tbody>
</table>
### Table 3-10, Material Input Quantities for Light Gauge(1) CFS in Detroit, MI

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>0.0037</td>
<td>Ton</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25mm Thk) Foam Insulation</td>
<td>2.9543</td>
<td>m²</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>8.6636</td>
<td>kg</td>
</tr>
<tr>
<td>Galvanized Studs structural System</td>
<td>0.0169</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>0.0497</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0605</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts</td>
<td>0.0016</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0030</td>
<td>Ton</td>
</tr>
</tbody>
</table>

### Table 3-11, Material Input Quantities for Heavy Gauge(1) CFS in Detroit, MI

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>0.0037</td>
<td>Ton</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25mm Thk) Foam Insulation</td>
<td>1.4121</td>
<td>m²</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>8.6636</td>
<td>kg</td>
</tr>
<tr>
<td>Galvanized Studs structural System</td>
<td>0.0133</td>
<td>Ton</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>0.0497</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0605</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts</td>
<td>0.0014</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0030</td>
<td>Ton</td>
</tr>
</tbody>
</table>

### Table 3-12, Material Input Quantities for Aluminum Frame in Detroit, MI

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Quantity</th>
<th>Quantity Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Structural frame and brackets</td>
<td>0.0158</td>
<td>Ton</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25mm Thk) Foam Insulation</td>
<td>3.3000</td>
<td>m²</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>14.4000</td>
<td>kg</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>0.0551</td>
<td>Ton</td>
</tr>
<tr>
<td>Polypropylene Used in lieu of polycarbonate (not available in ATHENA database)</td>
<td>0.0663</td>
<td>Ton</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts</td>
<td>0.0010</td>
<td>Ton</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>0.0035</td>
<td>Ton</td>
</tr>
</tbody>
</table>
Table 3-13, Annual Energy Consumption by Each Wall System

<table>
<thead>
<tr>
<th>Wall System</th>
<th>Annual Energy Consumption (BTU)</th>
<th>Tampa, FL</th>
<th>Washington D.C. and Albuquerque, NM</th>
<th>Detroit, MI</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGWPS</td>
<td>172200000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traditional Wood Frame</td>
<td>165400000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Gauge Design (1)</td>
<td>168250253</td>
<td>166258980</td>
<td>164619109</td>
<td></td>
</tr>
<tr>
<td>Light Gauge Design (1)</td>
<td>168250253</td>
<td>165009554</td>
<td>165009554</td>
<td></td>
</tr>
<tr>
<td>Heavy Gauge Design (1)</td>
<td>168250253</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>168640698</td>
<td>166610381</td>
<td>165400000</td>
<td></td>
</tr>
</tbody>
</table>

Operational environmental costs in ATHENA Impact Estimator are based on annual energy consumption. In the analysis, Energy-10 values from Standley’s analysis (Standley, 2009) were used to determine the annual energy consumption for the original wall system and traditional wood frame system. For the potential wall designs, the energy consumption was determined by interpolating the energy values available – based on the respective thermal resistance of the walls. These are shown in Table 3-13. Details concerning the embodied energy breakdown – like manufacturing, the construction process, and end of life – can be found in Appendix C §2.1.

The second process to determine the environmental impact is also a quantitative process based on the embodied energy. This process is based on the amount of energy used during the manufacture, transportation, and final installation. Each material has a specific embodied energy per given mass and can be found in published sources – like the Inventory of Carbon & Energy (ICE) by Hammond and Jones (2008). To determine embodied energy, it is necessary to determine the mass of each element of the assembly. Tables 3-14 to 3-25 show the embodied energy breakdown for each wall system analyzed. Unlike the ATHENA Impact Estimator results, the RGWPS remains slightly more environmentally friendly – at least 15%.
<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Use</th>
<th>Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
<th>Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>Glazing Frame</td>
<td>12.6</td>
<td>28.8</td>
<td>363</td>
</tr>
<tr>
<td>Hard Coated Double Glazing Argon</td>
<td>Cladding</td>
<td>148.2</td>
<td>15</td>
<td>2223</td>
</tr>
<tr>
<td>EPDM Membrane Vapor Retarder</td>
<td></td>
<td>2.4</td>
<td>101.7</td>
<td>244</td>
</tr>
<tr>
<td>Glass Glazing Cladding</td>
<td></td>
<td>31.6</td>
<td>15</td>
<td>474</td>
</tr>
<tr>
<td>HSS Structural Frame</td>
<td></td>
<td>120.3</td>
<td>9.5</td>
<td>1143</td>
</tr>
<tr>
<td>Polycarbonate Structural Sheathing</td>
<td></td>
<td>28.1</td>
<td>112.9</td>
<td>3173</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td></td>
<td>1.3</td>
<td>9.5</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>7632</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Material Use</th>
<th>Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
<th>Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#15 Organic Felt Vapor Retarder</td>
<td></td>
<td>2.5</td>
<td>31.7</td>
<td>79</td>
</tr>
<tr>
<td>½” Regular Gypsum Board Interior Cladding</td>
<td></td>
<td>26.4</td>
<td>1.8</td>
<td>48</td>
</tr>
<tr>
<td>Aluminum Siding Brackets</td>
<td></td>
<td>0.4</td>
<td>28.8</td>
<td>12</td>
</tr>
<tr>
<td>Fiberglass Batt R-20 Thermal Insulation</td>
<td></td>
<td>3.3</td>
<td>28</td>
<td>92</td>
</tr>
<tr>
<td>Joint Compound Structural Sheathing</td>
<td></td>
<td>3.3</td>
<td>1.8</td>
<td>6</td>
</tr>
<tr>
<td>Nails Fastener</td>
<td></td>
<td>0.6</td>
<td>9.5</td>
<td>6</td>
</tr>
<tr>
<td>OSB Structural Sheathing</td>
<td></td>
<td>25.1</td>
<td>15</td>
<td>377</td>
</tr>
<tr>
<td>Dimensional Lumber (Kiln-Dried) Structural Frame</td>
<td></td>
<td>28.5</td>
<td>8.5</td>
<td>242</td>
</tr>
<tr>
<td>Vinyl Siding Exterior Cladding</td>
<td></td>
<td>7.5</td>
<td>77.2</td>
<td>579</td>
</tr>
<tr>
<td>Latex Paint Finish</td>
<td></td>
<td>0.3</td>
<td>68</td>
<td>20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>1460</strong></td>
</tr>
</tbody>
</table>
### Table 3-16, Material Embodied Energy for Light Gauge (1) CFS in Tampa, FL

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Total Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>3.7</td>
<td>34.1</td>
<td>126</td>
</tr>
<tr>
<td>Polyurethane Foam Insulation</td>
<td>1.3</td>
<td>72.1</td>
<td>94</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>8.7</td>
<td>100</td>
<td>870</td>
</tr>
<tr>
<td>Galvanized Studs Structural System</td>
<td>12.3</td>
<td>9.5</td>
<td>117</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>49.7</td>
<td>15</td>
<td>746</td>
</tr>
<tr>
<td>Polycarbonate Structural Sheathing</td>
<td>75.8</td>
<td>112.9</td>
<td>8468</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td>2</td>
<td>9.5</td>
<td>19</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>3</td>
<td>9.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10467</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3-17, Material Embodied Energy for Light Gauge (2) CFS in Tampa, FL

<table>
<thead>
<tr>
<th>Material Use</th>
<th>Total Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Glazing Frame</td>
<td>8.1</td>
<td>34.1</td>
<td>276</td>
</tr>
<tr>
<td>Polyurethane Foam Insulation</td>
<td>1</td>
<td>72.1</td>
<td>72</td>
</tr>
<tr>
<td>Fiberglass Structural thermal breaks</td>
<td>0.0061</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Galvanized Studs Structural System</td>
<td>12.3</td>
<td>9.5</td>
<td>117</td>
</tr>
<tr>
<td>Single Glazing Cladding</td>
<td>49.7</td>
<td>15</td>
<td>746</td>
</tr>
<tr>
<td>Polycarbonate Structural Sheathing</td>
<td>75.8</td>
<td>112.9</td>
<td>8558</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts Fasteners</td>
<td>2</td>
<td>9.5</td>
<td>19</td>
</tr>
<tr>
<td>Steel Plate Pressure Plate</td>
<td>3</td>
<td>9.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9817</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3-18, Material Embodied Energy for Heavy Gauge (1) CFS in Tampa, FL

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Total Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Glazing Frame</td>
<td>3.7</td>
<td>34.1</td>
<td>126</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Foam Insulation</td>
<td>1.7</td>
<td>72.1</td>
<td>123</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>Structural thermal breaks</td>
<td>8.7</td>
<td>100</td>
<td>870</td>
</tr>
<tr>
<td>Galvanized Studs</td>
<td>Structural System</td>
<td>17.9</td>
<td>9.5</td>
<td>170</td>
</tr>
<tr>
<td>Single Glazing</td>
<td>Cladding</td>
<td>49.7</td>
<td>15</td>
<td>746</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>Structural Sheathing</td>
<td>75.2</td>
<td>112.9</td>
<td>8490</td>
</tr>
<tr>
<td>Screws Nuts &amp; Bolts</td>
<td>Fasteners</td>
<td>1.8</td>
<td>9.5</td>
<td>17</td>
</tr>
<tr>
<td>Steel Plate</td>
<td>Pressure Plate</td>
<td>3</td>
<td>9.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>10570</strong></td>
</tr>
</tbody>
</table>

### Table 3-19, Material Embodied Energy for Aluminum Frame in Tampa, FL

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Total Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
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</tr>
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<tbody>
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<tr>
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<td>750</td>
</tr>
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<td><strong>10534</strong></td>
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### Table 3-20, Material Embodied Energy for Light Gauge (1) CFS in Washington D.C.

<table>
<thead>
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<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
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<td>126</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Foam Insulation</td>
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<td>72.1</td>
<td>151</td>
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<td>100</td>
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<td>49.7</td>
<td>15</td>
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<td>Fasteners</td>
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<td></td>
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### Table 3-21, Material Embodied Energy for Heavy Gauge (1) CFS in Washington D.C.

<table>
<thead>
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<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>126</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Foam Insulation</td>
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<td>72.1</td>
<td>72</td>
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<tr>
<td>Fiberglass</td>
<td>Structural thermal breaks</td>
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<td>100</td>
<td>870</td>
</tr>
<tr>
<td>Galvanized Studs</td>
<td>Structural System</td>
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<td>9.5</td>
<td>126</td>
</tr>
<tr>
<td>Single Glazing</td>
<td>Cladding</td>
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<td>15</td>
<td>746</td>
</tr>
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<td>Polycarbonate</td>
<td>Structural Sheathing</td>
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<td>112.9</td>
<td>7790</td>
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<tr>
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<td>Fasteners</td>
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<td>9.5</td>
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</tr>
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<td>Pressure Plate</td>
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Table 3-22, Material Embodied Energy for Aluminum Frame in Washington D.C.

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<th>Specific Embodied Energy (MJ/kg)</th>
<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
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</tr>
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<td>Foam Insulation</td>
<td>0.2</td>
<td>72.1</td>
<td>14</td>
</tr>
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<td>Structural thermal breaks</td>
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<td>100</td>
<td>650</td>
</tr>
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<td>Single Glazing</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>Polycarbonate</td>
<td>Structural Sheathing</td>
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<td>112.9</td>
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<td>Fasteners</td>
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<td>Steel Plate</td>
<td>Pressure Plate</td>
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<td>9.5</td>
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<td></td>
<td></td>
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Table 3-23, Material Embodied Energy for Light Gauge (1) CFS in Detroit, MI

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Total Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
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<td>34.1</td>
<td>126</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Foam Insulation</td>
<td>2.1</td>
<td>72.1</td>
<td>151</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>Structural thermal breaks</td>
<td>8.7</td>
<td>100</td>
<td>870</td>
</tr>
<tr>
<td>Galvanized Studs</td>
<td>Structural System</td>
<td>16.9</td>
<td>9.5</td>
<td>161</td>
</tr>
<tr>
<td>Single Glazing</td>
<td>Cladding</td>
<td>49.7</td>
<td>15</td>
<td>746</td>
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<tr>
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<td>112.9</td>
<td>6830</td>
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<td>Fasteners</td>
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<td>9.5</td>
<td>15</td>
</tr>
<tr>
<td>Steel Plate</td>
<td>Pressure Plate</td>
<td>3</td>
<td>9.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td></td>
<td></td>
<td><strong>8928</strong></td>
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Table 3-24, Material Embodied Energy for Heavy Gauge (1) CFS in Detroit, MI

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<thead>
<tr>
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<th>Use</th>
<th>Total Material Mass (kg)</th>
<th>Specific Embodied Energy (MJ/kg)</th>
<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Glazing Frame</td>
<td>3.7</td>
<td>34.1</td>
<td>126</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Foam Insulation</td>
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<td>72.1</td>
<td>72</td>
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<td>Fiberglass</td>
<td>Structural thermal breaks</td>
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<td>100</td>
<td>870</td>
</tr>
<tr>
<td>Galvanized Studs</td>
<td>Structural System</td>
<td>13.3</td>
<td>9.5</td>
<td>126</td>
</tr>
<tr>
<td>Single Glazing</td>
<td>Cladding</td>
<td>49.7</td>
<td>15</td>
<td>746</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>Structural Sheathing</td>
<td>60.5</td>
<td>112.9</td>
<td>6830</td>
</tr>
<tr>
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<td>Fasteners</td>
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<td>9.5</td>
<td>13</td>
</tr>
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<td>Pressure Plate</td>
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<td>9.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td></td>
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Table 3-25, Material Embodied Energy for Aluminum Frame in Detroit, MI

<table>
<thead>
<tr>
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<th>Total Material Embodied Energy (MJ)</th>
</tr>
</thead>
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<td>539</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Foam Insulation</td>
<td>2.4</td>
<td>72.1</td>
<td>173</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>Structural thermal breaks</td>
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<td>100</td>
<td>1440</td>
</tr>
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<td>Single Glazing</td>
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</tr>
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<td>Steel Plate</td>
<td>Pressure Plate</td>
<td>3.5</td>
<td>9.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>10506</strong></td>
</tr>
</tbody>
</table>

3.3 Sustainability Assessment and Conclusion

Tables 3-26 to 3-29 detail the environmental impacts of the wall systems. It may be noticed that the ATHENA models done previously by Standley were not used for the original wall system and traditional wood frame system (Standley, 2009). The reason stems from using a different
version of the ATHENA Impact Estimator and the lack of consideration of expected building lifetime in the previous work. To compensate for the lack of expected building lifetime, the analysis looked at a single year of operations and environmental costs. The version used by Standley did not include operational and beyond building life impacts (Standley, 2009).

<table>
<thead>
<tr>
<th>Table 3-26, ATHENA Estimated Environmental Impact for Baseline Wall Assemblies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Assembly Designation</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>RGWPS</td>
</tr>
<tr>
<td>Traditional Wood</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3-27, ATHENA Estimated Environmental Impact for Wall Assemblies in Tampa, FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Assembly Designation</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
</tr>
<tr>
<td>Aluminum Frame</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3-28, ATHENA Estimated Environmental Impact for Wall Assemblies in Washington D.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Assembly Designation</td>
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<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
</tr>
<tr>
<td>Aluminum Frame</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3-29, ATHENA Estimated Environmental Impact for Wall Assemblies in Detroit, MI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Assembly Designation</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
</tr>
<tr>
<td>Aluminum Frame</td>
</tr>
</tbody>
</table>

According to the ATHENA Impact Estimator output, the aluminum frame designs has the most environmental impact of all the redesigns. The aluminum frame design is only 2.5% less environmentally friendly than the original system. What can’t be definitively said is whether the
light gauge or heavy gauge is better across all climate zones. Overall, when compared to the original system the redesigns with CFS structures have reduced environmental impact, at least 6%. However, the redesigns are far from achieving the low environmental impact of the traditional wood frame. The redesigns have at least 10% greater environmental impact than that of the traditional wood frame. Appendix C§2.1 shows the entire relevant data generated from the ATHENA Impact Estimator.

<table>
<thead>
<tr>
<th>Wall Designation</th>
<th>Total Embodied Energy</th>
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<tr>
<td></td>
<td>(MJ)</td>
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<td>RGWPS</td>
<td>7632</td>
</tr>
<tr>
<td>Traditional Wood Frame</td>
<td>1460</td>
</tr>
<tr>
<td>Light Gauge (1) CFS Tampa, FL</td>
<td>10467</td>
</tr>
<tr>
<td>Light Gauge (2) CFS Tampa, FL</td>
<td>9817</td>
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<tr>
<td>Heavy Gauge (1) CFS Tampa, FL</td>
<td>10570</td>
</tr>
<tr>
<td>Aluminum Frame Tampa, FL</td>
<td>10534</td>
</tr>
<tr>
<td>Light Gauge (1) CFS Washington D.C.</td>
<td>9887</td>
</tr>
<tr>
<td>Heavy Gauge (1) CFS Washington D.C.</td>
<td>9772</td>
</tr>
<tr>
<td>Aluminum Frame Washington D.C.</td>
<td>9709</td>
</tr>
<tr>
<td>Light Gauge (1) CFS Detroit, MI</td>
<td>8928</td>
</tr>
<tr>
<td>Heavy Gauge (1) CFS Detroit, MI</td>
<td>8812</td>
</tr>
<tr>
<td>Aluminum Frame Detroit, MI</td>
<td>10506</td>
</tr>
</tbody>
</table>

As for the quantitative approach, there is some divergence with the ATHENA Impact Estimator analysis. Though the values are not exactly the same, the trends shown by the two
methods, however, generally agree. The quantitative approach indicates that the redesigns have
greater environmental impact than the original system and the traditional wood frame system.
Table 3-30 shows the embodied energy of each wall assembly. Aluminum frame designs are only
environmentally competitive in the mixed climate zone. The primary difference between the two
analyses is using recycled materials and actual polycarbonate – not possible in the ATHENA
Impact Estimator. Therefore it is recommended, when possible, to use recycled materials for the
designs. The greatest contributor to embodied energy is the polycarbonate sheathing and thermal
insulation. Using actual polycarbonate in lieu of a similar polypropylene had the greatest impact
on embodied energy, where by polycarbonate has a specific embodied energy of 112.9 MJ/kg
while polypropylene is only 86.4 MJ/kg (Hammond and Jones, 2008). The only similarity among
the redesign in both analyses is that heavy gauge CFS has consistently less environmental impact
in cold climates.
Chapter 4

Structural Design

4.1 Introduction

An assembly’s structure is essential to resist externally induced forces – like gravity and wind. Failure in the structural system is usually cataclysmic, resulting in more immediate and perceived than those of serviceability failures such as moisture leakage. There are many strategies and materials that can be used and assembled to create a structural system for the wall designs. Chapter 4 focuses on the general aspects of structural design, namely – required member dimensions and connection detailing.

The transparent PC sheathing wall system is a combination of traditionally independent systems. Typically in traditional walls the two independent systems are the structural framing system and window glazing system. As a result, the wall system is compact. It also means that the transparent PC sheathing wall system must resist both gravity and lateral loads. In the transparent PC sheathing wall system, the structural framing takes up two duties; one is carry gravity loads, and the second is out-of-plane loads – like out-of-plane wind loads. The transparent PC sheathing, like OSB sheathing, resists the in-plane lateral forces and transfers to the floor and eventually transferred to the foundations.

The original wall system used heavy structural steel tubing sections, which requires refinement for practical applications for the residential sector. Unlike commercial construction, the majority of residential construction is primarily geared towards wood and some cases cold formed steel (CFS) sections, but not heavy structural steel framing structures other than a main longitudinal steel beam to support gravity loads (Jellen, 2014). To improve practicality for
adoption in residences, materials and profiles more commonly found in the residential construction sector were used. This means exploring the use of light gauge CFS, heavy gauge CFS, and structural aluminum frame. Though on the surface aluminum may seem out of place in residential construction, aluminum was chosen as a potential structural material because to its extensive use in residential window glazing systems. Table 4-1 lists the codes and standards used in designing the structures.

<table>
<thead>
<tr>
<th>Code</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012 International Building Code (IBC)</td>
<td>General building code provisions</td>
</tr>
<tr>
<td>2012 International Residential Code (IRC)</td>
<td>General building code provisions</td>
</tr>
<tr>
<td>ASCE 7-10</td>
<td>Load determination</td>
</tr>
<tr>
<td>2008 American Iron and Steel Institute (AISI) Standard 100 and 200</td>
<td>Cold-formed stud wall design</td>
</tr>
<tr>
<td>2010 Aluminum Design Manual (ADM)</td>
<td>Structural aluminum member design</td>
</tr>
</tbody>
</table>

4.2 Literature Review

In traditional residential wall systems, natural daylighting can only enter through the windows. Using large windows constrains the structural system’s performance under extreme loading conditions, because there is less space for the structural load bearing system. The typical window glazing systems do not carry lateral or gravity loads of the building, the result is the addition of independent gravity and lateral force resisting systems – which are taken up by the dimensional lumber framing and plywood and OSB.

4.2.1 Window Glazing

Glazing breakage is a danger that is handled various ways – such as serviceability limits, the type of glass selected, and panel size. According to §2403.3 of the 2012 IBC glazing is only
allowed to deflect no more than 1/175 times its edge length, however the deflection shall not be
greater than 3/4in. Safety glazing is required once individual panels reach a certain size and
when positioned at certain locations. The provisions concerning the use of safety glazing was
covered previously in the building science chapter. If the exterior glazing is not glass but a
plastic material, then it can only be used when the exterior wall is less than 50ft above grade and
when individual panels are no larger than 300 ft² (2012 IBC §2605.2). Other properties – like
maximum unsupported spans, forms, and thicknesses – of the plastic material is not explicitly
defined by code but is required to be checked by the local building official (2012 IBC §2606.5).

In terms of anchoring the glazing to the building, there is no standardized method so it is
usually done in accordance to the system’s manufacturer. If the anchoring system is designed
from scratch, then the embedded anchor should be able to adequately transfer the load from the
frame to the wall system (2012 IRC §R612.7.2.2).

4.2.2 Structural Frame

Most exterior wall designs in the residential sector is prescriptive. The only times when it is
not so, is when the materials, conditions, or assumptions differ from norm. Prescriptive wall
design is a step-by-step process with limited options for subjective reasoning. Tables and
diagrams exist for the selection of a design – based on loads that the residence experiences. In
residential construction, the majority of the design process is generally prescriptive – ranging
from: minimum member dimensions to permissible member modifications. Plastic sheathing –
like transparent PC – is not a common material. The result is that the gravity system cannot be
designed with prescriptive methods (2012 IRC §R602 and R603). On the other hand, it is not
clear whether or not the prescriptive lateral force resisting sheathing design method can be used,
because §R602.10 of the 2012 IRC does not explicitly state the applicable structural sheathing, which the design method is valid for.

Figure 4-1, Code Requirements for Hole Positioning and Dimensions
Source: 2012 IRC §R603.2.5.1

Structural cold formed steel studs carrying gravity loads can use the prescriptive design methods. §R603.2.4 of the 2012 IRC define that fasteners must be spaced a minimum of 1/2" from the edge to prevent premature tear-out during construction. Holes for electrical conduits and mechanical components are defined by §R603.2.5.1 of the 2012 IRC and is illustrated in Figure 4-1. The prescriptive design methods for structural cold form steel may not be applicable when pressure forces are significant – hurricane zones. This is especially true for Florida where the wind velocity easily exceeds 110 miles per hour, at which point the prescriptive design method is no longer permissible.

One weak link in general structural design has to do with the connections. Whenever the connections fail, the remaining structural wall elements do not develop their maximum load
bearing capacity – thus wasting the remaining load bearing capacity (Salim et al., 2005). Under out-of-plane loading conditions – like wind pressure – wall systems act as beams. To reduce wall restraint complexity, it was decided that the wall system is simply supported.

![Figure 4-2, Transparent PC Fracture](image)

Figure 4-2, Transparent PC Fracture
Source: Standley (2009)

Connection design becomes more critical when the wall system is located in regions experiencing significant lateral loads – seismic, hurricane and tornado zones. In residential buildings, connections joining the lateral force resisting elements and gravity force resisting elements are also critical. Should this connection fail then the residential building will have a greater collapse potential, due to the inability to transfer lateral loads to the ground and p-Δ induced buckling (Geschwindner, 2008). Generally, structural sheathing is used to resist lateral loads in most residential buildings. It is recommended that compatible connection and respective methods be used to join the structural sheathing and gravity system – studs (Standley, 2009). For transparent PC, previous research showed that self-drilling screws positioned no closer than 0.7” to the edge are recommended for fastening the structural sheathing to the gravity system (Standley, 2009). The reason stems from preventing fracturing the structural sheathing during construction and under cyclical loading in particular at the corners, as shown in Figure 4-2. The
only times self-tapping screws are recommended are in prefabricated systems where holes are pre-drilled into the structural sheathing (Standley, 2009).

![Figure 4-3, Steel Plate Web Connection](source: Kuczynski (2012))

![Figure 4-4, Typical Stud-Track Flange Connection](source: Kuczynski (2012))

Cold form steel studs are vulnerable to tear-out failure, caused by the fastener and fastener hole. Under high loading conditions, this becomes a problem and will warrant a more robust connection method – shown in Figure 4-3 – as opposed to the more common method shown in Figure 4-4 (Salim et al., 2005). There are multiple ways to reduce tear-out failure, including the following: greater edge distance to fastener hole, and use of thicker gauge steel for the cold form steel studs.
steel studs and track. If all of the mentioned remedies fail then a smaller diameter fastener can be used in conjunction with washers to better distribute the load (Kuczynski, 2012).

Using fasteners can pose potential problems. The greatest is galvanic induced corrosion. It arises from incompatible materials – specifically metals. It is a long term issue that can be avoided but is typically passed over. Galvanic induced corrosion arises from the use of dissimilar metals with 0.25 or more difference in the anodic index (Roberge, 1999). Anodic index is a measurement of a material’s ease in giving-up electrons (Industrial Fastener Institute, 2008). Typically only the material with the smaller anodic index will corrode. Table 4-2 shows the anodic index for common metals. Hot and humid climates accelerate galvanic corrosion, shown in Figure 4-5. From the anodic index of each metal, copper flashing should not be combined with low chromium steels, galvanized steel, and aluminum. It is relevant because copper, aluminum, and steel are usually common in all construction – especially in the realm of fasteners, flashing, and window mullions. Potential materials for use in the redesigns and their respective anodic index are shown in Table 4-3 to 4-5.

<table>
<thead>
<tr>
<th>Table 4-2, Anodic Indices of Common Metals</th>
<th>Source: Roberge (1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>Index (V)</td>
</tr>
<tr>
<td>Copper</td>
<td>-0.35</td>
</tr>
<tr>
<td>Brass and Bronzes</td>
<td>-0.40</td>
</tr>
<tr>
<td>Corrosion Resistant Steel (Chromium ≥ 18%)</td>
<td>-0.50</td>
</tr>
<tr>
<td>Corrosion Resistant Steel (Chromium ≥ 12%)</td>
<td>-0.60</td>
</tr>
<tr>
<td>Aluminum (2000 Series)</td>
<td>-0.75</td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>-1.20</td>
</tr>
<tr>
<td>Zinc</td>
<td>-1.75</td>
</tr>
</tbody>
</table>
Table 4-3, Anodic Index of Various CFS Grades

<table>
<thead>
<tr>
<th>Material</th>
<th>Designation/Grade</th>
<th>Anodic Index (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>A653 Gr. 33</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>A653 Gr. 50</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>A792 Gr. 33</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>A792 Gr. 50A</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>A875 Gr. 33</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>A875 Gr. 50</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

Table 4-4, Anodic Index of Various Glazing Frame Grades

<table>
<thead>
<tr>
<th>Material</th>
<th>Designation/Grade</th>
<th>Anodic Index (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>3003</td>
<td>-0.9</td>
</tr>
<tr>
<td></td>
<td>3004</td>
<td>-0.9</td>
</tr>
<tr>
<td></td>
<td>3105</td>
<td>-0.9</td>
</tr>
<tr>
<td></td>
<td>5005</td>
<td>-0.9</td>
</tr>
<tr>
<td></td>
<td>6063</td>
<td>-0.9</td>
</tr>
<tr>
<td>Steel</td>
<td>304</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>316</td>
<td>-0.5</td>
</tr>
<tr>
<td>Material</td>
<td>Designation/Grade</td>
<td>Anodic Index (V)</td>
</tr>
<tr>
<td>----------</td>
<td>-------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2017</td>
<td>-0.75</td>
</tr>
<tr>
<td></td>
<td>2024</td>
<td>-0.75</td>
</tr>
<tr>
<td></td>
<td>6061</td>
<td>-0.9</td>
</tr>
<tr>
<td></td>
<td>7075</td>
<td>-0.9</td>
</tr>
<tr>
<td>Steel</td>
<td>A307</td>
<td>-1.2, -0.85</td>
</tr>
<tr>
<td></td>
<td>A325</td>
<td>-1.2, -0.85</td>
</tr>
<tr>
<td></td>
<td>A449</td>
<td>-1.2, -0.85</td>
</tr>
<tr>
<td></td>
<td>A490</td>
<td>-0.85</td>
</tr>
</tbody>
</table>

### 4.2.3 Transparent PC Sheathing

Transparent PC sheathing – like other structural sheathing products – transfer lateral loads to the ground, and ties the individual studs together to resist loads as an integrated wall system. Structural sheathing in walls also has a secondary function that is to prevent exterior environmental conditions from severely impacting the controlled interior environment (Memari, 2013). Some exterior environmental conditions that are kept out by the structural sheathing in walls are: wind driven rain (Straub, 2006) and airborne debris.

Polycarbonate (PC) itself is not a new material but its application as a structural sheathing is more recent (Standley and Memari, 2012). PC is used in a variety of other applications such as: privacy, greenhouse transparent panels, laminate in impact resistant glass – like safety glass –, and optical lenses. PC is a thermal plastic that can experience large deformations before failure – meaning that there is little risk of catastrophic failure should an object impact it. Figure 4-6 shows the stress and strain relation of polycarbonate.
4.3 Methodology

Three potential solutions were formulated and explored in this study – light and heavy gauge CFS stud walls, as well as a structural aluminum system. All three potential solutions were designed for the environmental loads of the four locations selected during the building science design phase. However, before design could commence a typical home had to be selected, assumptions made, and specific materials selected. Selecting a typical residence permitted the determination of governing design loads. Figures 4-7 to 4-9 shows the residential building selected (typical in central PA), along with the respective physical parameters.
Figure 4-9, Section and Wall Assembly of Selected Residence

Source: Jellen (2014)
Specific material selection is based on a multitude of factors, which were organized into a rubric point system where the materials with the greatest accumulation of points were selected. Selection factors included (but not limited to) the following: typical use of the material, weight, and corrosion resistance. It should be noted that the selection method is subjective and will likely vary with different designers and manufacturers. The point breakdown for selecting the structural material can be found in Table 4-7. Tables 4-6 and 4-8 show the characteristics of possible material selections for use in structural members.

<table>
<thead>
<tr>
<th>Material</th>
<th>Grade</th>
<th>Advantages</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>3003</td>
<td>Readily available, easily worked into various shapes</td>
<td>Not heat treatable, mainly available in sheet form, little deformation before rupture, discolor when aging</td>
</tr>
<tr>
<td></td>
<td>3004</td>
<td>Significant deformation before failure, high strength, easily worked into various shapes, strength retention at low temperatures</td>
<td>Mainly available in sheet form, less commonly available than 3003</td>
</tr>
<tr>
<td></td>
<td>3105</td>
<td>Readily available, easily worked into various shapes</td>
<td>High thermal conductivity</td>
</tr>
<tr>
<td></td>
<td>5005</td>
<td>Doesn't discolor with aging</td>
<td>Not heat treatable, mainly available in sheet and plate form, high thermal conductivity, more difficult to machine than 3003</td>
</tr>
<tr>
<td></td>
<td>6063</td>
<td>Commonly used for framed openings and architectural applications, ease of applying finish, high level of corrosion resistance</td>
<td>High thermal conductivity, expensive</td>
</tr>
<tr>
<td>Steel</td>
<td>304</td>
<td>Significant deformation before failure, resists most oxidizing acids and salt sprays, easily worked into various shapes, readily available</td>
<td>Weight, pitting corrosion</td>
</tr>
<tr>
<td></td>
<td>316</td>
<td>Significant deformation before failure, strength retention at elevated temperatures, highly corrosion resistant and typically used in marine environments</td>
<td>Weight, less wearing resistance and costs more than 304</td>
</tr>
</tbody>
</table>
Table 4-2, Glazing Frame Material Selection

<table>
<thead>
<tr>
<th>Material</th>
<th>Designation/Grade</th>
<th>Availability</th>
<th>Workability</th>
<th>Corrosion Resistance</th>
<th>Finish</th>
<th>Thermal Performance</th>
<th>Strength-to-Weight</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3003</td>
<td></td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>3004</td>
<td></td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>3105</td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>5005</td>
<td></td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>6063</td>
<td></td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>304</td>
<td></td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>316</td>
<td></td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>21</td>
</tr>
</tbody>
</table>
No specific steel material was specified for the CFS studs. The explanation is that there are a multitude of steel alloys and specific use in CFS depends on the manufacturer. What is certain is that the strength property, follows one of the two main strength grades – 33 ksi and 50 ksi. Whether 33 ksi or 50 ksi is used will be determined in the design process. Frame materials with the greatest number of points were selected. In the case of the steels, grade 304 will be used – even though it is tied with grade 316 – primarily due to its lower cost.

<table>
<thead>
<tr>
<th>Material</th>
<th>Designation/Grade</th>
<th>Advantages</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2017</td>
<td>Used in a variety of fastening applications</td>
<td>Corrosion resistance</td>
</tr>
<tr>
<td></td>
<td>2024</td>
<td>Easily machined</td>
<td>Corrosion resistance</td>
</tr>
<tr>
<td></td>
<td>6061</td>
<td>High corrosion resistance</td>
<td>Lower strength when compared to other aluminum grades, difficult to machine</td>
</tr>
<tr>
<td></td>
<td>7075</td>
<td>High strength, resistant to pitting corrosion</td>
<td>Typically used in aerospace applications,</td>
</tr>
<tr>
<td>Steel</td>
<td>A307</td>
<td>Used in a variety of fastening applications</td>
<td>Lower strength when compared to other steel grades</td>
</tr>
<tr>
<td></td>
<td>A325</td>
<td>Standard structural bolt, more corrosion resistant than other high strength steels</td>
<td>Typically used in slip critical applications</td>
</tr>
<tr>
<td></td>
<td>A449</td>
<td>Similar to A325</td>
<td>Lower level of prescribed quality assurance, less commonly used</td>
</tr>
<tr>
<td></td>
<td>A490</td>
<td>Standard structural bolt, high strength</td>
<td>Not coated with zinc, emissivity</td>
</tr>
</tbody>
</table>

It was determined that steel fasteners similar to A307 will be used. Table 4-8 shows additional advantages and disadvantages of the potential fastening material. One of the determining points is availability; Table 4-9 shows that A307 is produced by a significant number of mills. Second, the anodic index between A307 and the respective CFS steel, as well as the aluminum frame is within the acceptable 15V difference. Only for connecting the CFS steels must
A307 be galvanized, to meet the acceptable anodic index difference. It is not a problem to galvanize A307, since it is available in both plain and galvanized coatings (Fastenal, 2005). Another reason is the generally low demand of design loads, which does not warrant the use of high strength fastening materials.

Another consideration pertaining to fasteners concerns preserving thermal and moisture performance in the building science design phase. Fasteners are not allowed to penetrate through the entire assembly. The rationale is that fasteners generally have less thermal resistance than the surrounding material, whereby those penetrating deep into an assembly typically act as short-circuits through the wall thermal insulation and waterproofing layers.

<table>
<thead>
<tr>
<th>Location</th>
<th>Floor Level</th>
<th>Unfactored Gravity Load (lb/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dead</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>2</td>
<td>521</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>156</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>2</td>
<td>521</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>156</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>2</td>
<td>521</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>156</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>2</td>
<td>521</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>156</td>
</tr>
</tbody>
</table>
Once a residence and materials were selected, the gravity loads and lateral loads were calculated. These calculations are based on ASCE7-10. Though the live load component of the gravity load could be reduced – live load reduction in ASCE7-10 –, the decision was made not to. The other component of gravity loads are dead loads, for them the weight of the existing structural system was acquired from the construction drawings and tabulated material weight lists in AISC – can be found in Appendix D§1.1. The unfactored live and dead loads for each of the four locations are listed in Table 4-10. As for the lateral load, it was determined using a simplified method – Envelope Procedure (Enclosed Simple Diaphragm) for wind and Equivalent Lateral Force Procedure for seismic – and resulted in wind as the controlling lateral load. These loads were used in the design of the PC sheathing and respective connection. Both the controlling lateral wind load and out-of-plane Components and Cladding (CCL) wind loads are shown in Tables 4-11 to 4-12. CCL wind loads were used to design the studs and columns for flexure. Hand calculations detailing the lateral load can be found in Appendix D§1.2.
### Table 4-6, Forces arising from Wind Loads

#### Forces Arising from In-Plane Wind Loading in Tampa, FL (Story 2)

<table>
<thead>
<tr>
<th>Location</th>
<th>Resisting Direction</th>
<th>Element C.R.</th>
<th>In-Plane Lateral Force (lb)</th>
<th>Vertical Force (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wind on Perpendicular to Front</td>
<td>Wind Perpendicular to Left</td>
</tr>
<tr>
<td>Front</td>
<td>x</td>
<td>0</td>
<td>10856.7</td>
<td>3363.8</td>
</tr>
<tr>
<td>Back</td>
<td>x</td>
<td>30</td>
<td>10856.7</td>
<td>-1572.8</td>
</tr>
<tr>
<td>Left</td>
<td>y</td>
<td>0</td>
<td>15554.9</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>y</td>
<td>36</td>
<td>15554.9</td>
<td></td>
</tr>
</tbody>
</table>

#### Forces Arising from In-Plane Wind Loading in Tampa, FL (Story 1)

<table>
<thead>
<tr>
<th>Location</th>
<th>Resisting Direction</th>
<th>Element C.R.</th>
<th>In-Plane Lateral Force (lb)</th>
<th>Vertical Force (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wind on Perpendicular to Front</td>
<td>Wind Perpendicular to Left</td>
</tr>
<tr>
<td>Front</td>
<td>x</td>
<td>0</td>
<td>17814.6</td>
<td>3363.8</td>
</tr>
<tr>
<td>Back</td>
<td>x</td>
<td>30</td>
<td>17814.6</td>
<td>-1572.8</td>
</tr>
<tr>
<td>Left</td>
<td>y</td>
<td>0</td>
<td>24158.7</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>y</td>
<td>36</td>
<td>24158.7</td>
<td></td>
</tr>
</tbody>
</table>

#### Forces Arising from In-Plane Wind Loading in Other Locations (Story 2)

<table>
<thead>
<tr>
<th>Location</th>
<th>Resisting Direction</th>
<th>Element C.R.</th>
<th>In-Plane Lateral Force (lb)</th>
<th>Vertical Force (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wind on Perpendicular to Front</td>
<td>Wind Perpendicular to Left</td>
</tr>
<tr>
<td>Front</td>
<td>x</td>
<td>0</td>
<td>5625.2</td>
<td>1752.8</td>
</tr>
<tr>
<td>Back</td>
<td>x</td>
<td>30</td>
<td>5625.2</td>
<td>-807.8</td>
</tr>
<tr>
<td>Left</td>
<td>y</td>
<td>0</td>
<td>8025.1</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>y</td>
<td>36</td>
<td>8025.1</td>
<td></td>
</tr>
</tbody>
</table>

#### Forces Arising from In-Plane Wind Loading in Other Locations (Story 1)

<table>
<thead>
<tr>
<th>Location</th>
<th>Resisting Direction</th>
<th>Element C.R.</th>
<th>In-Plane Lateral Force (lb)</th>
<th>Vertical Force (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wind on Perpendicular to Front</td>
<td>Wind Perpendicular to Left</td>
</tr>
<tr>
<td>Front</td>
<td>x</td>
<td>0</td>
<td>9229.7</td>
<td>1752.8</td>
</tr>
<tr>
<td>Back</td>
<td>x</td>
<td>30</td>
<td>9229.7</td>
<td>-807.8</td>
</tr>
<tr>
<td>Left</td>
<td>y</td>
<td>0</td>
<td>12490.9</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>y</td>
<td>38</td>
<td>12490.9</td>
<td></td>
</tr>
</tbody>
</table>
Table 4-7, Out-of-Plane Wind Loads

<table>
<thead>
<tr>
<th>Location</th>
<th>Edge</th>
<th>( \lambda ) (ASCE 7-10 Figure 30.5-1)</th>
<th>( P_{\text{out}} ) (lb/ft(^2)) (ASCE 7-10 Figure 30.5-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>Long</td>
<td>38.2</td>
<td>-38.2</td>
</tr>
<tr>
<td></td>
<td>Short</td>
<td>38.2</td>
<td>-38.2</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>Long</td>
<td>19.8</td>
<td>-19.8</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>Long</td>
<td>19.8</td>
<td>-19.8</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>Long</td>
<td>19.6</td>
<td>-19.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Edge</th>
<th>Wind Loading on CCL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( P_{\text{out}} ) (lb/ft(^2))</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>Long</td>
<td>53.5</td>
</tr>
<tr>
<td></td>
<td>Short</td>
<td>53.5</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>Long</td>
<td>27.7</td>
</tr>
<tr>
<td></td>
<td>Short</td>
<td>27.7</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>Long</td>
<td>27.7</td>
</tr>
<tr>
<td></td>
<td>Short</td>
<td>27.7</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>Long</td>
<td>27.7</td>
</tr>
<tr>
<td></td>
<td>Short</td>
<td>27.7</td>
</tr>
</tbody>
</table>
Load Resistance Factor Design (LRFD) method was predominately used to design the structural members. In doing so, the controlling load combination had to be determined. The

---

Table 4-8, Controlling Load Combinations

<table>
<thead>
<tr>
<th>Location</th>
<th>Use of Load Combinations</th>
<th>Load Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>Gravity Loading</td>
<td>1.2D + 1.6L + 0.5Lr</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>Gravity Loading</td>
<td>DNC</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>Gravity Loading</td>
<td>DNC</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>Gravity Loading</td>
<td>DNC</td>
</tr>
</tbody>
</table>

Figure 4-1, Member Designation and Loads Acting on Frame

Load Resistance Factor Design (LRFD) method was predominately used to design the structural members. In doing so, the controlling load combination had to be determined. The
existence of wind uplift, required all loads – gravity and lateral – to be broken into equivalent vertical and horizontal components. Then load factors were applied to the load components. The force magnitudes of all the valid LRFD load combinations were compared and resulted in two governing load cases. As can be seen in Table 4-13, there were two governing load cases. For more information like the values, please see Appendix D §1.3. The next step was designing and selecting the structural members for the wall systems. Structural framing member designations are visually shown in Figure 4-10.

For the initial design, flexural and beam-column (combined loading) members were sized for moment and limiting deflection. Those members experiencing combined loadings were then checked for axial load capacity and adherence to the axial load-moment interaction equation. If the members selected – under the initial design – passed the mentioned processes, the next step was checking for the potential for local failures. Checking for potential local failures include: lateral torsional buckling, distortional buckling and slenderness. Members passing the mentioned process were compiled. The member chosen was based on lightness and depth.

The scope of the design does not cover detailed connections; therefore only general connection designs were formulated. The general connection design permitted a more accurate cost estimate and constructability assessment in a later chapter. Initially the fasteners securing the transparent PC sheathing were selected based on shear capacity. Here it was assumed that the fasteners were spaced 6” apart. Then the edge spacing of the fasteners was checked for adequacy. The process involved checking the transparent PC sheathing and frame for bearing and tear-out potential. Likewise, for connections between framing members the process is similar with the exception of the fastener spacing.
Before moving on to the design, structural design guidelines were formulated to ensure practicality and preserve performance. One of which is minimizing fastener quantities and types. Connections with many fasteners and types of fasteners slow construction and make quality control harder to ensure. In addition, fasteners act as thermal bridges – thermal performance degrades as the number of fasteners increases. Furthermore, certain connections were not used – like welds – to keep the wall system relatively inexpensive. As a note; potential for modularization, actual cost, and labor requirements will be covered in greater depth in the constructability section. Assumptions made were generally based on predominant practices and observations. Below general assumptions and prerequisites are listed:

1. Residence selected was simplified to eliminate irregularities
2. Diaphragms are generally flexible
3. In-plane lateral loads are wholly handled by the structural sheathing
4. Limit structural member depth to no more than 6”
5. Composite structural thermal breaks have similar strength properties as aluminum
6. System is designed as 48” wide units for potential modularization
4.4 Design

4.4.1 Light Gauge CFS

The first possible solution explored is light gauge CFS studs. Light gauge CFS studs are defined to be no thicker than 14 gauge. The thinness of light gauge CFS studs minimizes member weight, thus reducing strain on the worker and fastening system. Governing the design of light gauge CFS are AISI 100 and 200. The primary concern whilst designing the structural system was slenderness of the member’s elements. For convenience, the governing design loads are shown in Table 4-14. Whilst designing the structural system according to AISI 100 and 200, it was observed that there were similarities to AISC structural steel design methods, like Euler buckling and beam-column design. The similarity permitted the use of some assumptions in the original system’s structural design. The assumptions made are listed below:

1. No thicker than 14 gauge
2. All holes made in compression members adhere to AISI 100§B2.2
3. Kd is 0.05
4. Stiffeners were not used
5. Studs are only supported at ends and mid-height against lateral torsional buckling (LTB)
6. Dimensional lumber top plate and floor handles all the flexural demand for the top track
7. Lip for the studs are not significantly bent

<table>
<thead>
<tr>
<th>Member</th>
<th>Load Combination Designation</th>
<th>Load Combination</th>
<th>Pu (lb)</th>
<th>Mu (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
<td>1863.3</td>
</tr>
<tr>
<td>1</td>
<td>Grav</td>
<td>1.2D + 1.6L + 0.5(Lr</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Grav-Lat</td>
<td>1.2D + 1.0W + L + 0.5(Lr</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
<td>603.7</td>
</tr>
<tr>
<td>5</td>
<td>Grav</td>
<td>1.2D + 1.6L + 0.5(Lr</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Grav-Lat</td>
<td>1.2D + 1.0W + L + 0.5(Lr</td>
<td></td>
<td>S</td>
</tr>
</tbody>
</table>
Before considering slenderness effects, the members were selected according to flexural capacity. With the design loads in hand, the first step of this task was acquiring the required section modulus and strong-axis moment of inertia, which are shown in Table 4-15. Both were determined from back calculations of defined flexural and deflection formulas. Using the gross properties table in AISI design manual, a number of potential members were selected. Potential members were limited to a depth of no more than 6”. The rationale behind the decision is maintaining a wall assembly depth roughly equivalent to the typical traditional residential wall assembly depth.
Only from here onwards were the member’s elements checked for local failure. Localized failure is classified as failure of the member’s elements – like webs and flanges. Localized failure arises from lack of stiffness stemming from slender elements and lateral bracing of elements. The potential member’s elements were checked for lateral torsional buckling (LTB) and distortional buckling, as shown in Tables 4-16 to 4-17. Whenever Euler bucking value \( F_e \) is between 2.78 and 0.56 times the yield strength \( F_y \), then LTB buckling occurs. If the moment causing LTB and distortional buckling is greater than the required moment \( M_u \) – in Table 4-15 – then the potential member can be used.

LTB is a phenomenon where the compression flange buckles whilst the member experiences global flexure. As for distortional buckling, it occurs when an element – acting as stiffener to another, like web and flanges – of a member buckles, either due to slenderness or other buckling modes. Trends started to appear, one of which is local strength properties govern over global strength requirements. Local strength properties become more dominant as the elements become more slender. Slenderness effects can be offset by using stronger material grade. Another trend observed is that members with deep webs and wide flanges don’t necessarily translate to greater capacities, when compared to members with narrower less slender webs.

Next the potential members are vetted by checking their compliance to design axial and combined loads. The proportion of flexural demand is significantly greater than those of axial compression. The axial compression demand is less because the studs are braced at mid height, this reduces the unbraced height – thereby increasing the axial capacity of the structural member. Detailed hand calculations of the design and analysis can be found in Appendix D§2.1. Table 4-18 and Figures 4-11 to 4-14 show the general assembly and light gauge CFS members selected.
Table 4-13, Structural Member Size for Light Gauge CFS Systems

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Description</th>
<th>Member Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>1</td>
<td>Vertical Stud</td>
<td>400S200-54</td>
</tr>
<tr>
<td>2</td>
<td>Same as member (1)</td>
<td>400S200-54</td>
</tr>
<tr>
<td>3</td>
<td>Horizontal Top Track</td>
<td>400T150-54</td>
</tr>
<tr>
<td>4</td>
<td>Horizontal Bottom Track</td>
<td>400T150-54</td>
</tr>
<tr>
<td>5</td>
<td>Horizontal Middle Bridging</td>
<td>350S162-54</td>
</tr>
</tbody>
</table>

Figure 4-2, Diagram of Structural PC Sheathing and Light Gauge CFS Frame Screw Connection

SCREWS SHALL BE NO CLOSER THAN 3/4" FROM DIAPHRAGM EDGE

(9) #10 SELF DRILLING SCREWS EQUALLY SPACED FOR CONNECTING DIAPHRAGM TO EACH TRACK

#10 SELF DRILLING SCREWS EQUALLY SPACED AT NO MORE THAN 6" O.C. FOR CONNECTING DIAPHRAGM TO EACH STUD
MINIMUM 1/2" DIA. BOLT WITH MINIMUM 4" DEPTH

MINIMUM 1/2" DIA. ANCHOR BOLT EMBEDDED A MINIMUM 7" INTO FOUNDATION

Figure 4-3, Diagram of Light Gauge CFS Framing and Anchor Bolt Use
Figure 4-4, Diagram of Light Gauge CFS Framing Hold-downs and Angle Connections (Tampa, FL)

CFS STUD BRACING

SIMPSON STRONG-TIE HOLD-DOWN S/HD8S, ALTERNATES SHALL BE RATED FOR 3000LB.

CFS TRACK SHALL HAVE MINIMUM FLANGE 1-1/2"

SIMPSON STRONG-TIE UTILITY CLIP SSC2.25
In order for the whole wall assembly to work in unison, connections are required to transfer loads effectively. Designing the connection between light gauge CFS elements is fairly straightforward and guided by AISI 100. The main fasteners used are screws and bolts. The screws are only used connecting the studs to the track. The design limit states are generally the same – bolt shear, block shear, and bearing/tear-out. The only difference is that screws induce another design
limit state, pull-over. The connection between the transparent PC sheathing and light gauge CFS
is based on a combination of published research findings, engineering mechanics, and elastic
behavioral response. The primary reason for the less straightforward design and analysis is the
new application of PC as a structural sheathing material. As a result, there are no valid
recommended prescriptive fastening guides.

The design process for the structural members revealed several trends. One is that the light
gauge CFS studs and track are governed by local element properties, as opposed to the global
member properties. Larger ratios of flange width to flange thickness usually point to early onset
of localized element buckling. It also means that members with deep webs and wide flanges don’t
necessarily have greater capacities than members with narrower webs. The local buckling effects
can be reduced through using stronger steel grades. Another trend involves members appearing as
columns – like studs –, which according to calculations experience significantly greater flexural
loads; primarily arising from out-of-plane wind loads. This is so much so that the out-of-plane
wind loads are greater than the gravity loads.

4.4.2 Heavy Gauge CFS

Next, the heavy gauge CFS system was designed. The main difference between heavy gauge
CFS and light gauge CFS is thickness – where heavy gauge is thicker. Thicker gauge CFS reduces
element slenderness and potentially reduces local element failure in the structural members.
Anticipating that heavy gauge CFS will be stronger, the studs are spaced further apart, at 24” O.C.
Like the light gauge CFS stud system, AISI 100 and 200 is the pervading code and is designed in
a similar manner. Likewise, the assumptions made in the design of heavy gauge CFS were the
same as those of light gauge CFS. Table 4-19 and Figures 4-15 to 4-18 show the members selected and structure, respectively.

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Description</th>
<th>Member Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vertical Stud</td>
<td>600S137-68</td>
</tr>
<tr>
<td>2</td>
<td>Same as member (1)</td>
<td>600S137-68</td>
</tr>
<tr>
<td>3</td>
<td>Horizontal Top Track</td>
<td>600T150-68</td>
</tr>
<tr>
<td>4</td>
<td>Horizontal Bottom Track</td>
<td>600T150-68</td>
</tr>
<tr>
<td>5</td>
<td>Horizontal Middle Bridging</td>
<td>250S137-68</td>
</tr>
</tbody>
</table>

Table 4-14, Structural Member Size for Heavy Gauge CFS Systems

Figure 4-6, Diagram of Structural PC Sheathing and Heavy Gauge CFS Frame Screw Connection
MINIMUM 1/2" DIA. BOLT WITH MINIMUM 4" DEPTH

MINIMUM 1/2" DIA. ANCHOR BOLT EMBEDDED A MINIMUM 7" INTO FOUNDATION

Figure 4-7, Diagram of Heavy Gauge CFS Framing and Anchor Bolt Use
Figure 4-8, Diagram of Heavy Gauge CFS Framing Hold-downs and Angle Connections (Tampa, FL)

CFS STUD BRACING

SIMPSON STRONG-TIE HOLD-DOWN S/HD8S, ALTERNATES SHALL BE RATED FOR 3000LB.

CFS TRACK SHALL HAVE MINIMUM FLANGE 1-1/2"

SIMPSON STRONG-TIE UTILITY CLIP SSC4.25
As expected, the heavy gauge CFS has greater resistance to local elemental buckling. So much so, that the global required strength and deflection limits govern design. Due to thicker gauge of CFS used, the heavy gauge system requires greater force and larger screws to successfully connect the transparent PC sheathing to the structural frame – based on Simpson Strong-Tie recommendations. The outcome is stronger fastener resistance to failure, along with lower...
threshold for base material – transparent PC sheathing and CFS – failure. Though there is a base material strength reduction, it is not significant and does not warrant base material dimensional increases or edge distance increases.

4.4.3 Structural Aluminum Frame

Both CFS structural systems are deep and do not engage with the flexural and axial capacity of the window glazing’s frame. Reducing wall depth – required to resist design loads – is the rationale behind exploring the use of extruded structural aluminum, whereby the structural system with the window glazing’s frame are combined into one. Aluminum and its forming process offers unique characteristics – both opportunities and challenges. The advantages of aluminum are:

1. Generally corrosion resistant
2. Lighter weight than steel
3. Ease of forming into various shapes
4. Integrated connections – formed into the member

Like most alternatives there are challenges. One is lower strength-to-weight ratio, when compared to steel. Aluminum is also incompatible with various metals. If the aluminum is put into contact with an incompatible metal, galvanic corrosion will occur. The high thermal conductance of aluminum is another challenge, because there is greater potential for thermal bridging to occur. As a fact, the thermal conductance of aluminum is significantly greater than steel. Simplifications to the design process was made through using the following assumptions:

1. All elements are supported at both ends and are not slender
2. No internal stiffeners
3. Each axial element of the members shares the axial load proportional to respective length
4. Members are approximated to be closed shapes

5. Structural composite bridges have similar strengths as aluminum

6. Use Simpson Strong Tie to tie in the wall system to the floor

7. No welded connections

Designing an aluminum structure is similar to those of steel. As a result, the general progression through design is generally straightforward. First, members are sized based on the required design flexural loads and deflection limits. Next, it is checked if there is any local elemental failure. If the member or elements fail, then resizing is necessary. Else the member is checked for compliance for axial and combined loading scenarios. Only one of the satisfying members is selected, mainly based on weight and dimensions. Table 4-20 and Figures 4-19 to 4-22 show the members selected and schematics of the aluminum frame system.

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Description</th>
<th>Member Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>1</td>
<td>Vertical Column</td>
<td>(2) 2-1/4”x5-1/2”x3/16” C-Shape</td>
</tr>
<tr>
<td>2</td>
<td>Same as Member (1)</td>
<td>(2) 2-1/4”x5-1/2”x3/16” C-Shape</td>
</tr>
<tr>
<td>3</td>
<td>Aluminum Top Plate</td>
<td>(1) 1-1/2”x2”x1/8”</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum Bottom Plate</td>
<td>(1) 1-1/2”x2”x1/8”</td>
</tr>
<tr>
<td>5</td>
<td>Horizontal Middle Beam</td>
<td>(2) 1-1/2”x3-1/4”x1/8” C-Shape</td>
</tr>
</tbody>
</table>
Screws shall be no closer than 3/4" from diaphragm edge.

(9) #10 self drilling screws equally spaced for connecting diaphragm to each track.

#10 self drilling screws equally spaced at no more than 6" O.C. for connecting diaphragm to each stud.

Figure 4-10, Diagram of Structural PC Sheathing and Aluminum Frame Screw Connection
MINIMUM 1/2" DIA. BOLT WITH MINIMUM 4" DEPTH

MINIMUM 1/2" DIA. ANCHOR BOLT EMBEDDED A MINIMUM 7" INTO FOUNDATION

Figure 4-11, Diagram of Aluminum Framing and Anchor Bolt Use
Figure 4-12, Three Side Views of Aluminum Frame Connections (Tampa, FL)
After the member design is completed, the connection is optimized. Screws were selected to join the members. Welds were not chosen because of their quality in the field and required specialized knowledge that is not common in the residential sector. Screw material selection is based on compatibility with the aluminum members, general availability, and manufacturer’s recommendations.

The connection between aluminum frame and transparent PC sheathing was kept the same as those for CFS. As the primary source of failures are the screws and spacing limits – all necessary to prevent sheathing buckling. Main difference with the CFS systems is that the holes need to
be predrilled into the aluminum, due to material thickness and maintenance of screw structural integrity – arising from material thickness.

In terms of trends, there are a few. One is that the majority of the column’s (member 1) depth is dictated by the thermal insulation thickness. The reason is that the required depth to resist the loads is less than that of the thermal insulation depth. Generally larger sections are required to meet deflection limits due to lower elastic modulus – when compared to steel. However, the greater section size is still lighter than that of the equivalent strength steel section. As for the connections, shear rupture generally controls. Here the fasteners fails before the connecting material fails, including for the structural PC sheathing and structural frame connection.

4.5 Conclusions

It will be concluded that structural design of the wall system yielded some surprising results and revealed the impact of material behavior. Before that, the CFS structural material will be discussed. Though the structural material was selected for the aluminum frame and connectors, for CFS a steel type was not. The reason is the varying types of steel used by each CFS manufacturer, therefore only a required yield strength is specified – either 33 or 55 ksi.

One surprise, thicker CFS gauge structural members do not necessarily mean greater strength. Initially, it was assumed that flexural structural members with wider flanges has greater load bearing capacity – based on previous structural steel design. This is not true when the flange of a flexural structural member is slender, because the structural member experiences local failure - flange buckling. The second is that the connection securing the structural PC sheathing to the structural frame are the weak link. It was originally assumed that either the PC or framing member flange would fail first - when the maximum load is exceeded. Other than the potential for localized
failure the remainder of CFS and aluminum design by hand was straightforward and were very similar to structural steel design governed by the AISC manual.

In the study this marks the end of the structural frame design. However, it is not the end, therefore suggestions for further study in the future are as follows: carry out structural design and analyze the performance of composite tracks, evaluate the use of wood framing with structural PC sheathing, and develop prescriptive screw connection design for securing structural PC sheathing to structural frame.
5.1 Introduction

Construction practicality is an important aspect for product adoption. Products and systems that do not generally embody low financial burden and ease of assembly are usually not adopted. However, due to the wide breadth of ease of assembly, only direct factors – like cost and prefabrication – and the role of familiarity were explored. The evaluation of the wall designs from the previous chapters were heavily based on the literature review.

5.2 Literature Review

Construction practicality generally depends on construction management methods. Improving construction practicality holistically requires identifying and verification that certain methods deliver. Exact methods will require the mentioned process, however verification is beyond the scope of this thesis. The main focus will be productivity, which is a measure of construction practicality and is affected by a multitude of factors. Some of these factors are direct impacts – like material availability, weight, and modularity – and familiarity.

5.2.1 Impacts on Construction Productivity

Construction productivity is affected by two general categories: direct factors, pre-construction and management practices. Pre-construction and management practices are not the focus of this thesis; therefore it will not be discussed in detail. What can be said is that pre-construction and management factors include: team building, safety, existence of incentives,
design and construction planning, along with automation and integrated information systems (Caldas et al., 2015).

Material and equipment availability is a direct factor, and lack of them can reduce labor output by 30% (Goodrum et al., 2009). Lack of material and equipment arises from inability to manage sufficient quantities efficiently, and can result in additional work hours and increased idleness. The amount of material and equipment should be gauged to maximum demand during construction to avoid the mentioned inefficiencies. The second direct factor arises from overcrowded worksite. Whenever the worksite is overcrowded, the workers get into each other’s way – causing conflict and inefficiencies.

<table>
<thead>
<tr>
<th>Division</th>
<th>Impact Factors</th>
<th>Material Technology Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Work</td>
<td>0.14 0.12 0.45 0.27</td>
<td>0.32</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.15 0.26 0.46 0.54</td>
<td>0.37</td>
</tr>
<tr>
<td>Masonry</td>
<td>0.10 0.00 0.09 0.09</td>
<td>0.17</td>
</tr>
<tr>
<td>Metals</td>
<td>0.00 0.00 0.38 0.38</td>
<td>0.18</td>
</tr>
<tr>
<td>Wood and Plastic</td>
<td>0.13 0.00 0.20 0.50</td>
<td>0.23</td>
</tr>
<tr>
<td>Thermal and Moisture Control</td>
<td>0.09 0.00 0.93 0.50</td>
<td>0.46</td>
</tr>
<tr>
<td>Doors and Windows</td>
<td>0.00 0.00 0.23 0.31</td>
<td>0.11</td>
</tr>
<tr>
<td>Finishes</td>
<td>0.01 0.00 0.18 0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>Specialties</td>
<td>0.00 0.00 0.00 0.33</td>
<td>0.07</td>
</tr>
<tr>
<td>Special Construction</td>
<td>0.00 0.00 0.33 0.33</td>
<td>0.13</td>
</tr>
<tr>
<td>Average</td>
<td>0.06 0.04 0.33 0.33</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Material and assembly characteristics themselves – such as weight, curability, technology, and modularity – are also direct factors. Workers are less physically fatigued when a material or assembly is lightweight, when compared to heavier weight items. Modularity aids in improving productivity by reducing on-site adjustments and customization, which are time consuming and impede other work from progressing. Table 5-1 shows the impact of technology on the
productivity in each subdivision of construction. Based on the numbers, technology has aided thermal and moisture control strategies and materials the most. It could also be deduced that modularization has the greatest positive impact on thermal and moisture control, concrete construction, as well as plastics.

High financial costs and associated risks also make adoption of newer products and technologies less likely. Only when the benefits are realized to outweigh the cost and risks, will adoption become an option. High costs and risks arise from a multitude of reasons, one of them is technical unreliability (Caldas et al., 2015). Technical unreliability occurs when a product or technology is complex and there is a lack of practitioners (PATH, 2002). Another reason is lack of standardizations; stemming from a combination of proprietary resources, lack of tools and materials, as well as lack of unifying code.

Additional direct factors include: delays arising from inspection, worker fatigue, worker know how and capabilities, as well as rework and changes.

5.2.2 Role of Familiarity

Familiarity has a significant impact on constructability. Its opposite – unfamiliarity and uncertainty – impedes product and method adoption. Familiar methods and products require less attention and less mental resources (Scheuer, 2007). To achieve familiarity in a product or method, certain steps must be followed. It is typically known that familiarity is achieved through knowledge and experience. That is an easy thing to say, but reaching that point is different.

The first step to adopting a product or method, is demand by the owner. This push is an incentive for the builders to learn and potentially adopt the product or method in question. Significant unknowns exist when transitioning from more traditional products and methods to
those recently available. To successfully learn, it is best to break the information into multiple parts to reduce the potential feeling of frustration (Scheuer, 2007). In doing so, the builders will absorb the information in a concrete manner. In addition, incentives should be provided. It has been found to aid in the adoption of new products and methods. New roles and responsibilities must also be defined, providing the builders with a purpose and define where their duties begin and end (PATH, 2002).

5.3 Methodology

The aim of this chapter is to analyze the level of constructability for the original wall system, traditional wood frame, and redesigns. The main reason for including the traditional wood frame is to gauge the performance of the new systems with a well-understood system. To achieve the goal; direct financial burden, assembly weight, number of sub-assemblies, potential for modularity, as well as the required education necessary to achieve familiarity are considered.

Direct financial burden is evaluated by first determining the material quantity for a unitized panel (4′x8′). With the material quantities determined, the total costs were determined from unit cost data from the R.S. Means Database. The numerical based assumptions include: waste factor (5% to 10%), 10% profit and overhead, and taxes set to 6%. The quantity take-offs and itemized costs of the wall systems can be found in Appendix E§1.1 and §1.2. What were not included are the top and bottom wood plates. The rationale behind the exclusion is that all designs shared the same top and bottom wood plates, and will not be the foreseeable determining factor.

Assessing the potential for modularity and prefabrication was achieved through reducing the number of sub-assemblies assembled on-site. The purpose here is to reduce the need for extensive education necessary to successfully assemble and place the wall systems into place.
The level of modularity and prefabrication was based on practical considerations, such as: weight of sub-assemblies and potential damage during the construction process.

### 5.4 Direct Cost Analysis

**Table 5-2, Costs of Original System and Traditional Wood Frame (per Panel)**

<table>
<thead>
<tr>
<th>Design Designation</th>
<th>Material (No Waste Factor)</th>
<th>Labor</th>
<th>Equipment</th>
<th>Total Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGWPS</td>
<td>4472</td>
<td>902</td>
<td>129</td>
<td>5779</td>
</tr>
<tr>
<td>Traditional Wood Frame (Tampa, FL)</td>
<td>166</td>
<td>291</td>
<td></td>
<td>479</td>
</tr>
<tr>
<td>Traditional Wood Frame (Washington D.C.)</td>
<td>175</td>
<td>292</td>
<td></td>
<td>490</td>
</tr>
<tr>
<td>Traditional Wood Frame (Detroit, MI)</td>
<td>180</td>
<td>331</td>
<td></td>
<td>537</td>
</tr>
</tbody>
</table>

**Table 5-3, Costs of Various Designs for Tampa, FL (per Panel)**

<table>
<thead>
<tr>
<th>Design Designation</th>
<th>Material (No Waste Factor)</th>
<th>Labor</th>
<th>Equipment</th>
<th>Total Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Gauge (1)</td>
<td>3383</td>
<td>836</td>
<td>2.5</td>
<td>4432</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>3335</td>
<td>902</td>
<td>2.0</td>
<td>4452</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td>3391</td>
<td>813</td>
<td>3.4</td>
<td>4418</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>3562</td>
<td>919</td>
<td>0.9</td>
<td>4707</td>
</tr>
</tbody>
</table>

**Table 5-4, Costs of Various Designs for Washington D.C. and Albuquerque, NM (per Panel)**

<table>
<thead>
<tr>
<th>Design Designation</th>
<th>Material (No Waste Factor)</th>
<th>Labor</th>
<th>Equipment</th>
<th>Total Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Gauge (1)</td>
<td>4331</td>
<td>956</td>
<td>4.2</td>
<td>5556</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td>4300</td>
<td>946</td>
<td>2.0</td>
<td>5511</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>4438</td>
<td>1034</td>
<td>0.9</td>
<td>5641</td>
</tr>
</tbody>
</table>
The direct cost analysis revealed several trends. From Tables 5-2 to 5-5, it can be seen that colder climates tend to yield more expensive wall assemblies – primarily arising from additional thermal insulation and thermal breaking material. Besides the thermal insulation and thermal breaks, the other significant differentiators are metallic elements – generated up to 300 USD difference between the redesign wall systems. Another trend is, the aluminum frame system is the most expensive wall assembly type of the redesigns. Overall, in all climate conditions the heavy gauge CFS wall systems are the least expensive, but are still more expensive than the traditional wood frame wall system.
When comparing the direct cost estimates with similar wall systems available on the market, the redesigns are competitive with the commercial window glazing systems – curtain walls using IGUs and storefront glazing units. The direct costs of the similar wall systems are graphed in Figure 5-1. When it comes to residential window glazing systems – casement windows, sliding glass doors –, the redesigns are at a slight disadvantage; being more expensive.

Though the traditional wood frame wall system is still significantly less expensive; there are ways, which the redesigns could become more financially competitive. One way is economies of scale, whereby the wall system is produced in significant quantities. In doing so, the raw materials costs are reduced – due to buying in bulk, which is less expensive (Alfred, 1993). Also the profit margins and overhead are lowered – without significantly reducing revenue (Ander, 2010). For economies of scale to occur, demand must be increased. This will take time to occur, because initially there is little knowledge of the system’s existence and benefits. The second way is modularization, whereby the various components are assembled into sub-assemblies for easier on-site installation. The result is lower labor associated costs (Caldas et al., 2015). As a note, the mentioned cost reduction methods were not factored into the direct cost analysis of the wall systems.

5.5 Construction Practicality Evaluation

The evaluation is primarily based on a few criterions; these include: wall dimensions – like weight –, fasteners, total number of components, and the time needed to complete a panel. In addition, the potential for prefabrication and modularity were briefly explored. Tables 5-6 to 5-8 detail the total weight of one complete panel, the total number of fasteners required, as well as the total number of components of each wall system. What could be said is that the aluminum
frame system excels in lightness, minimum number of fasteners and components, overall the redesigns and the original wall system. The aluminum frame only lags behind the wood wall in lightness, primarily due to the use of denser structural material.

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>382</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>399</td>
</tr>
<tr>
<td>Heavy Gauge</td>
<td>389</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>336</td>
</tr>
<tr>
<td>Original Wall System</td>
<td></td>
</tr>
<tr>
<td>Typical Wood Wall</td>
<td>191</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>217</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>217</td>
</tr>
<tr>
<td>Heavy Gauge</td>
<td>201</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>97</td>
</tr>
<tr>
<td>Original Wall System</td>
<td></td>
</tr>
<tr>
<td>Typical Wood Wall</td>
<td>112</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>250</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>248</td>
</tr>
<tr>
<td>Heavy Gauge</td>
<td>232</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>123</td>
</tr>
<tr>
<td>Original Wall System</td>
<td></td>
</tr>
<tr>
<td>Typical Wood Wall</td>
<td>149</td>
</tr>
</tbody>
</table>
Table 5-9, Number of Days for a 4’x8’ Unit to be Completed by a Crew

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>0.49</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>0.49</td>
</tr>
<tr>
<td>Heavy Gauge</td>
<td>0.49</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>0.49</td>
</tr>
<tr>
<td>Original Wall System</td>
<td></td>
</tr>
<tr>
<td>Typical Wood Wall</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Before considering prefabrication of the wall systems, the number of laborers required to complete 100 units were determined. Table 5-9 indicates that both light gauge and heavy gauge CFS require less time for approximately similar crews to complete in a day, when compared to other redesigns. What will be said, however, is that both the typical wood wall and original wall system require less time than the redesigns. A reason is the complexity of the redesigns – which generally has greater number of components and fasteners. The other reason is the use of materials less commonly found in residential construction – like CFS and PC.
Figure 5-3, Wall Modularization using Glazing, Sheathing, and Structural Frame Wall Units

Figure 5-4, Whole Panel Prefabrication
Installation of two units per day – for the redesigns – in its present form is slow. One way to increase the productivity is prefabricating and assembling the components into sub-assemblies at the factory. Based on the literature review, prefabrication is the end goal for the designed systems. Primarily because it reduces the amount of time on the field installing the system, as well as the ease in maintaining a high level of quality of control at the factory – when compared to on-site. The different numbers of potential sub-assemblies are shown in Figures 5-2 to 5-4. Each level of prefabrication – depends on the number of sub-assemblies – is limited by a certain

### Table 5-10, Limiting Productivity Rate for Two Sub-Assemblies per Panel

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Productivity Limiting Component</th>
<th>Limiting Rate (Days to Complete Panel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Bolts and washers securing top track to wood top plate</td>
<td>0.017</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>Bolts and washers securing top track to wood top plate</td>
<td>0.017</td>
</tr>
<tr>
<td>Heavy Gauge</td>
<td>Bolts and washers securing top track to wood top plate</td>
<td>0.017</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>Securing glazing panel to structural frame and PC</td>
<td>0.029</td>
</tr>
</tbody>
</table>

### Table 5-11, Limiting Productivity Rate for Three Sub-Assemblies per Panel

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Productivity Limiting Component</th>
<th>Limiting Rate (Days to Complete Panel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Screws securing PC sheathing to the structural frame</td>
<td>0.53</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td>Screws securing PC sheathing to the structural frame</td>
<td>0.53</td>
</tr>
<tr>
<td>Heavy Gauge</td>
<td>Screws securing PC sheathing to the structural frame</td>
<td>0.53</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td>Screws securing PC sheathing to the structural frame</td>
<td>0.29</td>
</tr>
</tbody>
</table>
task, and is shown in Tables 5-10 and 5-11. The tables show that reducing the number of connections and parts, which need to be assembled on-site, thus speeds up the installation process to approximately a maximum of sixty per day. Fasteners like screws and bolts are the main culprit for reducing productivity on-site – even with current power tools –, and is the reason for the two sub-assembly prefabrication having a greater productivity rate than the three sub-assembly prefabrication. The sixty panels a day limit is only limited by the connection process between the sub-assemblies and to the floor system. For the aluminum frame system this is less, at approximately 34 panels. What is not considered is the numerical impact of weight and panel dimensions on the productivity. This can only be done with real world testing and physical construction of the wall systems – which is beyond the scope of this thesis.

There is a potential for greater prefabrication, where the entire panel is completed at the factory. This level of prefabrication was not chosen because the glass glazing could easily be damaged during the early construction phases and heavy weight. Avoiding these downsides is doable but incurs losses in productivity arising from greater level of quality control and laborer tiredness. It was settled that the redesigns should be prefabricated to two sub-assemblies – one is the glazing unit, and the other is the structure. The structure sub-assembly includes the structural frame, PC sheathing, and thermal insulation. During construction the structure would be assembled first, only when the building is nearly completed will the glazing unit be installed and fastened to the structure sub-assembly.

Once modularization and prefabrication is considered and implemented, then greater construction productivity and reduced on-site labor costs can be realized. The potential is paramount and was accessed by assembling majority of the wall system into sub-assemblies for better handling, damage control, and reduce on-site installation time. The greatest reduction on
components requiring on-site assembly had the greatest modularization and prefabrication potential. Modularization and prefabrication may bring benefits, but it also presents difficulties. For one, the wall specifications will have to be completed in advance – before sending it to the fabricator. Mistakes and changes will be expensive, because on-site modification is nearly impossible and the wall panels will have to be sent back to the fabricator. Table 5-12 entails what must be learned for successful implementation of the redesigns.

<table>
<thead>
<tr>
<th>Necessary Knowledge and Skills</th>
<th>Wall Design</th>
<th>CFS</th>
<th>Aluminum Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Material handling</td>
<td></td>
<td></td>
<td>- Material characteristics and response to loads</td>
</tr>
<tr>
<td>- Response to moisture</td>
<td></td>
<td></td>
<td>- Compatibility of fasteners</td>
</tr>
<tr>
<td>- Elemental weaknesses</td>
<td></td>
<td></td>
<td>- Compatibility with other materials</td>
</tr>
<tr>
<td>(flanges and webs)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Permissible hole dimensions and locations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Fastening methods</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the lightness, modularization and prefabrication potential, as well as the number of fasteners, the aluminum frame design is easier to construct. In this system the only assembly required does not require specialized material and fastening knowledge – when compared to the CFS systems and original wall system.

5.6 Conclusions

The results showed that the wood frame system commonly found in residences is still more financially affordable at 1/8 the cost, a minimum of 75% lighter, and more easily constructed than the wall redesigns and the original wall system (RGWPS). However, progress has been made, whereby the redesigns are at least 31% less expensive and 50% lighter than the original wall system. Of all the redesigns, the aluminum frame excels the most in lightness, number of
components, and potential for prefabrication. The aluminum frame system is not without its faults; it is more expensive to construct – arising from material selected –, takes longer to assemble a whole panel – if prefabrication is not considered. Based on the higher productivity rates – when compared to all work done on-site – and constant quality control, prefabrication is recommended for the redesigns. Let it be said that the systems analyzed were in regions where wind loads control lateral loads over seismic loads. Should these designs be adopted to more seismically active regions then the current constructability analysis may not yield the same results. Therefore, a new constructability analysis must be implemented.

Due to the scope of the thesis – which lacks lab and field verifications – it is suggested that future studies explore strategies and more specific design verification, like surveys and hands-on experience.
Chapter 6

Summary and Conclusions

The intent of this study is to create a more practical transparent PC sheathing wall system that will promote viable adoption of sustainable technologies and practices in residences. The original concept was developed as a transparent load-bearing wall system that can be used as an alternative to conventional wood-frame system. One reason for comparison of the RGWPS and the alternatives developed here is to compare conventional wood-framed systems to gauge the performance of these new systems with respect to a well-understood system. As a note, this study is a follow-on of the thesis – Development of a Transparent Sustainable Wall System with Load Bearing Back-Up Framing for Residential Construction – done by Standley (2009). To fulfill the intent, this study had three objectives, which include: consideration of building science design, structural design, and constructability in developing new alternatives.

The first part of the study was designing the wall system to satisfy building science requirements. Here the physical impacts on the built environment were studied, which include: condensation formation and moisture control, the impact of climate, and comfort. The first task was to determine the minimum insulation needed, based on 2012 IRC §N1102.1.3. Then the climate data and interior conditions for comfort were gathered. This was done for the cities exemplifying the four prevalent climate zones. Thirdly, the preliminary designs were formulated considering the required insulation thickness. After determining that condensation occurs no deeper than the exterior face of the structural PC sheathing and that the material at the condensation plane would not degrade with the presence of condensation, then the three preliminary designs were modeled using THERM to determine effective thermal breaking strategies. The last step in
the first part of the study involved final designs, THERM simulation, as well as light transmission and acoustical attenuation evaluations.

Table 6-1 summarizes the results of the building science component of this study. From the R-Value at the frame, the thermal performance of the redesigns are at least six times that of the RGWPS – which had approximately 1.1 R-Value. Of all the redesigns the aluminum frame system has the best thermal performance, primarily, due to the use of structural thermal breaks in the wall cavity and limited fasteners penetrating through the wall system. For light transmission acceptability based on 2012 IRC, which would require 30% light transmission for a tinted window, the designs will be acceptable if we think of the translucent insulation as a type of tint.

<table>
<thead>
<tr>
<th>Wall Design</th>
<th>City</th>
<th>R-Value (Frame)</th>
<th>Daylight Transmission</th>
<th>Sound Transmission Coefficient (STC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Gauge (1)</td>
<td>Tampa, FL</td>
<td>7.5</td>
<td>50%</td>
<td>42</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td></td>
<td>7.8</td>
<td>50%</td>
<td>42</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>7.5</td>
<td>50%</td>
<td>42</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>11.2</td>
<td>50%</td>
<td>42</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Washington D.C.;</td>
<td>8.1</td>
<td>~10%</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Albuquerque, NM;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Detroit, MI</td>
<td>7.8</td>
<td>~10%</td>
<td>42</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>13.4</td>
<td>~10%</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wall Design</th>
<th>City</th>
<th>Total Embodied Energy (MJ)</th>
<th>Quantity Method</th>
<th>ATHENA Impact Estimator</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGWPS</td>
<td></td>
<td>7632</td>
<td>224960</td>
<td></td>
</tr>
<tr>
<td>Traditional Wood Frame</td>
<td></td>
<td>1460</td>
<td>189550</td>
<td></td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Tampa, FL</td>
<td>10467</td>
<td>205200</td>
<td></td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td></td>
<td>9817</td>
<td>211410</td>
<td></td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>10570</td>
<td>205430</td>
<td></td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>10534</td>
<td>226050</td>
<td></td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Washington D.C.;</td>
<td>9887</td>
<td>202810</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Albuquerque, NM;</td>
<td>9772</td>
<td>201700</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9709</td>
<td>219440</td>
<td></td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>8928</td>
<td>200090</td>
<td></td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Detroit, MI</td>
<td>8812</td>
<td>200980</td>
<td></td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>10506</td>
<td>220250</td>
<td></td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sustainability for the designed transparent wall systems was then evaluated. To evaluate sustainability, the study calculates the embodied energy of each wall system. Two methods were used, specifically ATHENA Impact Estimator and the quantity method. First, quantity take-offs were done for a 4ft by 8ft panel of each wall system. Since the materials in ATHENA Impact Estimator are predefined and cannot easily be modified, material not available in the databases were substituted with an alternate. For the quantity method, the embodied energy data for each material was attained from published sources like the Inventory of Carbon & Energy (ICE) by Hammond and Jones (2008). Next, the annual energy consumption for each wall system was calculated by interpolating available data on the RGWPS and traditional wood frame wall systems – dependent upon R-Value. Table 6-2 details the total embodied energy of the wall systems, as well as the baselines. It will be noticed that the ATHENA results are significantly greater than those of the quantitative method. The reason is the consideration of recycling for the quantitative method, while ATHENA does not. Even though the magnitudes are different, the trends are similar. The aluminum frame design has the greatest embodied energy of all the redesigns and RGWPS, despite superior thermal performance. Also in cold climates, the results show that the heavy gauge (1) design has the least environmental impact of all the redesigns.

The third part of the study is the structural design. Here the structural steel tubing is replaced with cold formed steel (CFS) and aluminum framing members. The scope of this section involves structural member selection. First, a realistic design, a typical home in central Pennsylvania was selected to apply structural loads based on ACSE 7-10, i.e., the gravity and lateral loads acting on the building. Then the loads acting on the designed wall panel members were determined. Onwards, the minimum member size – like minimum required moment of inertia and section modulus – were determined from back calculating the global strength equations in ADM 2010 and
AISI 100-07. The last step was checking the potential structural members for localized failures – such as lateral torsional buckling (LTB) and distortional buckling. With the structural members selected, only then can constructability be evaluated.

Table 6-3, Results of Constructability Evaluation of a 4x8 Panel

<table>
<thead>
<tr>
<th>Wall Design</th>
<th>City</th>
<th>Total Cost (USD)</th>
<th>Total Weight (lb)</th>
<th>Total Number of Fasteners</th>
<th>Total Number of Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGWPS</td>
<td></td>
<td>5779</td>
<td>825</td>
<td>127</td>
<td>144</td>
</tr>
<tr>
<td>Traditional Wood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Tampa, FL</td>
<td>4432</td>
<td>382</td>
<td>217</td>
<td>250</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td></td>
<td>4452</td>
<td>399</td>
<td>217</td>
<td>248</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>4418</td>
<td>389</td>
<td>201</td>
<td>232</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>4707</td>
<td>336</td>
<td>97</td>
<td>123</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Washington D.C.;</td>
<td>5556</td>
<td>390</td>
<td>177</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>Albuquerque, NM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Detroit, MI</td>
<td>6554</td>
<td>387</td>
<td>161</td>
<td>192</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>6587</td>
<td>400</td>
<td>177</td>
<td>208</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>6768</td>
<td>358</td>
<td>85</td>
<td>112</td>
</tr>
</tbody>
</table>

Table 6-4, Limiting Productivity Rate (Number of Days to Complete 4x8 Panel)

<table>
<thead>
<tr>
<th>Wall Design</th>
<th>City</th>
<th>100% On-Site Assembly</th>
<th>Two Sub-Assemblies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Gauge (1)</td>
<td>Tampa, FL</td>
<td>0.49</td>
<td>0.017</td>
</tr>
<tr>
<td>Light Gauge (2)</td>
<td></td>
<td>0.49</td>
<td>0.017</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>0.49</td>
<td>0.017</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>0.49</td>
<td>0.029</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Washington D.C.;</td>
<td>0.49</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>Albuquerque, NM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>0.49</td>
<td>0.017</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>0.49</td>
<td>0.029</td>
</tr>
<tr>
<td>Light Gauge (1)</td>
<td>Detroit, MI</td>
<td>0.49</td>
<td>0.017</td>
</tr>
<tr>
<td>Heavy Gauge (1)</td>
<td></td>
<td>0.49</td>
<td>0.017</td>
</tr>
<tr>
<td>Aluminum Frame</td>
<td></td>
<td>0.49</td>
<td>0.029</td>
</tr>
</tbody>
</table>

Lastly, the wall designs were evaluated for constructability. Direct construction cost was first determined by using the 2014 R.S. Means unit cost data and the quantity take-offs. The total cost of each wall system is shown in Table 6-3. Second, the ease of construction was measured through
total 4ft by 8ft wall panel weight, total number of connections, and the total number of components. In addition, prefabrication was studied and Table 6-4 shows the increase in productivity. The calculated productivity is based on 2014 R.S. Means labor productivity rates. Prefabrication was studied because available literature shows that assembling the wall panels completely on-site cuts down on productivity and that constant quality control is harder to achieve, when compared to factory manufacture. Based on Table 6-3, the heavy gauge CFS wall design studied is at least 31% less expensive than the RGWPS and only 8% heavier than the aluminum frame design. When looking at Table 6-4, it is evident that prefabrication increases the productivity by nearly 16 times greater than 100% on-site assembly. As a result, prefabrication is the preferred construction method.

When the results of the study are brought together it is evident that the design using heavy gauge CFS excels in locations with cool, mixed-humid, and hot-dry climates. This is especially true when looking at the system’s embodied energy, total construction cost, and prefabrication. As for warmer and more humid climates, the aluminum frame design performs better than the redesigns and RGWPS – when the corrosion resistance and constructability are considered. However, one fact remains, the traditional wood frame wall system is still dominant in thermal performance and constructability. The thermal performance of the traditional wood frame system meets code requirements, while the redesigns merely approach it. The main reason is originally designing the wall systems to compete with a different benchmark – RGWPS. Improvements of the redesigns over the original system (RGWPS) – evident from the tabulated results – showed that progress is achievable and that the redesigns can be developed to approach the competitiveness of the predominant residential wall system – traditional wood frame.
6.1 Suggestions for Future Study

The work done for this thesis is merely a step and in no way an end to improving the adaption of sustainable technologies and practices in the residential sector. Much more needs to be done, and below are some suggestions for further exploration in the future:

1. Short and long-term environmental impact of aerogel production, installation, recycling potential, and eventual end-of-life disposal.

2. Lab and field verification on the impact of prefabricated wall panel’s physical dimensions and weight on construction productivity, with eventual numerical equation formulation to determine the mentioned impacts on construction productivity.

3. Experimental determination and verification of light transmissibility through various thicknesses of translucent and transparent thermal insulation, ending in formulation of accessible light transmissibility equations per given material and thickness.

4. Explore the use of wood frame in the transparent sheathing wall system to improve thermal performance, constructability.

5. Design a transparent sheathing PC wall system for more seismically active zones and evaluate the impact on building science and constructability.

6. Whether incorporating photovoltaic elements into the redesigns are advantageous, and what are the constraints.

7. Evaluate where the transparent residential wall system fits into the current architectural trends and its potential impact on architecture.
Appendix A

Preliminary Building Science Calculations

A.1 Required Thermal Insulation

<table>
<thead>
<tr>
<th>City</th>
<th>IRC 2012 Climate Zone</th>
<th>Required R-Value (hr-ft²-°F/BTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>2</td>
<td>12.2</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>4</td>
<td>17.5</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>6</td>
<td>20.8</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>3</td>
<td>17.5</td>
</tr>
</tbody>
</table>
A. Required Insulation Thk

1. Cellular Pu

\[ K = 0.16 \text{ BTU-in}/(\text{hr-ft}^2-\text{F}) \]

\[ T = K \cdot R_{req} \]

\[ T_{ripo} = 0.16 \times 12.2 \]

\[ T_{ripo} = 3.18 \text{ in} \]

\[ T_{sc} = 0.16 \times 17.5 \]

\[ T_{sc} = 4.57 \text{ in} \]

\[ T_{geom} = 0.16 \times 20.8 \]

\[ T_{geom} = 3.33 \text{ in} \]

\[ T_{Alb} = 0.16 \times 17.5 \]

\[ T_{Alb} = 4.57 \text{ in} \]

2. FRP

\[ K = 2.776 \text{ BTU-in}/(\text{hr-ft}^2-\text{F}) \]

***Req. thk are shown in the following Table, calc. in similar manner as above

3. Granular Aerogel

\[ K = 0.125 \text{ BTU-in}/(\text{hr-ft}^2-\text{F}) \]

***Req. thk are shown in the following Table, calc. in similar manner as above

4. Monolithic Aerogel

\[ K = 0.018 \text{ BTU-in}/(\text{hr-ft}^2-\text{F}) \]

***Req. thk are shown in the following Table, calc. in similar manner as above
A.2 Thermal Performance and Condensation Potential

A.2.1 Wall Assemblies in Tampa, FL

A.2.1.1 CFS
B. Total \( R \) and \( R_{v} \) for Walls

1. Tampa, FL

a) CF:

- Stud spacing 16"
- Aluminum frame spacing 48"

i) Monolithic Float Glass w/ Cellular PC (Assembly I)

\[
R = \frac{\text{Total spacing between studs} \times \text{Panel Width}}{\text{Panel Width}} + \frac{\text{wall thickness} \times \text{Panel Width}}{\text{Panel Width}}
\]

\[
R = \frac{44}{48} a (0.24 + 12.32 + 0.32) + \frac{4}{48} a (0.001 + \frac{0.325}{2} + 0.32)
\]

\[R = 11.7 \text{ h}-\Omega\text{-F/FTU}
\]

Assume moisture can penetrate all impermeable elements.

\[R_v = \frac{2}{3} R_w
\]

\[R_v = 2.32 + 0.36
\]

\[R_v = 2.7
\]

ii) Monolithic Float Glass w/ Granular Aerogel (Assembly II)

\[
R = \frac{44}{48} a (0.24 + 13.00 + 0.32) + \frac{4}{48} a (0.001 + \frac{1.65}{2} + 0.32)
\]

\[R = 12.3 \text{ h}-\Omega\text{-F/FTU}
\]

\[R_v = 1.67 + 0.36
\]

\[R_v = 1.93
\]

iii) Monolithic Float Glass w/ Monolithic Aerogel (Assembly III)

\[
R = \frac{44}{48} a (0.24 + 13.00 + 0.32) + \frac{4}{48} a (0.001 + \frac{0.38}{2} + 0.32)
\]

\[R = 12.7 \text{ h}-\Omega\text{-F/FTU}
\]

\[R_v = 0.15 + 0.36
\]

\[R_v = 0.51
\]
4) $\delta U$ w/ $2.74$ Cellular PL (Assembly #)

$$R = \frac{\delta U}{Q} = \frac{1}{R_\delta} \left( (2.083 + 12.324 \times \frac{0.001}{0.73} + 0.327) + \frac{1}{R_\delta} (2.083 + 0.001 \times \frac{0.001}{2} + 0.327) \right)$$

$$R = 12.1 \text{ hr}^2 \cdot \text{F} / \text{BTU}$$

$$R_v = 2.32 + 0.36$$

$$R_v = 2.7$$

C. Temperature Gradient Across Assembly

1. Assembly 1

a) Winter

1) High

$$T_{int} = 70^\circ\text{F}$$

$$T_{int} = 72^\circ\text{F}$$

$$T_1 = T_{int}$$

$$T_2 = T_{int}$$

$$T_3 = \frac{R_1}{\sum R_i} \left| (T_1 - T_2) \right| + T_2$$

$$T_3 = 0.002 \left| (70 - 70) \right| + 70$$

$$T_3 = 70.002^\circ\text{F}$$

$$T_3 = \frac{R_2}{\sum R_i} \left| (T_1 - T_2) \right| + T_2$$

$$T_3 = 0.97 \left| (70.004 - 72) \right| + 70.004$$

$$T_3 = 71.9^\circ\text{F}$$

2) Low

$$T_{int} = 52^\circ\text{F}$$

$$T_{int} = 72^\circ\text{F}$$

$$T_1 = 72^\circ\text{F}$$

$$T_1 = 72^\circ\text{F}$$

$$T_3 = 0.002 \left| (52 - 72) \right| + 72$$

$$T_3 = 52.004^\circ\text{F}$$

$$T_3 = 0.97 \left| (52.04 - 72) \right| + 52.04$$

$$T_3 = 71.3^\circ\text{F}$$
b) Summer

1) High

\[ T_{ext} = 91^\circ F \]
\[ T_{in} = 75^\circ F \]
\[ T_2 = 0.002 \times (75 - 91) + 91 \]
\[ T_2 = 90.97^\circ F \]
\[ T_3 = 0.97 \times (75 - 91) + 90.97 \]
\[ T_3 = 75.4^\circ F \]

2) Low

\[ T_{ext} = 79^\circ F \]
\[ T_{in} = 75^\circ F \]
\[ T_2 = 0.002 \times (75 - 79) + 79 \]
\[ T_2 = 79.002^\circ F \]
\[ T_3 = 0.97 \times (75 - 79) + 79.002 \]
\[ T_3 = 79.17^\circ F \]
### Table A-2, Temperature Gradient Across Assembly 2

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>R_i/R</th>
<th>Winter</th>
<th></th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>70.0</td>
<td>52.0</td>
<td>91.0</td>
</tr>
<tr>
<td>2</td>
<td>0.971</td>
<td>71.9</td>
<td>71.5</td>
<td>75.4</td>
</tr>
<tr>
<td>3</td>
<td>0.027</td>
<td>72.0</td>
<td>72.0</td>
<td>75.0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>72</td>
<td>72</td>
<td>75</td>
</tr>
</tbody>
</table>

### Table A-3, Temperature Gradient Across Assembly 3

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>R_i/R</th>
<th>Winter</th>
<th></th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>70.0</td>
<td>52.0</td>
<td>91.0</td>
</tr>
<tr>
<td>2</td>
<td>0.972</td>
<td>71.9</td>
<td>71.5</td>
<td>75.4</td>
</tr>
<tr>
<td>3</td>
<td>0.026</td>
<td>72.0</td>
<td>72.0</td>
<td>75.0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>72</td>
<td>72</td>
<td>75</td>
</tr>
</tbody>
</table>

### Table A-4, Temperature Gradient Across Assembly 4

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>R_i/R</th>
<th>Winter</th>
<th></th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.174</td>
<td>70.3</td>
<td>55.5</td>
<td>88.2</td>
</tr>
<tr>
<td>2</td>
<td>0.799</td>
<td>71.9</td>
<td>71.5</td>
<td>75.4</td>
</tr>
<tr>
<td>3</td>
<td>0.027</td>
<td>72.0</td>
<td>72.0</td>
<td>75.0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>72</td>
<td>72</td>
<td>75</td>
</tr>
</tbody>
</table>
D. RH Distribution Across Assembly

1. Assembly 1

\[ \text{All Temperatures in } ^{\circ}F \text{ must be converted to Kelvin} \]
\[ P_{\text{sat},1} = 1000 \text{C} \]
\[ P_{\text{ext}} = P_{\text{sat},1} \times \text{Exterior RH} \]
\[ P_{\text{int}} = P_{\text{sat},1} \times \text{Interior RH} \]
\[ P_{j} = \left( P_{\text{int}} - P_{\text{ext}} \right) \times \frac{R_{j}}{\sum R_{i}} + P_{\text{sat},1} \]
\[ P_{j} = \left( P_{\text{int}} - P_{\text{ext}} \right) \times \frac{R_{j}}{\sum R_{i}} + P_{\text{sat},1} \]

a) Winter

i) High

\[ P_{\text{sat},1} = 1000 \text{C} \]
\[ P_{\text{sat},1} = 2515 \text{ Pa} \]
\[ P_{\text{sat},1} = 1000 \text{C} \]
\[ P_{\text{sat},1} = 2696 \text{ Pa} \]
\[ RH_{\text{ext}} = 100\% \]
\[ RH_{\text{int}} = 50\% \]
\[ P_{j} = 2514 \text{ Pa} \]
\[ P_{j} = \left( 1315 - 2514 \right) \times 0.57 + 2514 \]
\[ P_{j} = 1501 \text{ Pa} \]
\[ RH_{\text{ext}} = \frac{2514}{2515} = 99.6\% \]
\[ RH_{\text{int}} = \frac{1501}{2696} = 55.9\% \]
2) Low
\[
\begin{align*}
P_{\text{Sat, low}} &= 1000 \text{ Pa} \\
P_{\text{Sat, low}} &= 1331 \text{ Pa} \\
P_{\text{Sat, low}} &= 1000 \text{ Pa} \\
P_{\text{Sat, low}} &= 2640 \text{ Pa} \\
P_1 &= 1329 \text{ Pa} \\
P_3 &= (1345 - 1519) \times 0.87 + 1329 \\
P_3 &= 1543 \text{ Pa} \\
RH_2 &= 1329 / 1331 \\
RH_2 &= 99.87\% \\
RH_3 &= 1543 / 1670 \\
RH_3 &= 50.97\% \\
\end{align*}
\]

b) Summer

3) High
\[
\begin{align*}
P_{\text{Sat, high}} &= 1000 \text{ Pa} \\
P_{\text{Sat, high}} &= 4980 \text{ Pa} \\
P_{\text{Sat, high}} &= 1000 \text{ Pa} \\
P_{\text{Sat, high}} &= 3021 \text{ Pa} \\
P_3 &= 4986 \text{ Pa} \\
P_3 &= (4988 - 4986) \times 0.87 + 4986 \\
P_3 &= 4954 \text{ Pa} \\
RH_2 &= 4986 / 4986 \\
RH_2 &= 100.0\% \\
RH_3 &= 1954 / 3021 \\
RH_3 &= 64.77\% \\
\end{align*}
\]
2) Low

\[ P_{\text{atm,1}} = 1000 \text{ Pa} \]
\[ P_{\text{atm,2}} = 2878 \text{ Pa} \]
\[ P_{\text{atm,3}} = 1000 \text{ Pa} \]
\[ P_{\text{atm,4}} = 2973 \text{ Pa} \]

\[ P_2 = 2878 \text{ Pa} \]

\[ P_3 = (2973 - 2878) \times 0.87 + 2978 \]

\[ P_3 = 1673 \text{ Pa} \]

\[ \text{RH}_2 = \frac{2878}{2978} \]
\[ \text{RH}_2 = 100 \% \]

\[ \text{RH}_3 = \frac{1673}{2973} \]
\[ \text{RH}_3 = 56.3 \% \]
Table A-5, RH Distribution across Wall Assembly

### Relative Humidity Distribution Across Assembly 2 (100% Exterior RH)

<table>
<thead>
<tr>
<th>Layer</th>
<th>$R_w$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>205.4</td>
<td>284.3</td>
<td>305.9</td>
<td>256.5</td>
<td>2514</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>295.4</td>
<td>253.1</td>
<td>297.0</td>
<td>2514</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>295.4</td>
<td>253.1</td>
<td>297.0</td>
<td>2514</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

### Relative Humidity Distribution Across Assembly 3 (100% Exterior RH)

<table>
<thead>
<tr>
<th>Layer</th>
<th>$R_w$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>205.4</td>
<td>284.3</td>
<td>305.9</td>
<td>256.5</td>
<td>2514</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>295.4</td>
<td>253.1</td>
<td>297.0</td>
<td>2514</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>295.4</td>
<td>253.1</td>
<td>297.0</td>
<td>2514</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

### Relative Humidity Distribution Across Assembly 4 (100% Exterior RH)

<table>
<thead>
<tr>
<th>Layer</th>
<th>$R_w$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>205.4</td>
<td>284.3</td>
<td>305.9</td>
<td>256.5</td>
<td>2514</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>295.4</td>
<td>253.1</td>
<td>297.0</td>
<td>2514</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>295.4</td>
<td>253.1</td>
<td>297.0</td>
<td>2514</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
### A.2.1.2 Aluminum Frame

#### Table A-6, R-Value of Wall Components

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$C = \frac{K}{L}$</th>
<th>$R_i = \frac{1}{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.13</td>
<td>34.88</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>IGU</td>
<td></td>
<td>0.30</td>
<td>2.083</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.50</td>
<td>2776.00</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>3.25</td>
<td>0.08</td>
<td>1.776</td>
</tr>
<tr>
<td></td>
<td>Granular Aerogel</td>
<td>1.63</td>
<td>0.08</td>
<td>1.874</td>
</tr>
<tr>
<td></td>
<td>Monolithic Aerogel</td>
<td>0.38</td>
<td>0.07</td>
<td>1.946</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>2.00</td>
<td>694.00</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
<td>4</td>
<td>Still Air</td>
<td>2.50</td>
<td>0.07</td>
<td>2.163</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>2.50</td>
<td>555.20</td>
<td>0.000</td>
</tr>
</tbody>
</table>

#### Table A-7, $R_v$-Value of Wall Components

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$\mu/T$</th>
<th>$R_{vi} = 1/\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.13</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>IGU</td>
<td></td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.50</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
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173
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<th>Description</th>
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<th>Total Rᵥ-Value</th>
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<td>Monolithic Float Glass w/ Cellular PC</td>
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Table A-9, RH Distribution across Wall Assemblies for the Aluminum Frame Design

### Relative Humidity Distribution Across Assembly 1 (100% Exterior RH)

<table>
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<th>Layer Interface</th>
<th>$R_v/R_e$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>High Low</td>
<td>High Low</td>
<td>High Low</td>
</tr>
<tr>
<td>1</td>
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<td>305.9 296.5</td>
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<td>4016 2878</td>
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<tr>
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<td>204.3 284.3</td>
<td>305.9 296.5</td>
<td>2515 1331</td>
<td>4018 2879</td>
</tr>
<tr>
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<td>297.3 297.0</td>
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<td>3020 2793</td>
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<td>2976 2976</td>
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<tr>
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<td>2976 2976</td>
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### Relative Humidity Distribution Across Assembly 2 (100% Exterior RH)

<table>
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<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>High Low</td>
<td>High Low</td>
<td>High Low</td>
</tr>
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<td>305.9 296.5</td>
<td>2514 1329</td>
<td>4016 2878</td>
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<td>305.9 296.5</td>
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<td>2691 2691</td>
<td>2976 2976</td>
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### Relative Humidity Distribution Across Assembly 3 (100% Exterior RH)

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<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
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</thead>
<tbody>
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<td>Winter</td>
<td>Summer</td>
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<td></td>
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<td>High Low</td>
<td>High Low</td>
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<td>4016 2878</td>
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<td>2976 2976</td>
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### Relative Humidity Distribution Across Assembly 4 (100% Exterior RH)

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<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Low</td>
<td>High Low</td>
<td>High Low</td>
<td>High Low</td>
</tr>
<tr>
<td>1</td>
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<td>204.3 284.3</td>
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<td>4016 2878</td>
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A.2.2 Wall Assemblies in Washington, D.C.

A.2.2.1 CFS

Table A-10, R-Value of Wall Components

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<th>Layer Interface</th>
<th>Material</th>
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<th>M = μ/T</th>
<th>Rvi = 1/M</th>
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<td>IGU</td>
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Table A-11, Rv-Value of Wall Components

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<td>Steel</td>
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<td>Description</td>
<td>Total R-Value (h·ft²·°F/Btu)</td>
<td>Total Rₐ-Value</td>
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<td>-------------------------------------------------------</td>
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Table A-13, RH Distribution across Wall Assemblies for the CFS Design

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<td>295.4</td>
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<td>0.91</td>
<td>295.4</td>
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<td>0.91</td>
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<table>
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</tr>
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<td>Winter</td>
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<td>0.00</td>
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<tr>
<td>2</td>
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<td>279.3</td>
</tr>
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<td>0.91</td>
<td>295.4</td>
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<table>
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</tr>
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<td>279.3</td>
</tr>
<tr>
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<table>
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<td>0.91</td>
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### A.2.2.2 Aluminum Frame

#### Table A-14, R-Value of Wall Components

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<td>0.000</td>
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<td>Cellular PC</td>
<td>4.75</td>
<td>0.06</td>
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<tr>
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<td>Granular Aerogel</td>
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<td>0.06</td>
<td>2.595</td>
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<td>PC</td>
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#### Table A-15, $R_v$-Value of Wall Components

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<th>$R_{vi} = 1/M$</th>
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<td>Granular Aerogel</td>
<td>2.25</td>
<td>0.68</td>
<td>1.48</td>
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<td>3.04</td>
<td>0.33</td>
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<tr>
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Table A-17, RH Distribution across Wall Assemblies for the Aluminum Frame Design

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<th>RH (%)</th>
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### A.2.3 Wall Assemblies in Albuquerque, NM

#### A.2.3.1 CFS

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<td>Total $R_v$-Value</td>
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Table A-21, RH Distribution across Wall Assemblies for the CFS Design

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### A.2.3.2 Aluminum Frame

#### Table A-22, R-Value of Wall Components

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#### Table A-23, $R_v$-Value of Wall Components

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<td>Aluminum</td>
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<td></td>
<td>$\infty$</td>
</tr>
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<td></td>
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<tr>
<td>Designation</td>
<td>Description</td>
<td>Total R-Value (h-ft²·°F/Btu)</td>
<td>Total $R_v$-Value</td>
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<td>--------------------------------------------</td>
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<tr>
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<td>Monolithic Float Glass w/ Cellular PC</td>
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<td>3.8</td>
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</tr>
<tr>
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<td>Monolithic Float Glass w/ Granular Aerogel Cellular PC</td>
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<td>1.8</td>
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</tr>
<tr>
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<td>IGU w/ 4-1/4&quot; Cellular PC</td>
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Table A-25, RH Distribution across Wall Assemblies for the Aluminum Frame Design

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<tr>
<th>Layer Interface</th>
<th>R_in/R_out</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Winter</td>
<td>Low</td>
<td>High</td>
<td>Summer</td>
</tr>
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<td>1</td>
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<td>281.5</td>
<td>269.8</td>
<td>305.4</td>
<td>292.6</td>
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<tr>
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<td>281.5</td>
<td>269.9</td>
<td>305.4</td>
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## A.2.4 Wall Assemblies in Detroit, MI

### A.2.4.1 CFS

#### Table A-26, R-Value of Wall Components

<table>
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<th>Layer Interface</th>
<th>Material</th>
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<th>C = K/L</th>
<th>R_i = 1/C</th>
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<td>1</td>
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<td>IGU</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.50</td>
<td>2776.00</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>5.50</td>
<td>0.05</td>
<td>3.005</td>
</tr>
<tr>
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<td>0.04</td>
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<td>0.000</td>
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<td>PC</td>
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<td>0.047</td>
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<td>0.05</td>
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#### Table A-27, R_v-Value of Wall Components

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<th>R_vi = 1/M</th>
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<td>∞</td>
</tr>
<tr>
<td></td>
<td>IGU</td>
<td></td>
<td></td>
<td>∞</td>
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<td></td>
<td>Aluminum</td>
<td>0.50</td>
<td></td>
<td>∞</td>
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<td>Cellular PC</td>
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<td>PC</td>
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<td></td>
<td>0</td>
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<tr>
<td></td>
<td>Steel</td>
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<td>∞</td>
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Table A-28, R and $R_v$ Values of Various Wall Assemblies for the CFS Design

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<th>Total R-Value (h-ft²·°F/Btu)</th>
<th>Total $R_v$-Value</th>
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</thead>
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<tr>
<td>1</td>
<td>Monolithic Float Glass w/ Cellular PC</td>
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</tr>
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<td></td>
<td>Cellular PC</td>
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<td></td>
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<td>0.8</td>
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<td>4</td>
<td>IGU w/ 5&quot; Cellular PC</td>
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Table A-29, RH Distribution across Wall Assemblies for the CFS Design

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<th>Layer Interface</th>
<th>Relative Humidity Distribution Across Assembly 1 (100% Exterior RH)</th>
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<td>Temperature (K)</td>
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<tr>
<td></td>
<td>High</td>
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<tr>
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<tr>
<td>2</td>
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<tr>
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<tr>
<td>4</td>
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<table>
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<td>Temperature (K)</td>
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<table>
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<tr>
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<td>High</td>
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<tr>
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<th>Relative Humidity Distribution Across Assembly 4 (100% Exterior RH)</th>
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### A.2.4.2 Aluminum Frame

#### Table A-30, R-Value of Wall Components

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<th>R_i = 1/C</th>
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<td>0.000</td>
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#### Table A-31, R_v-Value of Wall Components

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<th>M = μ/T</th>
<th>R_v = 1/M</th>
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<td>IGU</td>
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<td>∞</td>
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<td>Aluminum</td>
<td>0.50</td>
<td></td>
<td></td>
<td>∞</td>
</tr>
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</tr>
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<td>Description</td>
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<td>Total Rᵥ-Value</td>
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<td>4.3</td>
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</table>
Table A-33, RH Distribution across Wall Assemblies for the Aluminum Frame Design

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<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
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<tbody>
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<td>2613</td>
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<td>2991</td>
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<table>
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<th>$R_w/R_e$</th>
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<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
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<td>Summer Low</td>
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<td>265.9</td>
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<td>358</td>
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<td>290.9</td>
<td>3995</td>
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<td>269.9</td>
<td>2991</td>
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<table>
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<tr>
<th>Layer Interface</th>
<th>$R_w/R_e$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
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<tr>
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<td>Winter High</td>
<td>Winter Low</td>
<td>Summer High</td>
<td>Summer Low</td>
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<td>265.9</td>
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<td>290.9</td>
<td>3995</td>
<td>2044</td>
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<td>0.52</td>
<td>295.0</td>
<td>294.9</td>
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<td>271.0</td>
<td>269.9</td>
<td>2991</td>
<td>2958</td>
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<td>0.08</td>
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<td>295.4</td>
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<td>297.0</td>
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<td>269.9</td>
<td>2991</td>
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</tbody>
</table>
Appendix B

Building Science Calculations and Analysis

B.1 Material Properties

Table B-1, Wall Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity, K (W/m-K)</th>
<th>Permeance, ρ (lb/in³)</th>
<th>Permeance, ρ (Perm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic Float Glass</td>
<td>0.63</td>
<td>0.10127</td>
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<td>IGU</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>16.20</td>
<td>0.29000</td>
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</tr>
<tr>
<td>Aluminum</td>
<td>200.00</td>
<td>0.09700</td>
<td></td>
</tr>
<tr>
<td>Cellular PC</td>
<td>0.04</td>
<td>0.00450</td>
<td></td>
</tr>
<tr>
<td>Fiber-Glass Reinforced Polyester</td>
<td>0.40</td>
<td>0.09400</td>
<td></td>
</tr>
<tr>
<td>Granular Aerogel</td>
<td>0.02</td>
<td>0.00330</td>
<td></td>
</tr>
<tr>
<td>Monolithic Aerogel</td>
<td>0.00</td>
<td>0.00720</td>
<td></td>
</tr>
<tr>
<td>Polyurethane Foam</td>
<td>0.03</td>
<td>0.00145</td>
<td></td>
</tr>
<tr>
<td>Batt Insulation (R-13)</td>
<td>0.04</td>
<td>0.00044</td>
<td></td>
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<tr>
<td>Batt Insulation (R-21)</td>
<td>0.04</td>
<td>0.00025</td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>0.22</td>
<td>0.04300</td>
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<tr>
<td>Gypsum Wall Board</td>
<td>0.17</td>
<td>0.08333</td>
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</tr>
<tr>
<td>Vinyl Siding</td>
<td>0.19</td>
<td>0.05019</td>
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<tr>
<td>Steel Web w/ 50% Openings</td>
<td>1.02</td>
<td>0.14502</td>
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<td>Steel</td>
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<td>Brick</td>
<td>1.00</td>
<td>0.05787</td>
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</tr>
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## B.2 Thermal Performance and Condensation Potential

### B.2.1 Wall Assemblies in Tampa, FL

#### B.2.1.1 Light Gauge (1), (2), and Heavy Gauge (1)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>$R_i = 1/C$</th>
<th>$R_i = 1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m$^2$-K/W</td>
<td>h-ft$^2$.°F/Btu</td>
<td>m$^2$-K/W</td>
</tr>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.13</td>
<td>899.20</td>
<td>0.000</td>
<td>0.001</td>
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<tr>
<td></td>
<td>Still Air</td>
<td>0.88</td>
<td>0.19</td>
<td>0.757</td>
<td>5.253</td>
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<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.13</td>
<td>11104.00</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td>0.44</td>
<td>0.324</td>
<td>2.251</td>
</tr>
<tr>
<td>3</td>
<td>Fiber-Glass Reinforced Polyester</td>
<td>0.13</td>
<td>22.21</td>
<td>0.006</td>
<td>0.045</td>
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<td>4</td>
<td>Steel</td>
<td>2.50</td>
<td>180.00</td>
<td>0.001</td>
<td>0.006</td>
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<td></td>
<td>Steel Web w/ 50% Openings</td>
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<td>150.06</td>
<td>0.001</td>
<td>0.007</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
<td>0.327</td>
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</table>

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>$R_i = 1/C$</th>
<th>$R_i = 1/C$</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m$^2$-K/W</td>
<td>h-ft$^2$.°F/Btu</td>
<td>m$^2$-K/W</td>
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<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td>17.44</td>
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<td>2</td>
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<td>0.18</td>
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<td>4</td>
<td>PC</td>
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<td>3.05</td>
<td>0.047</td>
<td>0.327</td>
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<tr>
<td>5</td>
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### Table B-4, $R_v$-Value of Wall Components (Frame)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Stainless Steel</td>
<td>0.13</td>
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<td>$\infty$</td>
</tr>
<tr>
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<td></td>
<td>Still Air</td>
<td>0.88</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Aluminum</td>
<td>0.13</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td></td>
<td>0</td>
</tr>
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<td>3</td>
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<td>Fiber-Glass Reinforced Polyester</td>
<td>0.13</td>
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</tr>
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<td>4</td>
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<td>Steel</td>
<td>2.50</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
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<td></td>
<td>Steel Web w/ 50% Openings</td>
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<td>0</td>
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<td>5</td>
<td></td>
<td>PC</td>
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<td>2.80</td>
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### Table B-5, $R_v$-Value of Wall Components (Between Studs)

<table>
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<th>Layer</th>
<th>Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
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<td>$\infty$</td>
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<td>PC</td>
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### Table B-6, R and $R_v$ Values of Various Thermal Paths through the Wall Frame

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft$^2$°F/Btu)</th>
<th>Total $R_v$-Value</th>
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<tr>
<td>1</td>
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<td>13.7</td>
<td>2.9</td>
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<tr>
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<td>Frame</td>
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</tr>
<tr>
<td>3</td>
<td>Average</td>
<td>12.7</td>
<td>2.9</td>
</tr>
</tbody>
</table>
A. R-Value

1. Average

\[ R_{av} = \frac{\text{Total Stud Flange Width} \times V_{st}}{\text{Total Panel Width}} + \frac{\text{Total Space BTW Studs} \times V_{con}}{\text{Total Panel Width}} \]

a) Tampa, FL

\[ R_{av} = \frac{W(L) \times 7.9 + \frac{(W-H)(L)}{49}}{49} + \frac{13.7}{CFS} \]

\[ R_{av} = 17.7 \text{ hr-ft}^2^\circ\text{F}/\text{BTU} \text{ CFS} \]

B. Temperature Gradient Across Assembly CFS

1. Winter

a) High

\[ T_{ext} = 90^\circ\text{F} \]
\[ T_{int} = 72^\circ\text{F} \]

\[ T_1 = \frac{T_{ext} - T_{con}}{R_1} + T_{con} \]
\[ T_2 = \frac{0.004 \times (72 - 70)}{70} \]
\[ T_3 = 0.055 \times (72 - 70) + 70.1 \]
\[ T_4 = 71.5^\circ\text{F} \]

\[ T_5 = \frac{R_3 \times (T_{int} - T_{con}) + T_3}{R_3} \]
\[ T_6 = 0.916 \times (71.5 - 70) + 71.5 \]
\[ T_7 = 71.9^\circ\text{F} \]
b) Low

\[ T_{\text{ext}} = 52^\circ \text{F} \]
\[ T_{\text{int}} = 72^\circ \text{F} \]
\[ T_2 = (72 - 52) \times 0.006 + 52 \]
\[ T_3 = 52.1^\circ \text{F} \]
\[ T_4 = (72 - 52.1) \times 0.155 + 52.1 \]
\[ T_5 = 63.1^\circ \text{F} \]
\[ T_4 = (72 - 63.1) \times 0.116 + 63.1 \]
\[ T_7 = 71.4^\circ \text{F} \]

2. Summer

a) High

\[ T_{\text{ext}} = 91^\circ \text{F} \]
\[ T_{\text{int}} = 75^\circ \text{F} \]
\[ T_2 = (75 - 91) \times 0.006 + 91 \]
\[ T_3 = 90.9^\circ \text{F} \]
\[ T_4 = (75 - 90.9) \times 0.155 + 90.9 \]
\[ T_5 = 82.1^\circ \text{F} \]
\[ T_4 = (75 - 82.1) \times 0.116 + 82.1 \]
\[ T_7 = 75.5^\circ \text{F} \]

b) Low

\[ T_{\text{ext}} = 74^\circ \text{F} \]
\[ T_{\text{int}} = 75^\circ \text{F} \]
\[ T_2 = (75 - 74) \times 0.006 + 74 \]
\[ T_3 = 74.004^\circ \text{F} \]
\[ T_4 = (75 - 74) \times 0.155 + 74.004 \]
\[ T_5 = 74.6^\circ \text{F} \]
\[ T_4 = (75 - 74.6) \times 0.116 + 74.6 \]
\[ T_7 = 75.0^\circ \text{F} \]
C. RH Distribution Across Assembly (CR)

1. Winter

a) High

** All temperatures calculated previously must be converted to Kelvin.**

\[ T_{	ext{int}} = \frac{-273.15 \times 5}{273.15} - 5.015 \text{K} \]

\[ P_{\text{sat,2}} = 1000 \text{ Pa} \]

\[ P_{\text{ext}} = P_{\text{sat,2}} \times \text{Exterior RH} \]

\[ P_{\text{int}} = P_{\text{sat,2}} \times \text{Interior RH} \]

\[ P_2 = (P_{\text{int}} - P_{\text{ext}}) \times \frac{R_{\text{v,2}}}{\sum R_{\text{v}}} + P_{\text{ext}} \]

\[ P_3 = (P_{\text{int}} - P_{\text{ext}}) \times \frac{R_{\text{v,3}}}{\sum R_{\text{v}}} + P_2 \]

\[ P_4 = (P_{\text{int}} - P_{\text{ext}}) \times \frac{R_{\text{v,4}}}{\sum R_{\text{v}}} + P_3 \]

\[ P_{\text{sat,2}} = 1000 \text{ Pa} \]

\[ P_{\text{sat,1}} = 2515 \text{ Pa} \]

\[ P_{\text{sat,1}} = 1000 \text{ Pa} \]

\[ P_{\text{sat,1}} = 2612 \text{ Pa} \]

\[ P_{\text{sat,1}} = 1000 \text{ Pa} \]

\[ P_{\text{ext}} = 2514 \text{ Pa} \]

\[ P_{\text{int}} = 1345 \text{ Pa} \]

\[ P_2 = 2514 \text{ Pa} \]

\[ P_3 = (1345 - 2514) \times 0.05 + 2514 \]

\[ P_3 = 1930 \text{ Pa} \]

\[ P_4 = (1345 - 1930) \times 0.375 + 1930 \]

\[ P_4 = 1492 \text{ Pa} \]

\[ \text{RH} = \frac{P_4}{P_{\text{sat,1}}} \]
\( \frac{RH_1}{2515} = 99.96\% \)
\( RH_2 = 1430 / 2612 \)
\( RH_3 = 73.4\% \)
\( R_y = (1492 / 2687) \)
\( R_y = 55.5\% \)

b) Low

\[ P_{\text{separated,1}} = 1000 \text{ Pa} \]
\[ P_{\text{separated,1}} = 1333 \text{ Pa} \]
\[ P_{\text{separated,3}} = 1981 \text{ Pa} \]
\[ P_{\text{separated,4}} = 1000 \text{ Pa} \]
\[ P_{\text{free}} = 2670 \text{ Pa} \]
\[ P_{\text{free}} = 1324 \text{ Pa} \]
\[ P_{\text{free}} = 1345 \text{ Pa} \]
\[ P_3 = 1337 \text{ Pa} \]
\[ P_4 = 1343 \text{ Pa} \]
\( RH_2 = 1430 / 1333 \)
\( RH_3 = 99.7\% \)
\( RH_4 = 1337 / 1481 \)
\( RH_5 = 69.5\% \)
\( RH_6 = 1343 / 2670 \)
\( RH_7 = 50.9\% \)
A) Low
- \( P_{\text{net}} = 1000 \text{ Pa} \)
- \( T = 287 \text{ K} \)

B) High
- \( P_{\text{net}} = 1000 \text{ Pa} \)
- \( T = 327 \text{ K} \)

\[
R_{\text{HI}} = \frac{4476}{4475} \text{ cm}^2 \text{ Pa/s} / \text{ m}^2 \\
K_{\text{HI}} = 33.7^\circ \text{ C/ m} \\
P_{\text{HI}} = 4476 \text{ Pa} \\
P_{\text{net}} = 4475 \text{ Pa}
\]
\[ P_a = 2973 \text{ Pa} \]
\[ P_3 = (P_{20} + 2876) / 4.65 + 2876 \]
\[ P_2 = 2183 \text{ Pa} \]
\[ P_2 = (P_{20} - 2183) \times 0.03 + 2183 \]
\[ P_3 = 1462 \text{ Pa} \]
\[ R.H. = 104.7\% \]
\[ R.H. = 74.5\% \]
\[ R.H. = 55.9\% \]

D. Condensation Quantity

*** Only analyzed time that condensation occurs is when R.H. is 100% during summer high temperatures.

*** Break the walls into two: one w/ only interface 1, the other w/ the remaining interfaces.

1) Interface 2 \( \Rightarrow 5 \)

a) RH

\[ R.H. = 100\% \]
\[ \Delta P_1 = |P_1 - P_2| \]
\[ \Delta P_2 = 4986 - 4975 \]
\[ \Delta P_3 = 11 \text{ Pa} \]
\[ P_3 = (P_{20} - P_2) \times \frac{R.H.}{100} + P_2 \]
\[ P_3 = (1472 - 4975) \times 0.05 - 4975 \]
\[ P_3 = 3232 \text{ Pa} \]
\[ P_4 = (P_{10} - P_2) \times \frac{R.H.}{100} + P_2 \]
\[ P_4 = (3232 - 3232) \times 0.03 + 3232 \]
\[ P_4 = 3232 \text{ Pa} \]
\[ R.H. = 3232 / 3760 = 86\% \]
\[ R.H. = 1924 / 3021 = 63.7\% \]

Condensation = \( \Delta P_2 / \sum R_i = 0.035 \text{ grams} / (\text{hr} \cdot \text{m}^2) \) insignificant.
### B.2.1.2 Aluminum Frame

#### Table B-7, R-Value of Wall Components (Frame)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>Rᵢ = 1/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m²·K/W</td>
<td>h·ft²·°F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.06</td>
<td>1798.40</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.75</td>
<td>0.22</td>
<td>0.649</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>2.50</td>
<td>0.08</td>
<td>1.730</td>
</tr>
<tr>
<td>3</td>
<td>Aluminum</td>
<td>0.13</td>
<td>11104.00</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
</tbody>
</table>

#### Table B-8, R-Value of Wall Components (Between Studs)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>Rᵢ = 1/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m²·K/W</td>
<td>h·ft²·°F/Btu</td>
</tr>
<tr>
<td>1</td>
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<td>0.25</td>
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<td>2.00</td>
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</tr>
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### Table B-9, $R_v$-Value of Wall Components (Frame)

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<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.06</td>
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<td>$\infty$</td>
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<tr>
<td></td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.75</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
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<td>Polyurethane Foam</td>
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<td>0.64</td>
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<td>Aluminum</td>
<td>0.13</td>
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<td>$\infty$</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>0.50</td>
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<td>0.4</td>
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</table>

### Table B-10, $R_v$-Value of Wall Components (Between Studs)

<table>
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<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
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<tr>
<td>2</td>
<td>Cellular PC</td>
<td>2.00</td>
<td>0.70</td>
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<td>4</td>
<td>PC</td>
<td>0.50</td>
<td>2.80</td>
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### Table B-11, $R$ and $R_v$ Values of Various Thermal Paths through the Wall Frame

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft²°F/Btu)</th>
<th>Total $R_v$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Between Studs</td>
<td>12.7</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>Frame</td>
<td>16.8</td>
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<tr>
<td>3</td>
<td>Average</td>
<td>12.9</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Table B-12, RH Distribution across the Aluminum Frame Design

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>$R_{o}/R_{n}$</th>
<th>$T_{w}$ (K)</th>
<th>$T_{s}$ (K)</th>
<th>$SVP_{w}$ (Pa)</th>
<th>$SVP_{s}$ (Pa)</th>
<th>$VP_{w}$ (Pa)</th>
<th>$VP_{s}$ (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
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<td>1</td>
<td>294.3</td>
<td>284.3</td>
<td>305.9</td>
<td>296.5</td>
<td>2514</td>
<td>1329</td>
<td>4986</td>
<td>2878</td>
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<tr>
<td>2</td>
<td>294.3</td>
<td>284.3</td>
<td>305.9</td>
<td>296.5</td>
<td>2515</td>
<td>1333</td>
<td>4975</td>
<td>2879</td>
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<td>294.9</td>
<td>290.9</td>
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<td>296.9</td>
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<td>2046</td>
<td>3671</td>
<td>2937</td>
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<td>295.3</td>
<td>295.1</td>
<td>297.3</td>
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<td>2644</td>
<td>3017</td>
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### B.2.2 Wall Assemblies in Washington D.C.

#### B.2.2.1 Light Gauge (1) and Heavy Gauge (1)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>R&lt;sub&gt;i&lt;/sub&gt; = 1/C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>m&lt;sup&gt;2&lt;/sup&gt;-K/W</td>
</tr>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.13</td>
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</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.88</td>
<td>0.19</td>
<td>0.757</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.13</td>
<td>11104.00</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td>0.44</td>
<td>0.324</td>
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<td>3</td>
<td>Fiber-Glass Reinforced Polyester</td>
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<td>Steel</td>
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<td>100.00</td>
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<td>Steel Web w/ 50% Openings</td>
<td>1.50</td>
<td>150.06</td>
<td>0.001</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
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<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>R&lt;sub&gt;i&lt;/sub&gt; = 1/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>m&lt;sup&gt;2&lt;/sup&gt;-K/W</td>
</tr>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td>17.44</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>2.00</td>
<td>0.13</td>
<td>1.093</td>
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<td>Cellular PC</td>
<td>0.75</td>
<td>0.35</td>
<td>0.410</td>
</tr>
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<td>4</td>
<td>Granular Aerogel</td>
<td>1.00</td>
<td>0.12</td>
<td>1.153</td>
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<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
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</table>
### Table B-15, $R_v$-Value of Wall Components (Frame)

<table>
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<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.13</td>
<td>$\infty$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.88</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.13</td>
<td>$\infty$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fiber-Glass Reinforced Polyester</td>
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<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>4.50</td>
<td>$\infty$</td>
<td></td>
</tr>
<tr>
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<td>Steel Web w/ 50% Openings</td>
<td>1.50</td>
<td>0</td>
<td></td>
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<tr>
<td>5</td>
<td>PC</td>
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</table>

### Table B-16, $R_v$-Value of Wall Components (Between Studs)

<table>
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<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
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<td>$\infty$</td>
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</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
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<td>Cellular PC</td>
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<td>1.9</td>
<td>0.5</td>
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<td>Granular Aerogel</td>
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<td>PC</td>
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### Table B-17, R and $R_v$ Values of Various Thermal Paths through the Wall Frame

<table>
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<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft$^2\cdot$°F/Btu)</th>
<th>Total $R_v$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Between Studs</td>
<td>18.8</td>
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</tr>
<tr>
<td>2</td>
<td>Frame</td>
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<td>3</td>
<td>Average</td>
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Table B-18, RH Distribution across the CFS Design

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>$R_{w}/R_{t}$</th>
<th>$R_{v}/R_{o}$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
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<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
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<td>284.8</td>
<td>300.5</td>
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<tr>
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<td>0.12</td>
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<td>295.4</td>
<td>297.0</td>
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Table B-19, Condensation Quantity

<table>
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<tr>
<th>Layer Interface</th>
<th>$R_{w}/R_{t}$</th>
<th>$R_{v}/R_{o}$</th>
<th>Temperature (K)</th>
<th>Vapor Pressure, $P_v$ (Pa)</th>
<th>$\Delta P_v$</th>
<th>RH (%)</th>
<th>Condensation (($\Delta P_v R_{v}/o$) grams/24-hr-m²</th>
<th>Condensation (grams/hr-ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
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<tr>
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<td>0.0</td>
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<td>0.000</td>
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<td>0.120</td>
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<td>297.0</td>
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### B.2.2.2 Aluminum Frame

Table B-20, R-Value of Wall Components (Frame)

<table>
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<th>Layer Interface</th>
<th>Material</th>
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<th>C = K/L</th>
<th>R_i = 1/C</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m²-K/W</td>
<td>h-ft²-°F/Btu</td>
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<td>Stainless Steel</td>
<td>0.06</td>
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<td>Aluminum</td>
<td>0.19</td>
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</tr>
<tr>
<td></td>
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<td>0.22</td>
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</tr>
<tr>
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<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
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<td>2.50</td>
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<td>Aluminum</td>
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<td>0.000</td>
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<tr>
<td></td>
<td>Polyurethane Foam</td>
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<td>Aluminum</td>
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<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
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Table B-21, R-Value of Wall Components (Between Studs)

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<th>R_i = 1/C</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>m²-K/W</td>
<td>h-ft²-°F/Btu</td>
</tr>
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<td>Monolithic Float Glass</td>
<td>0.25</td>
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<td>2</td>
<td>Cellular PC</td>
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<td>0.13</td>
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</tr>
<tr>
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<td>Cellular PC</td>
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</tr>
<tr>
<td>4</td>
<td>Granular Aerogel</td>
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<td>0.12</td>
<td>1.153</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
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</tbody>
</table>
### Table B-22, $R_v$-Value of Wall Components (Frame)

<table>
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<tr>
<th>Layer Interface</th>
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<th>Thk (in)</th>
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<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>$\infty$</td>
</tr>
<tr>
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<td>Aluminum</td>
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<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.75</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>2.50</td>
<td>0.64</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>Aluminum</td>
<td>0.13</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>1.50</td>
<td>1.07</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.8</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
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</table>

### Table B-23, $R_v$-Value of Wall Components (Between Studs)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>2.00</td>
<td>0.70</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>Cellular PC</td>
<td>0.50</td>
<td>2.80</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>Granular Aerogel</td>
<td>1.00</td>
<td>1.52</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.80</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table B-24, $R$ and $R_v$ Values of Various Thermal Paths through the Wall Frame

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft²-°F/Btu)</th>
<th>Total $R_v$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Between Studs</td>
<td>17.9</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>Frame</td>
<td>24.0</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>Average</td>
<td>18.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Layer Interface</td>
<td>$R_v/R_w$</td>
<td>Temperature (K)</td>
<td>Saturated Vapor Pressure (Pa)</td>
</tr>
<tr>
<td>----------------</td>
<td>----------</td>
<td>-----------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High  Low</td>
<td>High  Low</td>
</tr>
<tr>
<td>1</td>
<td>0.00</td>
<td>279.3 271.5</td>
<td>304.8 294.8</td>
</tr>
<tr>
<td>2</td>
<td>0.51</td>
<td>286.2 281.7</td>
<td>301.5 295.8</td>
</tr>
<tr>
<td>3</td>
<td>0.12</td>
<td>287.9 284.2</td>
<td>300.7 296.0</td>
</tr>
<tr>
<td>4</td>
<td>0.23</td>
<td>295.1 294.9</td>
<td>297.2 297.0</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>295.4 295.4</td>
<td>297.0 297.0</td>
</tr>
</tbody>
</table>

Table B-25, RH Distribution across the Aluminum Frame Design
### B.2.3 Wall Assemblies in Albuquerque, NM

#### B.2.3.1 Light Gauge (1) and Heavy Gauge (1)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$C = K/L$</th>
<th>$R_i = 1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>m$^2$-K/W</td>
</tr>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.13</td>
<td>899.20</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.88</td>
<td>0.19</td>
<td>0.757</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.13</td>
<td>11104.00</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td>0.44</td>
<td>0.324</td>
</tr>
<tr>
<td>3</td>
<td>Fiber-Glass Reinforced Polyester</td>
<td>0.13</td>
<td>22.21</td>
<td>0.006</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>4.50</td>
<td>100.00</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Steel Web w/ 50% Openings</td>
<td>1.50</td>
<td>150.06</td>
<td>0.001</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$C = K/L$</th>
<th>$R_i = 1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td>m$^2$-K/W</td>
</tr>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td>17.44</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>2.00</td>
<td>0.13</td>
<td>1.093</td>
</tr>
<tr>
<td>3</td>
<td>Cellular PC</td>
<td>0.75</td>
<td>0.35</td>
<td>0.410</td>
</tr>
<tr>
<td>4</td>
<td>Granular Aerogel</td>
<td>1.00</td>
<td>0.12</td>
<td>1.153</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table B-28, $R_v$-Value of Wall Components (Frame)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.13</td>
<td>∞</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.88</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.13</td>
<td>∞</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Fiber-Glass Reinforced Polyester</td>
<td>0.13</td>
<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>4.50</td>
<td>∞</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel Web w/ 50% Openings</td>
<td>1.50</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.8</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
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<td></td>
</tr>
</tbody>
</table>

### Table B-29, $R_v$-Value of Wall Components (Between Studs)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td>∞</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>2.00</td>
<td>0.7</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>Cellular PC</td>
<td>0.75</td>
<td>1.87</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>Granular Aerogel</td>
<td>1.00</td>
<td>1.52</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.8</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table B-30, $R$ and $R_v$ Values of Various Thermal Paths through the Wall Frame

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft²·°F/Btu)</th>
<th>Total $R_v$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Between Studs</td>
<td>18.8</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>Frame</td>
<td>7.9</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>Average</td>
<td>17.6</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Table B-31, RH Distribution across the CFS Design

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>( R_{	ext{e}}/R_{	ext{a}} )</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
</tr>
<tr>
<td>1</td>
<td>281.5 269.8</td>
<td>305.4 292.6</td>
<td>1103 481</td>
<td>4832</td>
<td>2269</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>281.5 269.9</td>
<td>305.3 292.6</td>
<td>1103 481</td>
<td>4832</td>
</tr>
<tr>
<td>3</td>
<td>0.48</td>
<td>287.1 280.2</td>
<td>302.0 294.4</td>
<td>1603 1010</td>
<td>3984</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>289.2 284.1</td>
<td>301.7 295.2</td>
<td>1855 1511</td>
<td>3793</td>
</tr>
<tr>
<td>5</td>
<td>0.22</td>
<td>295.1 294.9</td>
<td>297.2 297.0</td>
<td>2652 2619</td>
<td>3002</td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
<td>295.4 295.4</td>
<td>297.0 297.0</td>
<td>2691 2691</td>
<td>2976</td>
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</table>

Table B-32, Condensation Quantity

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>( R_{	ext{e}}/R_{	ext{a}} )</th>
<th>( R_{	ext{c}}/R_{	ext{a}} )</th>
<th>Temperature (K)</th>
<th>Vapor Pressure, ( P_{\text{v}} ) (Pa)</th>
<th>( \Delta P_{\text{v}} )</th>
<th>RH (%)</th>
<th>Condensation (( \Delta P_{\text{v}} R_{	ext{e}}/R_{	ext{a}} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.000</td>
<td>305.4</td>
<td>4825</td>
<td>7</td>
<td>100.0%</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
<td>0.479</td>
<td>305.3</td>
<td>3225</td>
<td>7</td>
<td>81.0%</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>0.18</td>
<td>0.180</td>
<td>302.0</td>
<td>2625</td>
<td>7</td>
<td>70.9%</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>0.57</td>
<td>0.221</td>
<td>306.7</td>
<td>1888</td>
<td>7</td>
<td>62.9%</td>
<td>N/A</td>
</tr>
<tr>
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<td>0.4</td>
<td>0.120</td>
<td>297.0</td>
<td>1488</td>
<td>7</td>
<td>50.0%</td>
<td>N/A</td>
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</table>
### B.2.3.2 Aluminum Frame

#### Table B-33, R-Value of Wall Components (Frame)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>$R_i = 1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m²-K/W</td>
<td>h-ft²°F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.06</td>
<td>1798.40</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.75</td>
<td>0.22</td>
<td>0.649</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>2.50</td>
<td>0.08</td>
<td>1.730</td>
</tr>
<tr>
<td>3</td>
<td>Aluminum</td>
<td>0.13</td>
<td>11104.00</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>1.50</td>
<td>0.14</td>
<td>1.038</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
</tbody>
</table>

#### Table B-34, R-Value of Wall Components (Between Studs)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>$R_i = 1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m²-K/W</td>
<td>h-ft²°F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td>17.44</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>2.00</td>
<td>0.13</td>
<td>1.093</td>
</tr>
<tr>
<td>3</td>
<td>Cellular PC</td>
<td>0.50</td>
<td>0.53</td>
<td>0.273</td>
</tr>
<tr>
<td>4</td>
<td>Granular Aerogel</td>
<td>1.00</td>
<td>0.12</td>
<td>1.153</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
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</tbody>
</table>
### Table B-35, $R_v$-Value of Wall Components (Frame)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.06</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.75</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>2.50</td>
<td>0.64</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>Aluminum</td>
<td>0.13</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>1.50</td>
<td>1.07</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.8</td>
<td>0.4</td>
</tr>
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</table>

### Table B-36, $R_v$-Value of Wall Components (Between Studs)

<table>
<thead>
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<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>2.00</td>
<td>0.70</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>Cellular PC</td>
<td>0.50</td>
<td>2.80</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>Granular Aerogel</td>
<td>1.00</td>
<td>1.52</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.80</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Table B-37, $R$ and $R_v$ Values of Various Thermal Paths through the Wall Frame

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft²°F/Btu)</th>
<th>Total $R_v$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Between Studs</td>
<td>17.9</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>Frame</td>
<td>24.0</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>Average</td>
<td>18.2</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Table B-38, RH Distribution across the Aluminum Frame Design

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>$R_{w}/R_{c}$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.13</td>
<td></td>
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</tr>
</tbody>
</table>
### B.2.4 Wall Assemblies in Detroit, MI

#### B.2.4.1 Light Gauge (1) and Heavy Gauge (1)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>R&lt;sub&gt;i&lt;/sub&gt; = 1/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m&lt;sup&gt;2&lt;/sup&gt;-K/W</td>
<td>h-ft&lt;sup&gt;2&lt;/sup&gt;-°F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.13</td>
<td>899.20</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.88</td>
<td>0.19</td>
<td>0.757</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.13</td>
<td>11104.00</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td>0.44</td>
<td>0.324</td>
</tr>
<tr>
<td>3</td>
<td>Fiber-Glass Reinforced Polyester</td>
<td>0.13</td>
<td>22.21</td>
<td>0.006</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>4.50</td>
<td>100.00</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Steel Web w/ 50% Openings</td>
<td>1.50</td>
<td>150.06</td>
<td>0.001</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>C = K/L</th>
<th>R&lt;sub&gt;i&lt;/sub&gt; = 1/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m&lt;sup&gt;2&lt;/sup&gt;-K/W</td>
<td>h-ft&lt;sup&gt;2&lt;/sup&gt;-°F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td>17.44</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>1.75</td>
<td>0.15</td>
<td>0.956</td>
</tr>
<tr>
<td>3</td>
<td>Granular Aerogel</td>
<td>2.00</td>
<td>0.06</td>
<td>2.307</td>
</tr>
<tr>
<td>4</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
<td>5</td>
<td></td>
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<td></td>
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### Table B-41, $R_v$-Value of Wall Components (Frame)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.13</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.88</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.13</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.38</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Fiber-Glass Reinforced Polyester</td>
<td>0.13</td>
<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>4.50</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Steel Web w/ 50% Openings</td>
<td>1.50</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Table B-42, $R_v$-Value of Wall Components (Between Studs)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$M = \mu/T$</th>
<th>$R_{vi} = 1/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td></td>
<td>$\infty$</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>1.75</td>
<td>0.8</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>Granular Aerogel</td>
<td>2.00</td>
<td>0.76</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>PC</td>
<td>0.50</td>
<td>2.8</td>
<td>0.4</td>
</tr>
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</table>

### Table B-43, R and $R_v$ Values of Various Thermal Paths through the Wall Frame

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft$^2\cdot$°F/Btu)</th>
<th>Total $R_v$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Between Studs</td>
<td>23.0</td>
<td>2.9</td>
</tr>
<tr>
<td>2</td>
<td>Frame</td>
<td>7.9</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>Average</td>
<td>21.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Table B-44, RH Distribution across the CFS Design

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>$R_{ni}/R_e$</th>
<th>Temperature (K) High</th>
<th>Temperature (K) Low</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Saturated Vapor Pressure (Pa) High</th>
<th>Saturated Vapor Pressure (Pa) Low</th>
<th>Vapor Pressure (Pa) High</th>
<th>Vapor Pressure (Pa) Low</th>
<th>RH (%) High</th>
<th>RH (%) Low</th>
<th>RH (%) High</th>
<th>RH (%) Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.25</td>
<td>273.2</td>
<td>265.9</td>
<td>301.0</td>
<td>290.9</td>
<td>611</td>
<td>358</td>
<td>3995</td>
<td>2044</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>273.2</td>
<td>266.0</td>
<td>302.0</td>
<td>290.9</td>
<td>617</td>
<td>358</td>
<td>3992</td>
<td>2046</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>0.45</td>
<td>279.6</td>
<td>274.5</td>
<td>300.6</td>
<td>292.7</td>
<td>570</td>
<td>6**</td>
<td>3672</td>
<td>2284</td>
<td>95.6%</td>
<td>115.3%</td>
<td>79.6%</td>
</tr>
<tr>
<td>4</td>
<td>0.45</td>
<td>295.1</td>
<td>285.0</td>
<td>297.1</td>
<td>297.0</td>
<td>2640</td>
<td>2623</td>
<td>2998</td>
<td>2961</td>
<td>47.6%</td>
<td>46.7%</td>
<td>60.0%</td>
</tr>
<tr>
<td>5</td>
<td>0.12</td>
<td>295.4</td>
<td>295.4</td>
<td>297.0</td>
<td>297.0</td>
<td>2691</td>
<td>2691</td>
<td>2976</td>
<td>2976</td>
<td>50.0%</td>
<td>50.0%</td>
<td>50.0%</td>
</tr>
</tbody>
</table>

Table B-45, Condensation Quantity

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>$R_{ni}/R_e$</th>
<th>$R_{ni}/R_{in}$</th>
<th>Temperature (K)</th>
<th>Vapor Pressure, $P_e$ (Pa)</th>
<th>$\Delta P_e$</th>
<th>RH (%)</th>
<th>Condensation ($\Delta P_{TR_{ni}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.000</td>
<td>302.0</td>
<td>3995</td>
<td>100.0%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>0.428</td>
<td>300.6</td>
<td>2921</td>
<td>79.6%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>0.450</td>
<td>297.1</td>
<td>1794</td>
<td>60.0%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>1.3</td>
<td>0.122</td>
<td>297.0</td>
<td>1488</td>
<td>50.0%</td>
<td>N/A</td>
<td>N/A</td>
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</tbody>
</table>

Table B-46, Condensation Quantity

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>$R_{ni}/R_e$</th>
<th>$R_{ni}/R_{in}$</th>
<th>Temperature (K)</th>
<th>Vapor Pressure, $P_e$ (Pa)</th>
<th>$\Delta P_e$</th>
<th>RH (%)</th>
<th>Condensation ($\Delta P_{TR_{ni}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.000</td>
<td>265.9</td>
<td>358</td>
<td>100.0%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>1.000</td>
<td>274.5</td>
<td>677</td>
<td>100.0%</td>
<td>1.912</td>
<td>0.114</td>
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<td>3</td>
<td>1.3</td>
<td>0.787</td>
<td>295.0</td>
<td>1203</td>
<td>98.2%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>0.36</td>
<td>0.213</td>
<td>295.4</td>
<td>1345</td>
<td>50.0%</td>
<td>N/A</td>
<td>N/A</td>
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</table>
### Table B-47, R-Value of Wall Components (Frame)

<table>
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<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$C = K/L$</th>
<th>$R_i = 1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$m^2$-$K/W$</td>
<td>h-ft$^2$-$^\circ$F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.06</td>
<td>1798.40</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.75</td>
<td>0.22</td>
<td>0.649</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>2.50</td>
<td>0.08</td>
<td>1.730</td>
</tr>
<tr>
<td>3</td>
<td>Aluminum</td>
<td>0.13</td>
<td>11104.00</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>1.50</td>
<td>0.14</td>
<td>1.038</td>
</tr>
<tr>
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<td>Aluminum</td>
<td>0.19</td>
<td>7402.67</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
<td>6</td>
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<td></td>
<td></td>
<td></td>
</tr>
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</table>

### Table B-48, R-Value of Wall Components (Between Studs)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>$C = K/L$</th>
<th>$R_i = 1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$m^2$-$K/W$</td>
<td>h-ft$^2$-$^\circ$F/Btu</td>
</tr>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td>17.44</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>1.75</td>
<td>0.15</td>
<td>0.956</td>
</tr>
<tr>
<td>3</td>
<td>Granular Aerogel</td>
<td>1.75</td>
<td>0.07</td>
<td>2.019</td>
</tr>
<tr>
<td>4</td>
<td>PC</td>
<td>0.50</td>
<td>3.05</td>
<td>0.047</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
### Table B-49, \( R_v \)-Value of Wall Components (Frame)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>( M = \mu/T )</th>
<th>( R_{vi} = 1/M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>0.06</td>
<td></td>
<td>( \infty )</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>( \infty )</td>
</tr>
<tr>
<td></td>
<td>Still Air</td>
<td>0.75</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>( \infty )</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>2.50</td>
<td>0.64</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>Aluminum</td>
<td>0.13</td>
<td></td>
<td>( \infty )</td>
</tr>
<tr>
<td></td>
<td>Polyurethane Foam</td>
<td>1.50</td>
<td>1.07</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum</td>
<td>0.19</td>
<td></td>
<td>( \infty )</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>0.50</td>
<td>2.8</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table B-50, \( R_v \)-Value of Wall Components (Between Studs)

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>Material</th>
<th>Thk (in)</th>
<th>( M = \mu/T )</th>
<th>( R_{vi} = 1/M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monolithic Float Glass</td>
<td>0.25</td>
<td></td>
<td>( \infty )</td>
</tr>
<tr>
<td>2</td>
<td>Cellular PC</td>
<td>1.75</td>
<td>0.80</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>Granular Aerogel</td>
<td>1.75</td>
<td>0.87</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>PC</td>
<td>0.50</td>
<td>2.80</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### Table B-51, \( R \) and \( R_v \) Values of Various Thermal Paths through the Wall Frame

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Total R-Value (h-ft(^2)-°F/Btu)</th>
<th>Total ( R_v )-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Between Studs</td>
<td>21.0</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>Frame</td>
<td>24.0</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>Average</td>
<td>21.2</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Table B-52, RH Distribution across the Aluminum Frame Design

<table>
<thead>
<tr>
<th>Layer Interface</th>
<th>$R_{x}/R_{c}$</th>
<th>Temperature (K)</th>
<th>Saturated Vapor Pressure (Pa)</th>
<th>Vapor Pressure (Pa)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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Appendix C
Acoustical and Sustainability Analysis

C.1 Acoustical Attenuation Analysis

C.1.1 Transmission Loss

<table>
<thead>
<tr>
<th>Designation</th>
<th>125Hz</th>
<th>250Hz</th>
<th>500Hz</th>
<th>1000Hz</th>
<th>2000Hz</th>
<th>4000Hz</th>
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<tbody>
<tr>
<td>1/8&quot; Monolithic Glass Window</td>
<td>18</td>
<td>21</td>
<td>26</td>
<td>31</td>
<td>33</td>
<td>22</td>
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<tr>
<td>1/4&quot; Monolithic Glass Window</td>
<td>25</td>
<td>28</td>
<td>31</td>
<td>34</td>
<td>30</td>
<td>37</td>
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<td>IGU</td>
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<td>26</td>
<td>24</td>
<td>33</td>
<td>44</td>
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</table>

Table C-2, TL of Various PC Thicknesses
Source: Khidir et al. (2012)

<table>
<thead>
<tr>
<th>Designation</th>
<th>125Hz</th>
<th>250Hz</th>
<th>500Hz</th>
<th>1000Hz</th>
<th>2000Hz</th>
<th>4000Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8&quot; PC</td>
<td>17</td>
<td>20</td>
<td>25</td>
<td>29</td>
<td>31</td>
<td>21</td>
</tr>
<tr>
<td>1/4&quot; PC</td>
<td>24</td>
<td>27</td>
<td>29</td>
<td>32</td>
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C.1.2 Sound Transmission Coefficient (STC)

<table>
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<tr>
<th>Room</th>
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<tbody>
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<td>Living Room</td>
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<tr>
<td>Kitchen</td>
<td>50</td>
</tr>
<tr>
<td>Bedroom</td>
<td>50</td>
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Figure C-1, STC Contour for Wall Assembly w/ Face Brick and 3-5/8" Metal Studs at 16" O.C. w/ Sheathing on Both Sides

Table C-4, Face Brick and 3-5/8" Metal Studs at 16" O.C. w/ Sheathing on Both Sides

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Deviation at Each Frequency</th>
<th>Sum of Deviation</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>3</td>
<td>24</td>
<td>Maximum allowable deviation at each frequency and maximum allowable sum of deviation are satisfied</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>0</td>
<td></td>
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<tr>
<td>4000</td>
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Figure C-2, STC Contour for Wall Assembly w/ 1/8" Monolithic Glazing, PC, and 2-1/2" Steel Channels at 24" O.C.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Deviation at Each Frequency</th>
<th>Sum of Deviation</th>
<th>Note</th>
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<tbody>
<tr>
<td>125</td>
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<td>20</td>
<td>Maximum allowable deviation at each frequency and maximum allowable sum of deviation are satisfied</td>
</tr>
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<tr>
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<td>1</td>
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<tr>
<td>1000</td>
<td>2</td>
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<tr>
<td>2000</td>
<td>8</td>
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Figure C-3, STC Contour for Wall Assembly w/ 1/4" Monolithic Glazing, PC, and 2-1/2" Steel Channels at 24" O.C.

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<th>Deviation at Each Frequency</th>
<th>Sum of Deviation</th>
<th>Note</th>
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<tr>
<td>250</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>8</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>0</td>
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</table>

Maximum allowable deviation at each frequency and maximum allowable sum of deviation are satisfied.
Figure C-4, STC Contour for Wall Assembly w/ IGU, PC, and 2-1/2" Steel Channels at 24" O.C.

Table C-7, IGU, PC, and 2-1/2" Steel Channels at 24" O.C.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Deviation at Each Frequency</th>
<th>Sum of Deviation</th>
<th>Note</th>
</tr>
</thead>
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<tr>
<td>250</td>
<td>4</td>
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<td>500</td>
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<tr>
<td>1000</td>
<td>2</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>8</td>
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<td></td>
</tr>
<tr>
<td>4000</td>
<td>0</td>
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Maximum allowable deviation at each frequency and maximum allowable sum of deviation are satisfied.
C.2 Sustainability Analysis

C.2.1 ATHENA Impact Estimator Simulation

Comparison of Smog Potential By Life Cycle Stage

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Unit</th>
<th>Product (A1 to A3)</th>
<th>Construction Process (A4 &amp; A5)</th>
<th>Use (B2 &amp; B4)</th>
<th>Total Operational Energy (B6)</th>
<th>End of Life (C1 to C4)</th>
<th>Beyond Building Life (D)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGWPS (1)</td>
<td>kg CO₂ eq</td>
<td>4.37E+01</td>
<td>1.22E+01</td>
<td>0.00E+00</td>
<td>2.42E+02</td>
<td>2.69E+00</td>
<td>-2.56E-01</td>
<td>3.00E+02</td>
</tr>
<tr>
<td>Traditional Wood (1)</td>
<td>kg CO₂ eq</td>
<td>3.96E+00</td>
<td>1.35E+00</td>
<td>0.00E+00</td>
<td>2.32E+02</td>
<td>9.81E-01</td>
<td>8.82E-03</td>
<td>2.39E+02</td>
</tr>
<tr>
<td>Aluminum Frame - Detroit, MI</td>
<td>kg CO₂ eq</td>
<td>3.41E+01</td>
<td>3.42E+00</td>
<td>0.00E+00</td>
<td>2.32E+02</td>
<td>6.02E-01</td>
<td>-1.93E-01</td>
<td>2.71E+02</td>
</tr>
<tr>
<td>Aluminum Frame - Tampa, FL</td>
<td>kg CO₂ eq</td>
<td>3.20E+01</td>
<td>3.25E+00</td>
<td>0.00E+00</td>
<td>2.37E+02</td>
<td>4.80E-01</td>
<td>-9.34E-02</td>
<td>2.73E+02</td>
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<tr>
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<td>kg CO₂ eq</td>
<td>3.01E+01</td>
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<td>0.00E+00</td>
<td>2.34E+02</td>
<td>4.56E-01</td>
<td>-9.34E-02</td>
<td>2.69E+02</td>
</tr>
<tr>
<td>Heavy Gauge (1) - Detroit, MI</td>
<td>kg CO₂ eq</td>
<td>2.68E+01</td>
<td>3.77E+00</td>
<td>0.00E+00</td>
<td>2.32E+02</td>
<td>5.77E-01</td>
<td>-8.70E-02</td>
<td>2.63E+02</td>
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<tr>
<td>Heavy Gauge (1) - Tampa, FL</td>
<td>kg CO₂ eq</td>
<td>2.91E+01</td>
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<td>0.00E+00</td>
<td>2.36E+02</td>
<td>6.82E-01</td>
<td>-7.78E-02</td>
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<td>6.03E-01</td>
<td>-8.70E-02</td>
<td>2.64E+02</td>
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<td>Light Gauge (1) - Detroit, MI</td>
<td>kg CO₂ eq</td>
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<td>2.31E+02</td>
<td>6.25E-01</td>
<td>-8.70E-02</td>
<td>2.63E+02</td>
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<tr>
<td>Light Gauge (1) - Tampa, FL</td>
<td>kg CO₂ eq</td>
<td>2.81E+01</td>
<td>3.86E+00</td>
<td>0.00E+00</td>
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<td>Light Gauge (1) - Washington DC</td>
<td>kg CO₂ eq</td>
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<td>-8.70E-02</td>
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<td>2.36E+02</td>
<td>6.01E-01</td>
<td>-7.80E-02</td>
<td>2.69E+02</td>
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Figure C-5, Smog Potential of Wall Assemblies
Comparison of Ozone Depletion Potential By Life Cycle Stage

Figure C-6, Estimated Ozone Depletion of Wall Assemblies
### Comparison of Global Warming Potential By Life Cycle Stage

![Graph showing comparison of global warming potential by life cycle stage.](image)

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Unit</th>
<th>Product (A1 to A3)</th>
<th>Construction Process (A4 &amp; A5)</th>
<th>Use (A2 &amp; A6)</th>
<th>Total Operational Energy (B6)</th>
<th>End of Life (C1 to C4)</th>
<th>Beyond Building Life (D)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGWPS (1)</td>
<td>kg CO2 eq</td>
<td>6.74E+02</td>
<td>2.26E+01</td>
<td>6.09E+00</td>
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<td>9.80E+00</td>
<td>-1.12E+01</td>
<td>1.21E+04</td>
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<tr>
<td>Traditional Wood (1)</td>
<td>kg CO2 eq</td>
<td>4.83E+01</td>
<td>8.02E+00</td>
<td>6.09E+00</td>
<td>1.99E+04</td>
<td>2.36E+00</td>
<td>-3.93E+01</td>
<td>5.19E+04</td>
</tr>
<tr>
<td>Aluminum Frame - Detroit, MI</td>
<td>kg CO2 eq</td>
<td>4.21E+02</td>
<td>1.04E+01</td>
<td>0.00E+00</td>
<td>1.93E+04</td>
<td>1.71E+00</td>
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<td>1.14E+04</td>
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<td>0.00E+00</td>
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<td>1.92E+00</td>
<td>-4.07E+00</td>
<td>1.15E+04</td>
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<td>0.00E+00</td>
<td>1.10E+04</td>
<td>1.58E+00</td>
<td>-4.07E+00</td>
<td>1.14E+04</td>
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<td>2.29E+00</td>
<td>-3.72E+00</td>
<td>1.12E+04</td>
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<td>kg CO2 eq</td>
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<td>2.75E+00</td>
<td>-3.36E+00</td>
<td>1.15E+04</td>
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<tr>
<td>Heavy Gauge (1) - Washington DC</td>
<td>kg CO2 eq</td>
<td>3.29E+02</td>
<td>1.28E+01</td>
<td>0.00E+00</td>
<td>1.09E+04</td>
<td>2.39E+00</td>
<td>-3.79E+00</td>
<td>1.13E+04</td>
</tr>
<tr>
<td>Light Gauge (1) - Detroit, MI</td>
<td>kg CO2 eq</td>
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<td>1.33E+01</td>
<td>0.00E+00</td>
<td>1.09E+04</td>
<td>2.55E+00</td>
<td>-2.75E+00</td>
<td>1.12E+04</td>
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<tr>
<td>Light Gauge (1) - Tampa, FL</td>
<td>kg CO2 eq</td>
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<td>1.31E+01</td>
<td>0.00E+00</td>
<td>1.11E+04</td>
<td>2.42E+00</td>
<td>-3.39E+00</td>
<td>1.15E+04</td>
</tr>
<tr>
<td>Light Gauge (1) - Washington DC</td>
<td>kg CO2 eq</td>
<td>3.40E+02</td>
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<td>0.00E+00</td>
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<td>2.83E+00</td>
<td>-3.75E+00</td>
<td>1.13E+04</td>
</tr>
<tr>
<td>Light Gauge (2) - Tampa, FL</td>
<td>kg CO2 eq</td>
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<td>0.00E+00</td>
<td>1.11E+04</td>
<td>2.31E+00</td>
<td>-3.36E+00</td>
<td>1.15E+04</td>
</tr>
</tbody>
</table>

**Figure C-7, Global Warming Potential of Wall Assemblies**
Comparison of Acidification Potential By Life Cycle Stage

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Unit</th>
<th>Product (A1 to A3)</th>
<th>Construction Process (A4 &amp; A5)</th>
<th>Use (B2 &amp; B4)</th>
<th>Total Operational Energy (E6)</th>
<th>End of Life (C1 to C4)</th>
<th>Beyond Building Life (D)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROWPS (1)</td>
<td>kg SO2 eq</td>
<td>1.9E+01</td>
<td>3.9E-01</td>
<td>0.0E+00</td>
<td>9.7E-01</td>
<td>1.9E-01</td>
<td>-2.5E-02</td>
<td>1.1E+02</td>
</tr>
<tr>
<td>Traditional Wood (1)</td>
<td>kg SO2 eq</td>
<td>1.1E+01</td>
<td>1.1E-01</td>
<td>0.0E+00</td>
<td>9.3E-01</td>
<td>2.8E-02</td>
<td>-5.8E-01</td>
<td>3.3E+01</td>
</tr>
<tr>
<td>Aluminum Frame - Detroit, MI</td>
<td>kg SO2 eq</td>
<td>2.1E+01</td>
<td>1.1E-01</td>
<td>0.0E+00</td>
<td>9.3E-01</td>
<td>1.6E-02</td>
<td>-1.0E-02</td>
<td>1.1E+02</td>
</tr>
<tr>
<td>Aluminum Frame - Tampa, FL</td>
<td>kg SO2 eq</td>
<td>2.6E+01</td>
<td>1.0E-01</td>
<td>0.0E+00</td>
<td>9.5E-01</td>
<td>1.5E-02</td>
<td>-9.2E-03</td>
<td>1.1E+02</td>
</tr>
<tr>
<td>Aluminum Frame - Washington DC</td>
<td>kg SO2 eq</td>
<td>1.7E+01</td>
<td>1.0E-01</td>
<td>0.0E+00</td>
<td>9.4E-01</td>
<td>1.5E-02</td>
<td>-9.2E-03</td>
<td>1.1E+02</td>
</tr>
<tr>
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<td>kg SO2 eq</td>
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<td>1.3E-01</td>
<td>0.0E+00</td>
<td>9.3E-01</td>
<td>2.3E-02</td>
<td>-8.6E-03</td>
<td>1.0E+02</td>
</tr>
<tr>
<td>Heavy Gauge (1) - Tampa, FL</td>
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<td>8.1E+00</td>
<td>1.5E-01</td>
<td>0.0E+00</td>
<td>9.4E-01</td>
<td>3.0E-02</td>
<td>-7.7E-03</td>
<td>1.0E+02</td>
</tr>
<tr>
<td>Heavy Gauge (1) - Washington DC</td>
<td>kg SO2 eq</td>
<td>7.9E+00</td>
<td>1.4E-01</td>
<td>0.0E+00</td>
<td>9.2E-01</td>
<td>2.8E-02</td>
<td>-8.6E-03</td>
<td>1.0E+02</td>
</tr>
<tr>
<td>Light Gauge (1) - Detroit, MI</td>
<td>kg SO2 eq</td>
<td>8.0E+00</td>
<td>1.4E-01</td>
<td>0.0E+00</td>
<td>9.4E-01</td>
<td>2.6E-02</td>
<td>-7.7E-03</td>
<td>1.0E+02</td>
</tr>
<tr>
<td>Light Gauge (1) - Tampa, FL</td>
<td>kg SO2 eq</td>
<td>8.0E+00</td>
<td>1.5E-01</td>
<td>0.0E+00</td>
<td>9.3E-01</td>
<td>2.9E-02</td>
<td>-8.6E-03</td>
<td>1.0E+02</td>
</tr>
<tr>
<td>Light Gauge (1) - Washington DC</td>
<td>kg SO2 eq</td>
<td>1.0E+01</td>
<td>1.4E-01</td>
<td>0.0E+00</td>
<td>9.4E-01</td>
<td>2.6E-02</td>
<td>-7.7E-03</td>
<td>1.0E+02</td>
</tr>
</tbody>
</table>

Figure C-8, Rainwater Acidification Potential of Wall Assemblies
### Comparison of Non-Renewable Energy By Life Cycle Stage

![Graph showing non-renewable energy use](image)

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Unit</th>
<th>Product (A1 to A3)</th>
<th>Construction Process (A4 &amp; A5)</th>
<th>Use (B2 &amp; B4)</th>
<th>Total Operational Energy (B6)</th>
<th>End of Life (C1 to C4)</th>
<th>Beyond Building Life (D)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGWPS (1)</td>
<td>MJ</td>
<td>2.83E+04</td>
<td>6.15E+02</td>
<td>0.00E+00</td>
<td>1.96E+05</td>
<td>1.42E+02</td>
<td>-5.08E+01</td>
<td>2.25E+05</td>
</tr>
<tr>
<td>Traditional Wood (1)</td>
<td>MJ</td>
<td>1.39E+03</td>
<td>1.27E+02</td>
<td>0.00E+00</td>
<td>1.08E+05</td>
<td>3.29E+01</td>
<td>0.00E+00</td>
<td>1.90E+05</td>
</tr>
<tr>
<td>Aluminum Frame - Detroit, MI</td>
<td>MJ</td>
<td>3.20E+04</td>
<td>2.30E+02</td>
<td>0.00E+00</td>
<td>1.88E+05</td>
<td>2.17E+01</td>
<td>-2.04E+01</td>
<td>2.20E+05</td>
</tr>
<tr>
<td>Aluminum Frame - Tampa, FL</td>
<td>MJ</td>
<td>3.38E+04</td>
<td>2.33E+02</td>
<td>0.00E+00</td>
<td>1.92E+05</td>
<td>2.65E+01</td>
<td>-1.85E+01</td>
<td>2.28E+05</td>
</tr>
<tr>
<td>Aluminum Frame - Washington DC</td>
<td>MJ</td>
<td>2.92E+04</td>
<td>2.19E+02</td>
<td>0.00E+00</td>
<td>1.50E+05</td>
<td>1.57E+01</td>
<td>-1.85E+01</td>
<td>2.19E+05</td>
</tr>
<tr>
<td>Heavy Gauge (1) - Detroit, MI</td>
<td>MJ</td>
<td>1.27E+04</td>
<td>2.46E+02</td>
<td>0.00E+00</td>
<td>1.88E+05</td>
<td>3.12E+01</td>
<td>-1.72E+01</td>
<td>2.01E+05</td>
</tr>
<tr>
<td>Heavy Gauge (1) - Tampa, FL</td>
<td>MJ</td>
<td>1.41E+04</td>
<td>2.85E+02</td>
<td>0.00E+00</td>
<td>1.91E+05</td>
<td>3.79E+01</td>
<td>-1.54E+01</td>
<td>2.06E+05</td>
</tr>
<tr>
<td>Heavy Gauge (1) - Washington DC</td>
<td>MJ</td>
<td>1.34E+04</td>
<td>2.63E+02</td>
<td>0.00E+00</td>
<td>1.88E+05</td>
<td>3.26E+01</td>
<td>-1.72E+01</td>
<td>2.01E+05</td>
</tr>
<tr>
<td>Light Gauge (1) - Detroit, MI</td>
<td>MJ</td>
<td>1.23E+04</td>
<td>2.59E+02</td>
<td>0.00E+00</td>
<td>1.87E+05</td>
<td>3.62E+01</td>
<td>-1.72E+01</td>
<td>2.00E+05</td>
</tr>
<tr>
<td>Light Gauge (1) - Tampa, FL</td>
<td>MJ</td>
<td>1.39E+04</td>
<td>2.74E+02</td>
<td>0.00E+00</td>
<td>1.91E+05</td>
<td>3.26E+01</td>
<td>-1.54E+01</td>
<td>2.06E+05</td>
</tr>
<tr>
<td>Light Gauge (1) - Washington DC</td>
<td>MJ</td>
<td>1.33E+04</td>
<td>2.79E+02</td>
<td>0.00E+00</td>
<td>1.88E+05</td>
<td>3.62E+01</td>
<td>-1.72E+01</td>
<td>2.03E+05</td>
</tr>
<tr>
<td>Light Gauge (2) - Tampa, FL</td>
<td>MJ</td>
<td>2.61E+04</td>
<td>2.74E+02</td>
<td>0.00E+00</td>
<td>1.91E+05</td>
<td>3.19E+01</td>
<td>-1.54E+01</td>
<td>2.12E+05</td>
</tr>
</tbody>
</table>

Figure C-9, Estimated Non-Renewable Energy Use for Wall Assemblies
Figure C-10, Estimated Fossil Fuel Use for Wall Assemblies
Figure C-11, Estimated Total Energy Use for Wall Assemblies
Appendix D

Structural Calculations and Analysis

D.1 Determination of Loads on Residence

D.1.1 Gravity Loads

<table>
<thead>
<tr>
<th>Floor Component</th>
<th>Unit Load (lb/ft²)</th>
<th>Roof Component</th>
<th>Unit Load (lb/ft²)</th>
<th>Wood Wall Component</th>
<th>Unit Load (lb/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardwood Flooring</td>
<td>4</td>
<td>Asphalt Shingles</td>
<td>2</td>
<td>Wood Stud Wall 2x6 w/ Gyp. Board 5/8 and 3/8&quot; Siding</td>
<td>12</td>
</tr>
<tr>
<td>Plywood 3/4&quot; Thk.</td>
<td>2.4</td>
<td>Water Resistant Membrane</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engineered I-Joist</td>
<td>1.9</td>
<td>Plywood 7/16&quot; Thk.</td>
<td>2.1</td>
<td>Vapor Retarder</td>
<td>0.7</td>
</tr>
<tr>
<td>11 7/8&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyp. Board 1/2&quot; Thk.</td>
<td>2.2</td>
<td>Engineered Wood Truss</td>
<td>2</td>
<td>Plywood 7/16&quot; Thk.</td>
<td>2.1</td>
</tr>
<tr>
<td>MEP Allowance</td>
<td>4</td>
<td>Fiberglass Insulation (9&quot;)</td>
<td>1.8</td>
<td>Collateral</td>
<td>3</td>
</tr>
<tr>
<td>Collateral</td>
<td>3</td>
<td>Gyp. Board 1/2&quot; Thk.</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEP Allowance</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collateral</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table D-2, Dead Loads per Building Component

<table>
<thead>
<tr>
<th>Building component</th>
<th>Unit Load (lb/ft²)</th>
<th>Calculated</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors</td>
<td>17.5</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Roofs</td>
<td>17.8</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Wood Walls</td>
<td>17.8</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

Table D-3, Recommended Live Loads on Typical Floor and Roof

<table>
<thead>
<tr>
<th>Location in Residence</th>
<th>Unit Load (lb/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping Areas</td>
<td>30</td>
</tr>
<tr>
<td>All Other Areas</td>
<td>40</td>
</tr>
<tr>
<td>Attic w/o Storage</td>
<td>10</td>
</tr>
<tr>
<td>Interior Partitions</td>
<td>15</td>
</tr>
<tr>
<td>Roof Live</td>
<td>20</td>
</tr>
</tbody>
</table>
Table D-4, Live Loads per Typical Floor and Roof

<table>
<thead>
<tr>
<th>Location in Residence</th>
<th>Unit Load (lb/ft²)</th>
<th>Calculated</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping Areas</td>
<td>45</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>All Other Areas</td>
<td>55</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Attic w/o Storage</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

Table D-5, Main House Roof Snow Load

<table>
<thead>
<tr>
<th>Location</th>
<th>Ground Snow Load (lb/ft²) (ASCE 7-10 Figure 7-1)</th>
<th>Thermal Factor (ASCE 7-10 Table 7-3)</th>
<th>Exposure Factor (ASCE 7-10 Table 7-2)</th>
<th>Roof Slope Factor (ASCE 7-10 Figure 7-2)</th>
<th>P_s (lb/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>0</td>
<td>1.2</td>
<td>0.9</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td>18.9</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td>18.9</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td>11.3</td>
</tr>
</tbody>
</table>

D.1.2 Lateral Loads

D.1.2.1 Wind Load

Table D-6, Wind Loading Adjustment Factors

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind Velocity (MPH) (ASCE 7-10 Figure 26.5.1A)</th>
<th>Topographic Factor (Table 26.8.2)</th>
<th>( \lambda ) (ASCE 7-10 Figure 28.6-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>160</td>
<td></td>
<td>1.35</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>115</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table D-7, ASCE 7-10 Wind Pressure for Simplified Method

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind Load Case</th>
<th>P_{S30} (lb/ft²) (ASCE 7-10 Figure 28.6-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>1</td>
<td>45.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>45.7</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>1</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>23.6</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>1</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>23.6</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>1</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>23.6</td>
</tr>
</tbody>
</table>
A. Lateral Loads

1. Wind

Mean Roof Height = 23'
End Length = 2a min
End Length = 26.3
End Length = 6

\[ P_3 = K_T \cdot 2\cdot P_{30} \]

\[ P_{30} \rightarrow \text{Value taken from ASCE 7-10 Figure 28.6-1} \]

\[ a = \begin{cases} 0.1 \cdot \text{Mean Roof Height} \\ 0.1 \cdot \text{Wall Length, Min.} \\ 3 \end{cases} \]

\[ K_T = \text{Topographic Factor} \]

*** Assume suburban area, Flat \( \rightarrow \text{Exposure C} \)

\[ \lambda = \text{Height Adjustment Factor} \]

2. Tampa, FL

1) Wind Load Case 1

\[ P_{3,a} = 1 \cdot 1.35 \cdot 45.7 \]
\[ P_{3,a} = 61.7 \text{ lb/ft}^2 \]
\[ P_{3,b} = 1 \cdot 1.35 \cdot 31.2 \]
\[ P_{3,b} = 31.2 \text{ lb/ft}^2 \]
\[ P_{3,c} = 1 \cdot 1.35 \cdot 36.3 \]
\[ P_{3,c} = 49.1 \text{ lb/ft}^2 \]
\[ P_{3,d} = 1 \cdot 1.35 \cdot 2.5 \]
\[ P_{3,d} = 3.38 \text{ lb/ft}^3 \]
\[ P_{3,e} = 1 \cdot 1.35 \cdot 3.5 \]
\[ P_{3,e} = 4.7 \text{ lb/ft}^2 \]
\[ P_{3,f} = 1 \cdot 1.15 \cdot 27.7 \]
\[ P_{3,f} = 33.4 \text{ lb/ft}^2 \]
\[ P_{3,g} = 1 \cdot 1.15 \cdot 1.2 \]
\[ P_{3,g} = 1.6 \text{ lb/ft}^2 \]
<table>
<thead>
<tr>
<th>Theta C. Nguyen</th>
<th>LOAD DETERMINATION</th>
</tr>
</thead>
</table>

\[
\begin{align*}
    p_{2,m} &= 1 \times 1.55 \times (-23.2) \\
    p_{3,u} &= -32.1 \text{ lb/ft}^2 \\
    p_{3,Em} &= 1 \times 1.55 \times (-16) \\
    p_{3,Em} &= -21.6 \text{ lb/ft}^2 \\
    p_{3,x_{in}} &= 1 \times 1.55 \times (-12.5) \\
    p_{3,x_{in}} &= -19.7 \text{ lb/ft}^2
\end{align*}
\]
### Table D-8, Wind Loading on Lateral Force Resisting Structure

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind Load Case</th>
<th>PS (lb/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>1</td>
<td>31.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>31.9</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>1</td>
<td>31.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>31.9</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>1</td>
<td>31.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>31.9</td>
</tr>
</tbody>
</table>

### Table D-9, Lateral Element Stiffness

<table>
<thead>
<tr>
<th>Element</th>
<th>I (in⁴)</th>
<th>Height (ft)</th>
<th>K/E</th>
</tr>
</thead>
<tbody>
<tr>
<td>36&quot;</td>
<td>3888</td>
<td>9</td>
<td>0.0093</td>
</tr>
<tr>
<td>42&quot;</td>
<td>6174</td>
<td></td>
<td>0.0147</td>
</tr>
<tr>
<td>48&quot;</td>
<td>9216</td>
<td></td>
<td>0.0219</td>
</tr>
</tbody>
</table>

### Table D-10, Torsional Properties

<table>
<thead>
<tr>
<th>Floor Level</th>
<th>Center of Mass</th>
<th>Center of Rigidity</th>
<th>Eccentricity</th>
<th>Eccentricity Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x (ft)</td>
<td>y (ft)</td>
<td>x (ft)</td>
<td>y (ft)</td>
</tr>
<tr>
<td>1</td>
<td>27.5</td>
<td>15.3</td>
<td>23.2</td>
<td>19.0</td>
</tr>
<tr>
<td>2</td>
<td>21.6</td>
<td>15.1</td>
<td>18.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>
1. Wind at Front Wall
   a) In-Plane Wind Load
      1) Floor Lvl 2
         \[ F_{L1} = F_{wind,1} + F_{wind,2} \]
         \[ F_{L1} = [42.1(10.5)(6) + 33.8(10.5)(36/2-6)] + [41.7(9)(6) + 49(9)(16/2-6)] \]
         \[ F_{L1} = 6911.4 \text{ kN} \]
         \[ F_{L1} = 15334.9 \text{ kN} = 15.5 \text{ kip} \]
         \[ F_{R1} = F_{L1} \]
         \[ F_{R1} = 15.5 \text{ kip} \]
      2) Floor Lvl 1
         \[ F_{L1} = F_{wind,1} + F_{wind,1} \]
         \[ F_{L1} = 15334.9 + [41.7(9)(6) + 49(9)(16/2-6)] \]
         \[ F_{L1} = 2415.8 \text{ kN} = 24.2 \text{ kip} \]
         \[ F_{R1} = F_{L1} \]
         \[ F_{R1} = 24.2 \text{ kip} \]
   b) Vertical Wind Load
      \[ \text{Maximum combined loading (flexure and tension) occurs when minimum tension exists per NDS 2005 Interaction Equation} \]
2. Wind ⊥ Left Wall

a) In-Plane Wind Load

1) Floor Lvl 2

\[ F_{\text{Front,2}} = \frac{23.8(15)(6.5)(22.5) - 18.5(15)(6)(7.1)}{10} \]
\[ F_{\text{Front,2}} = 3363.8 \text{ lb} \]
\[ F_{\text{Front,2}} = 3.4 \text{ kip} \]

\[ F_{\text{Back,2}} = \frac{23.8(15)(6.5)(7.5) - 18.5(15)(6)(22.5) + 10.5(15)(36/2 - 6)(7.5) - 10.5(15)(36/2 - 6)(22.5)}{10} \]
\[ F_{\text{Back,2}} = 1572.8 \text{ lb} \]
\[ F_{\text{Back,2}} = 1.6 \text{ kip} \]

b) Vertical Wind Load

\[ F_{\text{Tread,1}} = \frac{23.8(15)(6)}{8} \left[ \frac{18.5(15)(6)}{10} \right] + \frac{23.8(15)(8)}{8} \left[ \frac{18.5(15)(6)}{10} \right] \]
\[ F_{\text{Tread,1}} = 179 \text{ lb} \]
\[ F_{\text{Tread,1}} = 1.77 \text{ kips} \]
\[ F_{\text{Tread,1}} = F_{\text{Right}} \]
\[ F_{\text{Tread,1}} = 1.77 \text{ kips} \]
B. CCL

*** Used only for cladding and connection design.

\[ P_{net} = 2 \times P_{net, 10} \]

\[ 2 = \text{Height Adjustment Factor for CCL, ASCE7-10 Figure 30.5-1} \]

\[ P_{net, 10} \rightarrow \text{Value taken from ASCE7-10 Figure 30.5-1} \]
A. MWFRS

1. Wind ⊥ Front Wall
   a) In-Plane Wind Load
      1) Floor Lvl 2
         \[ F_{\text{wall}} = [2.17(10.6)(6) + 17.4(10.8)(12)] \]
         \[ + [31.9(9)(6) + 25.4(9)(12)] \]
         \[ F_{\text{floor}} = 2.17 \times 10^6 \text{ lb} = 8.0 \text{kips} \]
         \[ F_{\text{right}} = F_{\text{left}} \]
         \[ F_{\text{right}} = 8.0 \text{kips} \]

      2) Floor Lvl 1
         \[ F_{\text{right}} = F_{\text{left}} + F_{\text{wind}} \]
         \[ F_{\text{left}} = 8.0 \times 10^5 \text{ lb} = 12.5 \text{kips} \]
         \[ F_{\text{right}} = 12.5 \text{kips} \]

   b) Vertical Wind Load
         \[ F_{\text{front}} = [12.3(15)(6.5) - 9.6(15)(7.5)] \]
         \[ + 15.7(15)(12.5) - 15.7(15)(7.5)]/10 \]
         \[ F_{\text{front}} = 52.5 \text{kips} \]
         \[ F_{\text{front}} = 1752.8 \text{ lb} = 1.8 \text{kips} \]
         \[ F_{\text{back}} = [12.3(15)(4.5) - 9.6(15)(4.5)] \]
         \[ + 15.7(15)(11.5) - 15.7(15)(4.5)]/10 \]
         \[ F_{\text{back}} = -2432.5 \text{ lb} = 0.21 \text{kips} \]

2. Wind ⊥ Left Wall
   a) In-Plane Wind Load
      1) Floor Lvl 2
         \[ F_{\text{front,2}} = [31.9(9.2)(2.1) + 25.4(9.6)(12)] \]
         \[ F_{\text{front,2}} = 442.5 \text{ lb} = 5.6 \text{kips} \]
2) Floor Lvl 1

\[ F_{front} = F_{front_1} + F_{wind_1} \]
\[ F_{front_1} = 58 \times 1.2 + [3.14 \times 3 \times 3 + 15.7 \times 3 \times 12] \]
\[ F_{front_1} = 922.9 \text{ lb.} = 9.2 \text{ kip.} \]
\[ F_{back} = F_{front} \]

4) Vertical Wind Load

\[ F_{easter} = \left[ \frac{12.3 \times 5 \times 6}{4} - 9.6 \times 5 \times 6 \right] + \left[ 10.7 \times 12 \times 6.7 \times 12 \right] \]
\[ F_{easter} = 945 \text{ lb.} = 0.95 \text{ kip.} \]
\[ F_{wester} = F_{easter} \]
\[ F_{wester} = 0.95 \text{ kip.} \]
# D.1.2.2 Seismic Load

## Table D-11, Effective Building Weight

<table>
<thead>
<tr>
<th>Weight Type</th>
<th>Total Weight (lb)</th>
<th>Total Effective Weight at Floor 2</th>
<th>Total Effective Weight at Main Roof</th>
<th>Total Effective Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor-Dead</td>
<td>32842</td>
<td>74584</td>
<td>51065</td>
<td>125649</td>
</tr>
<tr>
<td>Floor-Live</td>
<td>59400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof-Dead</td>
<td>24173</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior Walls</td>
<td>53784</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Table D-12, Calculated Building Period (C_u) per ASCE 7-10 §12.8.2

<table>
<thead>
<tr>
<th>Location</th>
<th>C_u (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>1.7</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>1.7</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>1.7</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>1.6</td>
</tr>
</tbody>
</table>

## Table D-13, Seismic Response Coefficient

<table>
<thead>
<tr>
<th>Location</th>
<th>T (ASCE 7-10 §12.8.2)</th>
<th>T_L (ASCE 7-10 Figure 22-12)</th>
<th>C_s,max</th>
<th>C_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>1.7</td>
<td>6</td>
<td>0.006</td>
<td>0.010</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>1.7</td>
<td>6</td>
<td>0.007</td>
<td>0.025</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>1.7</td>
<td>12</td>
<td>0.012</td>
<td>0.016</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>1.6</td>
<td>6</td>
<td>0.012</td>
<td>0.041</td>
</tr>
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</table>

## Table D-14, Seismic Loads on Residence

<table>
<thead>
<tr>
<th>Location</th>
<th>V_base (lb)</th>
<th>Shear at Levels (lb)</th>
<th>M_base (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Floor Level 2</td>
<td>Roof Level</td>
<td></td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>1256</td>
<td>746</td>
<td>511</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>3093</td>
<td>1836</td>
<td>1257</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>2062</td>
<td>1224</td>
<td>838</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>5155</td>
<td>3060</td>
<td>2095</td>
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### Table D-15, Seismic Design Characterization

<table>
<thead>
<tr>
<th>Location</th>
<th>S₁ (ASCE 7-10 Figure 22-1)</th>
<th>S₁ (ASCE 7-10 Figure 22-2)</th>
<th>F₅ (ASCE 7-10 Table 11.4-1)</th>
<th>F₅ (ASCE 7-10 Table 11.4-2)</th>
<th>S₂ₜ</th>
<th>S₃ₜ</th>
<th>Seismic Design Category (ASCE 7-10 §11.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>0.05</td>
<td>0.03</td>
<td>2.4</td>
<td>2.4</td>
<td>0.053</td>
<td>0.048</td>
<td>A</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>0.15</td>
<td>0.05</td>
<td>2.2</td>
<td>2.2</td>
<td>0.160</td>
<td>0.067</td>
<td>B</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>0.1</td>
<td>0.05</td>
<td>2.4</td>
<td>2.4</td>
<td>0.107</td>
<td>0.080</td>
<td>B</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>0.25</td>
<td>0.1</td>
<td>1.8</td>
<td>1.8</td>
<td>0.267</td>
<td>0.120</td>
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</tbody>
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### D.1.3 Controlling Factored Loads

#### Table D-16, Calculations for Determining Controlling Load Combinations

<table>
<thead>
<tr>
<th>Location</th>
<th>Magnitude of Load Combination Components (1)</th>
<th>Load Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2D + 1.6L + 0.5(Lr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2D + 1.6L (lb-ft)</td>
<td>0.5Lr (lb-ft)</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>1284.9</td>
<td>112.5</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>88.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>88.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>52.9</td>
<td>0.0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Magnitude of Load Combination Components (2)</th>
<th>Load Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2D + L + 1.0W + 0.5(Lr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2D + L (lb-ft)</td>
<td>1.0W, 1.0W, 1.0W, 0.5Lr (lb-ft)</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>1037.4</td>
<td>93.4</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>48.7</td>
<td>5625.2</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>48.7</td>
<td>5625.2</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>48.7</td>
<td>5625.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum Magnitude of Vertical and Lateral Load Combination Components (Front and Back Walls) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2D + 1.6L + 0.5(Lr</td>
</tr>
<tr>
<td></td>
<td>Vertical (lb/ft)</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>1397.4</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>1397.4</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>1397.4</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>1397.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum Magnitude of Vertical and Lateral Load Combination Components (Front and Back Walls) (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2D + 1.0W + L + 0.5(Lr</td>
</tr>
<tr>
<td></td>
<td>Vertical (lb/ft)</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>1243.4</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>1198.6</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>1198.6</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>1198.6</td>
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</table>
D.2 Structural Design

D.2.1 Light Gauge CFS

<table>
<thead>
<tr>
<th>Table D-17, Member Description</th>
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<tbody>
<tr>
<td><strong>Member Designation</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D-18, CFS Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alloy</strong></td>
</tr>
<tr>
<td>A653 Gr. 33</td>
</tr>
<tr>
<td>A653 Gr. 50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D-19, Φ Factors for Respective Load Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load Type</strong></td>
</tr>
<tr>
<td>Compression (Partially to Fully Stiffened)</td>
</tr>
<tr>
<td>Shear</td>
</tr>
<tr>
<td>Flexure (Stiffened Comp. Flange)</td>
</tr>
<tr>
<td>Flexure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D-20, Φ Factors for Respective Connection Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Connection Type</strong></td>
</tr>
<tr>
<td>Screws (Shear)</td>
</tr>
</tbody>
</table>

D.2.1.1 Flexural Design

D.2.1.1.1 Member 1 in Figure 4-11
A. Req. Properties of Potential Members

1. Flexural

\[ M_u = \frac{P_{net}}{\text{Member spacing}} \times \text{(Height)}^2 / 8 \]

\[ M_m = F_y \times t \]

\[ \Delta_{M_u} = M_u \times (t) \]

\[ \Delta_m = \frac{M_m}{F_y} \]

\[ \Delta = \frac{5 \times P_{net} \times \text{Member spacing} \times \text{(Height)}^4}{384 \times E \times t} \]

\[ I_{eq} = 5 \times P_{net} \times \text{Member spacing} \times \text{(Height)}^4 \]

*All potential members were selected based on \( \Delta_m \) and \( \Delta_{eq} \)

a) Moment Capacity of Member (LTB)

\[ F_0 = \frac{r_o A_o \times \sqrt{S_i \times t}}{2} \]

\[ \Delta M_r = \phi F_o S_y \]

\[ F_o = \left( F_y, F_x \right) > 2.78 F_y \]

\[ F_o = \begin{cases} F_y, & F_x > 2.78 F_y \\ \left( \frac{10}{9} \times \left[ 1 - \left( \frac{10}{3} \frac{F_x}{F_y} \right) \right] \right), & F_x < 2.78 F_y \\ \left( \frac{10}{9} \times \left[ 1 - \left( \frac{10}{3} \frac{F_x}{F_y} \right) \right] \right), & F_x > 2.78 F_y \end{cases} \]

b) Moment Capacity of Member (Distorsional bucking)

\[ M_{net} = F_x S_y \]

\[ M_y = F_y S_t \]

\[ \lambda = \sqrt{M_y / M_{net}} \]

\[ \Delta M_r = \phi \times M_y \times \left( 1 - \frac{0.32}{\lambda} \right) \]

\[ \phi \]
<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size (b, h, Tth)</th>
<th>( r_h ) (in)</th>
<th>( r_t ) (in)</th>
<th>( s_e ) (in)</th>
<th>( T_{e} ) (in²)</th>
<th>( S_i ) (in²)</th>
<th>( A_i ) (in²)</th>
<th>( G ) (Kip/in²)</th>
<th>( J ) (in⁴)</th>
<th>( C_m ) (in⁴)</th>
<th>( K_e ) (in)</th>
<th>( \sigma_e ) (Kip/in²)</th>
<th>( a_e ) (Kip/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>405S200-54</td>
<td>2 x 4</td>
<td>0.0560</td>
<td>1.61</td>
<td>0.758</td>
<td>1.61</td>
<td>1.29</td>
<td>0.646</td>
<td>0.646</td>
<td>0.5</td>
<td>0.000534</td>
<td>1.1</td>
<td>72.6</td>
<td>48.7</td>
</tr>
<tr>
<td>550S162-54</td>
<td>1.625 x 5.5</td>
<td>0.0566</td>
<td>2.31</td>
<td>0.750</td>
<td>1.69</td>
<td>2.44</td>
<td>0.85</td>
<td>0.85</td>
<td>0.528</td>
<td>0.000564</td>
<td>1.1</td>
<td>42.1</td>
<td>46.4</td>
</tr>
<tr>
<td>600S137-43</td>
<td>1.375 x 6</td>
<td>0.0451</td>
<td>2.22</td>
<td>0.459</td>
<td>0.796</td>
<td>2.40</td>
<td>0.65</td>
<td>0.65</td>
<td>0.413</td>
<td>0.000284</td>
<td>0.633</td>
<td>26.6</td>
<td>34.9</td>
</tr>
<tr>
<td>1006200-SF (Ga 65)</td>
<td>2 x 4</td>
<td>0.0566</td>
<td>1.61</td>
<td>0.758</td>
<td>1.64</td>
<td>2.42</td>
<td>0.85</td>
<td>0.85</td>
<td>0.528</td>
<td>0.000574</td>
<td>1.1</td>
<td>72.6</td>
<td>48.7</td>
</tr>
<tr>
<td>362S162-54 (Ga 50)</td>
<td>1.625 x 3.625</td>
<td>0.0566</td>
<td>1.44</td>
<td>0.605</td>
<td>1.25</td>
<td>2.92</td>
<td>0.857</td>
<td>0.466</td>
<td>0.482</td>
<td>0.000451</td>
<td>0.457</td>
<td>46.3</td>
<td>36.5</td>
</tr>
<tr>
<td>600S137-33</td>
<td>1.375 x 6</td>
<td>0.0346</td>
<td>2.23</td>
<td>0.464</td>
<td>-0.807</td>
<td>2.42</td>
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<td>0.455</td>
<td>0.527</td>
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<td>27.2</td>
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</table>
## D.2.1.1.2 Member 5 in Figure 4-11

Table D-22, Potential Dimensional and Strength Limits

<table>
<thead>
<tr>
<th>Limit State</th>
<th>STL. Grade</th>
<th>M_u (lb-ft)</th>
<th>S_{req} (in$^3$)</th>
<th>I_{req} (in$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
<td>Tampa, FL</td>
<td>Other</td>
</tr>
<tr>
<td>Yielding</td>
<td>33</td>
<td>603.7</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>322.6</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
<td>Tampa, FL</td>
<td>Other</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>0.08</td>
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</table>
### Table D-23, Calculations for Determining Controlling Load Combinations

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>$t_a$ (in)</th>
<th>$t_b$ (in)</th>
<th>$t_bk$ (in)</th>
<th>$r_a$ (in)</th>
<th>$r_b$ (in)</th>
<th>$L_p$ (ft)</th>
<th>$S_p$ (ft²)</th>
<th>$S_k$ (ft²)</th>
<th>$A$ (ft²)</th>
<th>$G$ (Kip/ft²)</th>
<th>$J$ (ft²)</th>
<th>$C_b$ (ft²)</th>
<th>$K_b$</th>
<th>$L_b$ (ft)</th>
<th>$\sigma_{0y} (Kip/ft²)$</th>
<th>$\sigma_{0y} (Kip/ft²)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>350S162-54</td>
<td>1.625</td>
<td>3.5</td>
<td>0.056</td>
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<td>48.4</td>
<td>35.5</td>
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<tr>
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<td>3.625</td>
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<td>1.42</td>
<td>0.50</td>
<td>-0.99</td>
<td>1.80</td>
<td>0.857</td>
<td>0.466</td>
<td>0.34</td>
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<td>0.208</td>
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<td>30.5</td>
<td>30.4</td>
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<td>30.4</td>
</tr>
<tr>
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<td>3.625</td>
<td>0.0346</td>
<td>1.42</td>
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<td>-1.00</td>
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<td>0.264</td>
<td>0.215</td>
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<td>0.155</td>
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<td>30.4</td>
<td>30.4</td>
<td>30.4</td>
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<tr>
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<td>0.304</td>
<td>0.262</td>
<td>0.000198</td>
<td>0.237</td>
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<td>30.4</td>
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<td>30.4</td>
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<tr>
<td>400S137-33</td>
<td>1.375</td>
<td>4</td>
<td>0.0346</td>
<td>1.56</td>
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<td>0.259</td>
<td>0.302</td>
<td>0.249</td>
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<td>31.1</td>
<td>29.9</td>
<td>29.9</td>
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</table>
### Table D-24, LTB Check for Flexural Members

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>2.78F_y (Kip/in²)</th>
<th>0.56F_y (Kip/in²)</th>
<th>F_c (Kip/in²)</th>
<th>F_c (Kip/in²)</th>
<th>ΦM_n (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350S162-54</td>
<td>91.7</td>
<td>18.5</td>
<td>73.2</td>
<td>32.1</td>
<td>1168.0</td>
</tr>
<tr>
<td>362S137-43</td>
<td>48.6</td>
<td>29.8</td>
<td>800.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400S137-43</td>
<td>47.8</td>
<td>29.6</td>
<td>910.3</td>
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<td></td>
</tr>
<tr>
<td>362S137-33</td>
<td>48.5</td>
<td>29.7</td>
<td>621.5</td>
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<td></td>
</tr>
<tr>
<td>362S162-33</td>
<td>72.5</td>
<td>32.0</td>
<td>770.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400S137-33</td>
<td>47.8</td>
<td>29.6</td>
<td>708.5</td>
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<td></td>
</tr>
</tbody>
</table>

### Table D-25, Local Distortional Buckling Check (AISI 100 §C3.1.4)

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>M_y (Kip-in)</th>
<th>M_cr (Kip-in)</th>
<th>λ_d</th>
<th>h/t</th>
<th>b/t</th>
<th>h/b</th>
<th>F_d (Kip/in²)</th>
<th>ΦM_n (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350S162-54</td>
<td>15.2</td>
<td>7.6</td>
<td>1.4</td>
<td>61.8</td>
<td>28.7</td>
<td>2.2</td>
<td>16.6</td>
<td>680.9</td>
</tr>
<tr>
<td>362S137-43</td>
<td>11.2</td>
<td>5.0</td>
<td>1.5</td>
<td>80.4</td>
<td>30.5</td>
<td>2.6</td>
<td>14.7</td>
<td>479.0</td>
</tr>
<tr>
<td>400S137-43</td>
<td>12.8</td>
<td>5.7</td>
<td>1.5</td>
<td>88.7</td>
<td>30.5</td>
<td>2.9</td>
<td>14.7</td>
<td>546.7</td>
</tr>
<tr>
<td>362S137-33</td>
<td>8.7</td>
<td>2.3</td>
<td>2.0</td>
<td>104.8</td>
<td>39.7</td>
<td>2.6</td>
<td>8.6</td>
<td>296.8</td>
</tr>
<tr>
<td>362S162-33</td>
<td>10.0</td>
<td>1.9</td>
<td>2.3</td>
<td>104.8</td>
<td>47.0</td>
<td>2.2</td>
<td>6.2</td>
<td>294.8</td>
</tr>
<tr>
<td>400S137-33</td>
<td>10.0</td>
<td>2.6</td>
<td>2.0</td>
<td>115.6</td>
<td>39.7</td>
<td>2.9</td>
<td>8.6</td>
<td>339.5</td>
</tr>
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</table>

### Table D-26, Recommended Members

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>Location of Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
</tr>
<tr>
<td>350S162-54</td>
<td>1.625</td>
<td>3.5</td>
</tr>
<tr>
<td>400S137-33</td>
<td>1.375</td>
<td>4</td>
</tr>
</tbody>
</table>

### D.2.1.2 Axial Design

#### D.2.1.2.1 Member 1 in Figure 4-11

### Table D-27, Required Axial Capacity per Load Case

<table>
<thead>
<tr>
<th>Designation</th>
<th>Load Combination</th>
<th>P_u (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grav</td>
<td>1.2D + 1.6L + 0.5(Lr</td>
<td></td>
</tr>
<tr>
<td>Grav-Lat</td>
<td>1.2D + 1.0W + L + 0.5(Lr</td>
<td></td>
</tr>
</tbody>
</table>
2. Axial

No members experience pure axial loads; due to most also experiencing flexural loads, potential members were selected from the previous analysis.

\[
F_n = \left( 1 + \frac{2}{\lambda_y} \right) F_y
\]

\[
C_{ax} = \frac{1}{(1 + \frac{2}{\lambda_y})^2}
\]

\[
F_c = \frac{\sigma_y}{C_x + C_{ax}}
\]

\[
\lambda_y = \sqrt{\frac{F_y}{F_c}}
\]

\[
F_a = 0.95 \frac{F_c}{1 - \nu} \left( \frac{1}{\nu} \right)^{\frac{1}{2}}
\]

\[
P_{ax} = A F_a
\]

\[
\lambda_a = \sqrt{\frac{AF_y}{P_{ax}}}
\]
### Table D-28, Calculations for Determining Controlling Load Combinations

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>Properties of Potential Members</th>
<th>K</th>
<th>L (in)</th>
<th>$\sigma_{x}$ (Ksi)</th>
<th>$\sigma_{m}$ (Ksi)</th>
<th>$\rho$ (Ksi/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S200-54</td>
<td>2 x 4 0.0560</td>
<td>1.61 0.758 -1.64 2.42 0.65 0.646 0.5</td>
<td>1</td>
<td>11300</td>
<td>0.000534 1.08</td>
<td>48.7 81.9 48.7</td>
<td></td>
</tr>
<tr>
<td>550S162-54</td>
<td>1.625 5.5 0.0560</td>
<td>2.2 0.577 -1.09 2.44 0.85 0.845 0.528</td>
<td>1</td>
<td>11300</td>
<td>0.000564 1.1</td>
<td>46.4 139.3 46.4</td>
<td></td>
</tr>
<tr>
<td>600S137-43</td>
<td>1.375 6 0.0451</td>
<td>2.22 0.459 -0.796 2.40 0.65 0.681 0.413</td>
<td>1</td>
<td>11300</td>
<td>0.00028 0.633</td>
<td>34.9 155.7 34.9</td>
<td></td>
</tr>
<tr>
<td>400S200-54 (Gr 50)</td>
<td>2 x 4 0.0566</td>
<td>1.61 0.758 -1.64 2.42 0.59 0.646 0.5</td>
<td>1</td>
<td>11300</td>
<td>0.000534 1.08</td>
<td>48.7 81.9 48.7</td>
<td></td>
</tr>
<tr>
<td>362S162-54 (Gr 50)</td>
<td>1.625 3.625 0.0566</td>
<td>1.44 0.605 -1.28 2.09412 0.857 0.666 0.482</td>
<td>1</td>
<td>11300</td>
<td>0.000451 0.457</td>
<td>36.5 65.5 36.5</td>
<td></td>
</tr>
<tr>
<td>600S137-33</td>
<td>1.375 6 0.0346</td>
<td>2.23 0.464 -0.807 2.42 0.46 0.527 0.318</td>
<td>1</td>
<td>11300</td>
<td>0.000127 0.5</td>
<td>34.8 157.1 34.8</td>
<td></td>
</tr>
</tbody>
</table>
### Table D-29, Axial Yielding and LTB Check

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>( \lambda_c )</th>
<th>( F_n ) (Kip/in²)</th>
<th>( F_e ) (Kip/in²)</th>
<th>( \Phi P_n ) (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S200-54</td>
<td>1.04</td>
<td>21.0</td>
<td>30.5</td>
<td>8920.8</td>
</tr>
<tr>
<td>550S162-54</td>
<td>0.97</td>
<td>22.2</td>
<td>34.8</td>
<td>9960.9</td>
</tr>
<tr>
<td>600S137-43</td>
<td>1.08</td>
<td>20.3</td>
<td>28.5</td>
<td>7134.7</td>
</tr>
<tr>
<td>400S200-54 (Gr 50)</td>
<td>1.28</td>
<td>25.2</td>
<td>30.5</td>
<td>10706.1</td>
</tr>
<tr>
<td>362S162-54 (Gr 50)</td>
<td>1.46</td>
<td>20.5</td>
<td>23.4</td>
<td>8391.2</td>
</tr>
<tr>
<td>600S137-33</td>
<td>1.08</td>
<td>20.3</td>
<td>28.5</td>
<td>5492.9</td>
</tr>
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</table>

### Table D-30, Local Distortional Buckling Check (AISI 100 §C4.1.2, §C4.2)

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>( \lambda_d )</th>
<th>( P_{crd} ) (Kip)</th>
<th>( h/t )</th>
<th>( b/t )</th>
<th>( h/b )</th>
<th>( F_d ) (Kip/in²)</th>
<th>( \Phi P_n ) (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S200-54</td>
<td>5.49</td>
<td>0.55</td>
<td>70.7</td>
<td>35.3</td>
<td>2.0</td>
<td>1.1</td>
<td>14803.4</td>
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<tr>
<td>550S162-54</td>
<td>4.46</td>
<td>0.87</td>
<td>97.2</td>
<td>28.7</td>
<td>3.4</td>
<td>1.7</td>
<td>16608.8</td>
</tr>
<tr>
<td>600S137-43</td>
<td>4.74</td>
<td>0.61</td>
<td>133.0</td>
<td>30.5</td>
<td>4.4</td>
<td>1.5</td>
<td>16069.1</td>
</tr>
<tr>
<td>400S200-54 (Gr 50)</td>
<td>6.76</td>
<td>0.55</td>
<td>70.7</td>
<td>35.3</td>
<td>2.0</td>
<td>1.1</td>
<td>19946.9</td>
</tr>
<tr>
<td>362S162-54 (Gr 50)</td>
<td>5.49</td>
<td>0.80</td>
<td>64.0</td>
<td>28.7</td>
<td>2.2</td>
<td>1.7</td>
<td>22427.9</td>
</tr>
<tr>
<td>600S137-33</td>
<td>6.18</td>
<td>0.27</td>
<td>173.4</td>
<td>39.7</td>
<td>4.4</td>
<td>0.9</td>
<td>13856.7</td>
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### D.2.1.3 Combined Loading

#### D.2.1.3.1 Member 1 in Figure 4-11

### Table D-31, Combined Compression and Bending Interaction for Tampa, FL (AISI 100 §C5.2.2)

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>( C_{mx} )</th>
<th>( C_{my} )</th>
<th>( P_e ) (Kip)</th>
<th>( \alpha )</th>
<th>Portions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
<td>Thk (in)</td>
<td></td>
<td></td>
<td>Axial</td>
</tr>
<tr>
<td>400S200-54</td>
<td>2</td>
<td>4</td>
<td>0.0566</td>
<td>1</td>
<td>1</td>
<td>0.17</td>
</tr>
<tr>
<td>550S162-54</td>
<td>1.625</td>
<td>5.5</td>
<td>0.0566</td>
<td>1</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>600S137-43</td>
<td>1.375</td>
<td>6</td>
<td>0.0451</td>
<td>1</td>
<td>1</td>
<td>0.21</td>
</tr>
<tr>
<td>400S200-54 (Gr 50)</td>
<td>2</td>
<td>4</td>
<td>0.0566</td>
<td>1</td>
<td>1</td>
<td>0.14</td>
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</table>
Table D-32, Combined Compression and Bending Interaction for Other Locations (AISI 100 §C5.2.2)

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>( C_{mx} )</th>
<th>( C_{my} )</th>
<th>( P_e ) (Kip)</th>
<th>( \alpha )</th>
<th>Portions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
<td>Thk (in)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>362S162-54 (Gr 50)</td>
<td>1.625</td>
<td>3.625</td>
<td>0.0566</td>
<td>1</td>
<td>1</td>
<td>27.1</td>
</tr>
<tr>
<td>600S137-33</td>
<td>1.375</td>
<td>6</td>
<td>0.0346</td>
<td>49.0</td>
<td>0.72</td>
<td>0.28</td>
</tr>
<tr>
<td>600S137-43</td>
<td>1.375</td>
<td>6</td>
<td>0.0451</td>
<td>64.4</td>
<td>0.79</td>
<td>0.21</td>
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</table>

Table D-33, Recommended Members

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>Location of Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
</tr>
<tr>
<td>400S200-54 (Gr 50)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>600S137-43</td>
<td>1.375</td>
<td>6</td>
</tr>
</tbody>
</table>

D.2.1.4 Basic Connection Formulation

Table D-34, Design Load

<table>
<thead>
<tr>
<th>Location</th>
<th>Shear (lb)</th>
<th>In-PL</th>
<th>Out-of-PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>2969.1</td>
<td>402.5</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>937.5</td>
<td>215.0</td>
<td></td>
</tr>
</tbody>
</table>

Table D-35, Minimum Center Spacing and Limiting Material Thk. (in)

<table>
<thead>
<tr>
<th>Screw Diameter (in)</th>
<th>Type of Space</th>
<th>Max. Material Thk (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Screw-Screw</td>
<td>Edge-Screw</td>
</tr>
<tr>
<td>0.138</td>
<td>0.414</td>
<td>0.207</td>
</tr>
<tr>
<td>0.164</td>
<td>0.492</td>
<td>0.246</td>
</tr>
<tr>
<td>0.19</td>
<td>0.570</td>
<td>0.285</td>
</tr>
</tbody>
</table>

Table D-36, Clip Angle Property

Source: Simpson Strong-Tie (2015)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Thk. (in)</th>
<th>( F_y ) (Kip/in(^2))</th>
<th>( F_u ) (Kip/in(^2))</th>
<th>( V_{max} ) (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC2.25</td>
<td>0.0713</td>
<td>50</td>
<td>65</td>
<td>650</td>
</tr>
<tr>
<td>SSC4.25</td>
<td>0.0713</td>
<td>50</td>
<td>65</td>
<td>420</td>
</tr>
</tbody>
</table>
D.2.1.4.1 Connection w/ Clip Angle

A. Local Strength Capacities for 500 S100-34 (sec. 34) w/ Clip Angle

1. Required

A) Tension and Bearing Capacity

\[ P_{tu} = 1500 \times \left\{ \frac{2.7 T_{cl} \times \text{Screw Diameter} \times F_{u,cl}}{\text{min}} + \frac{2.7 T_{b} \times \text{Screw Diameter} \times F_{u,b}}{\text{min}} \right\} \]

\[ P_{tu} = 162.9 \text{ lb/screw} \]

\[ \Theta P_{tu,edge} = \Theta \times 1500 \times \left\{ \frac{T_{cl} \times \text{Edge Screw Space} \times F_{u,cl}}{\text{min}} + \frac{T_{b} \times \text{Edge Screw Space} \times F_{u,b}}{\text{min}} \right\} \]

\[ \Theta P_{tu,edge} = 3.1 \text{ 102/screw} \]

b) Pull-over and Block Shear

** = Similar to structural steel calculations.

\[ \Theta P_{pu} = \text{Pull-over strength} \]

\[ \Theta P_{pu} = \Theta \times 1000 \times 1.5 \times T_{cl} \times F_{u,cl} \times d_{w} \]

\[ \Theta P_{pu} = 0.5 \times (265)(1.5)(66) = 6690 \text{ lb} \]

\[ P_{pu} = 1067.1 \text{ lb} \]

\[ \Theta P_{pu,side} = \Theta \times 1500 \times \left\{ \frac{2.0 F_{y} A_{g} + F_{u} A_{r}}{\text{min}} + \frac{2.0 F_{u} A_{r} + F_{u} A_{r}}{\text{min}} \right\} \]

\[ \Theta P_{pu,side} = 2005 \text{ lb} \]

** Though connection only experiences out-of-plane loads close to the connection capacity, it was decided to use 2 screws instead of 1 + in for handling purposes and reliability.
Table D-37, Tilting and Bearing Strength Capacity

<table>
<thead>
<tr>
<th>Member</th>
<th>Selected CFS Stud</th>
<th>$t_s$ (in)</th>
<th>$t_{fs}$ (in)</th>
<th>$t_{tot}$ (in)</th>
<th>$t_y/t_b$</th>
<th>$P_{fa}$ (lb/screw)</th>
<th>$\Phi P_{fa, int}$ (lb/screw)</th>
<th>$\Phi P_{fa, edge}$ (lb/screw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400S200-54 (Gr 50)</td>
<td>0.0566</td>
<td>0.0713</td>
<td>0.128</td>
<td>1.3</td>
<td>1629</td>
<td>1629</td>
<td>1222</td>
</tr>
<tr>
<td></td>
<td>600S137-43</td>
<td>0.0451</td>
<td>0.0713</td>
<td>0.116</td>
<td>1.6</td>
<td>899</td>
<td>899</td>
<td>674</td>
</tr>
</tbody>
</table>

Table D-38, Pull-Over and Block Shear Strength Capacity

<table>
<thead>
<tr>
<th>Member</th>
<th>Selected CFS Stud</th>
<th>$d_s$ (in)</th>
<th>$A_{pt}$ (in$^2$)</th>
<th>$A_{pt}$ (in$^2$)</th>
<th>$A_{pt}$ (in$^2$)</th>
<th>$\Phi P_{pt} (lb)$</th>
<th>$\Phi R_2 (lb)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400S200-54 (Gr 50)</td>
<td>0.307</td>
<td>0.06</td>
<td>0.12</td>
<td>0.08</td>
<td>0.09</td>
<td>1067.1</td>
</tr>
<tr>
<td></td>
<td>600S137-43</td>
<td>0.307</td>
<td>0.15</td>
<td>0.24</td>
<td>0.14</td>
<td>0.022</td>
<td>1067.1</td>
</tr>
</tbody>
</table>
### Table D-40, Bearing and Tilting Strength Capacity

<table>
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<tr>
<th>Member</th>
<th>Location of Use</th>
<th>b (in)</th>
<th>h (in)</th>
<th>Thk (in)</th>
<th>( t_{ds} ) (in)</th>
<th>( t_y/t_1 )</th>
<th>( \Phi P_{in} ) (lb/screw)</th>
<th>( \Phi P_{n,edge} ) (lb/screw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S200-54 (Gr 50)</td>
<td>Tampa, FL</td>
<td>2</td>
<td>4</td>
<td>0.0566</td>
<td>0.5</td>
<td>0.11</td>
<td>744</td>
<td>1840</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.625</td>
<td>0.09</td>
<td>744</td>
<td>801</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.75</td>
<td>0.08</td>
<td>744</td>
<td>801</td>
</tr>
<tr>
<td>600S137-43</td>
<td>Other</td>
<td>1.375</td>
<td>6</td>
<td>0.0451</td>
<td>0.5</td>
<td>0.09</td>
<td>367</td>
<td>698</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>0.625</td>
<td>0.07</td>
<td>367</td>
<td>395</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.75</td>
<td>0.06</td>
<td>367</td>
<td>395</td>
</tr>
</tbody>
</table>

### Table D-41, Gross and Net Area of Screw Connections (CFS Frame)

<table>
<thead>
<tr>
<th>Description</th>
<th>Bolt/Screw Diameter (in)</th>
<th>Fastener Quantity per Connection</th>
<th>( \Delta_{gt} ) (in²)</th>
<th>( \Delta_{nt} ) (in²)</th>
<th>( \Delta_{nt} ) (in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Diaphragm Screw Conn. (Tampa, FL)</td>
<td>0.164</td>
<td>13</td>
<td>0.0566</td>
<td>0.0451</td>
<td>0.0566</td>
</tr>
<tr>
<td>Base Diaphragm Screw Conn. (Other)</td>
<td>0.164</td>
<td>9</td>
<td>2.63</td>
<td>2.01</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>0.19</td>
<td>9</td>
<td>2.63</td>
<td>2.01</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>0.19</td>
<td>9</td>
<td>2.63</td>
<td>2.01</td>
<td>0.036</td>
</tr>
</tbody>
</table>
### Table D-42, Block Shear Strength Limit (CFS Frame)

<table>
<thead>
<tr>
<th>Member</th>
<th>Location of Use</th>
<th>Member Dimensions</th>
<th>$\Phi_{R_{b,bs}}$ (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
</tr>
<tr>
<td>400S200-54 (Gr 50)</td>
<td>Tampa, FL</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>600S137-43</td>
<td>Other</td>
<td>1.375</td>
<td>6</td>
</tr>
</tbody>
</table>

### D.2.2 Heavy Gauge CFS

### D.2.2.1 Flexural Design

#### D.2.2.1.1 Member 1 in Figure 4-11

### Table D-43, Potential Dimensional and Strength Limits

<table>
<thead>
<tr>
<th>Limit State</th>
<th>STL. Grade</th>
<th>$M_u$ (lb-ft)</th>
<th>$S_{req}$ (in$^3$)</th>
<th>$I_{req}$ (in$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
<td>Tampa, FL</td>
</tr>
<tr>
<td>Yielding</td>
<td></td>
<td>1207.36</td>
<td>645.12</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>1207.36</td>
<td>645.12</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1207.36</td>
<td>645.12</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Tampa, FL</td>
<td>1207.36</td>
<td>645.12</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>0.31</td>
<td>0.16</td>
<td>1.8</td>
</tr>
</tbody>
</table>
### Table D-44, Properties of Potential Members

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>( r_1 ) (in)</th>
<th>( r_2 ) (in)</th>
<th>( r_3 ) (in)</th>
<th>( I_x ) (in(^4))</th>
<th>( S_y ) (in(^3))</th>
<th>( S_z ) (in(^3))</th>
<th>( A ) (in(^2))</th>
<th>( G ) (Kip/in(^2))</th>
<th>( J ) (in(^4))</th>
<th>( C_y ) (in(^4))</th>
<th>( K_\nu )</th>
<th>( L_1 ) (in)</th>
<th>( f_{\nu} ) (Kips/in(^2))</th>
<th>( f_{c} ) (Kip/in(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S162-97</td>
<td>3.625 x 4</td>
<td>0.073</td>
<td>1.54</td>
<td>0.752</td>
<td>-1.18</td>
<td>2.02</td>
<td>1.81</td>
<td>0.892</td>
<td>0.907</td>
<td>0.762</td>
<td>11300</td>
<td>0.00265</td>
<td>3.889</td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>400S250-68</td>
<td>3.625 x 4</td>
<td>0.073</td>
<td>1.64</td>
<td>0.929</td>
<td>-2.11</td>
<td>2.83</td>
<td>1.84</td>
<td>0.775</td>
<td>0.932</td>
<td>0.693</td>
<td>11300</td>
<td>0.00117</td>
<td>2.23</td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>600S137-68</td>
<td>3.625 x 6</td>
<td>0.073</td>
<td>2.2</td>
<td>0.443</td>
<td>-0.768</td>
<td>2.37</td>
<td>3.09</td>
<td>1.03</td>
<td>1.03</td>
<td>0.64</td>
<td>11300</td>
<td>0.00108</td>
<td>0.93</td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>362S137-68</td>
<td>3.625 x 3.625</td>
<td>0.073</td>
<td>1.4</td>
<td>0.481</td>
<td>-0.959</td>
<td>1.76</td>
<td>0.992</td>
<td>0.493</td>
<td>0.509</td>
<td>0.47</td>
<td>11300</td>
<td>0.000797</td>
<td>3.302</td>
<td>1</td>
<td>48</td>
</tr>
</tbody>
</table>

263
<table>
<thead>
<tr>
<th>Member Designation</th>
<th>2.78F&lt;sub&gt;y&lt;/sub&gt; (Kip/in&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>0.56F&lt;sub&gt;y&lt;/sub&gt; (Kip/in&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>F&lt;sub&gt;e&lt;/sub&gt; (Kip/in&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>F&lt;sub&gt;c&lt;/sub&gt; (Kip/in&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>ΦM&lt;sub&gt;n&lt;/sub&gt; (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S162-97</td>
<td>91.7</td>
<td>18.5</td>
<td>73.8</td>
<td>32.1</td>
<td>2184.3</td>
</tr>
<tr>
<td>400S250-68</td>
<td></td>
<td></td>
<td>160.2</td>
<td>33.0</td>
<td>2024.7</td>
</tr>
<tr>
<td>600S137-68</td>
<td></td>
<td></td>
<td>44.1</td>
<td>29.0</td>
<td>2243.1</td>
</tr>
<tr>
<td>362S137-68</td>
<td></td>
<td></td>
<td>50.0</td>
<td>29.9</td>
<td>1143.2</td>
</tr>
</tbody>
</table>
Table D-46, Distortional Buckling Variable Calculations

<table>
<thead>
<tr>
<th>Member</th>
<th>$b_{cr}$ (in)</th>
<th>$d_{cr}$ (in)</th>
<th>$x_{cr}$ (in)</th>
<th>$y_{cr}$ (in)</th>
<th>$k_0$ (in)</th>
<th>$A_0$ (in$^2$)</th>
<th>$I_{cr}$ (in$^4$)</th>
<th>$I_{cr}$ (in$^4$)</th>
<th>$L_{cr}$ (in)</th>
<th>$L_{cr}$ (in)</th>
<th>$C_{cr}$ (in$^5$)</th>
<th>$L_{cr}$ (in)</th>
<th>$L_{cr}$ (in)</th>
<th>$h_{cr}$ (in/in$^2$)</th>
<th>$h_{cr}$ (in/in$^2$)</th>
<th>$h_{cr}$ (in/in$^2$)</th>
<th>$h_{cr}$ (k/in$^2$)</th>
<th>$h_{cr}$ (k/in$^2$)</th>
<th>$h_{cr}$ (k/in$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4005162-67</td>
<td>1.52</td>
<td>0.45</td>
<td>0.59</td>
<td>-0.65</td>
<td>-0.94</td>
<td>0.20</td>
<td>0.000692</td>
<td>0.002</td>
<td>0.050</td>
<td>0.006</td>
<td>0.81</td>
<td>48</td>
<td>0</td>
<td>10.92</td>
<td>2.68</td>
<td>0.050</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4005253-48</td>
<td>2.43</td>
<td>0.59</td>
<td>0.98</td>
<td>-0.06</td>
<td>-1.45</td>
<td>0.22</td>
<td>0.003665</td>
<td>0.004</td>
<td>0.135</td>
<td>0.012</td>
<td>16.11</td>
<td>24</td>
<td>0</td>
<td>3.24</td>
<td>0.60</td>
<td>0.023</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6008127-66</td>
<td>1.30</td>
<td>0.34</td>
<td>0.52</td>
<td>-0.04</td>
<td>-0.79</td>
<td>0.12</td>
<td>0.000177</td>
<td>0.001</td>
<td>0.024</td>
<td>0.002</td>
<td>0.65</td>
<td>68</td>
<td>0</td>
<td>2.99</td>
<td>0.76</td>
<td>0.012</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3625137-68</td>
<td>1.30</td>
<td>0.34</td>
<td>0.52</td>
<td>-0.04</td>
<td>-0.79</td>
<td>0.12</td>
<td>0.000189</td>
<td>0.001</td>
<td>0.021</td>
<td>0.002</td>
<td>7.76</td>
<td>168</td>
<td>0</td>
<td>1.68</td>
<td>1.02</td>
<td>0.016</td>
<td>0.002</td>
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</table>
Table D-47, Local Distortional Buckling Check (AISI 100 §C3.1.4)

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>$M_y$ (Kip-in)</th>
<th>$M_{crd}$ (Kip-in)</th>
<th>$\lambda_d$</th>
<th>h/t</th>
<th>b/t</th>
<th>h/b</th>
<th>$F_d$ (Kip/in²)</th>
<th>$\Phi M_n$ (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S162-97</td>
<td>29.9</td>
<td>376.3</td>
<td>0.28</td>
<td>39.3</td>
<td>16.0</td>
<td>2.5</td>
<td>414.9</td>
<td>2244.8</td>
</tr>
<tr>
<td>400S250-68</td>
<td>30.8</td>
<td>49.8</td>
<td>0.79</td>
<td>56.1</td>
<td>35.1</td>
<td>1.6</td>
<td>53.5</td>
<td>2114.1</td>
</tr>
<tr>
<td>600S137-68</td>
<td>34.0</td>
<td>222.1</td>
<td>0.39</td>
<td>84.2</td>
<td>19.3</td>
<td>4.4</td>
<td>215.6</td>
<td>2549.3</td>
</tr>
<tr>
<td>362S137-68</td>
<td>16.8</td>
<td>136.3</td>
<td>0.35</td>
<td>50.8</td>
<td>19.3</td>
<td>2.6</td>
<td>267.8</td>
<td>1259.8</td>
</tr>
</tbody>
</table>

D.2.2.1.2 Member 5 in Figure 4-11

Table D-48, Potential Dimensional and Strength Limits

<table>
<thead>
<tr>
<th>Limit State</th>
<th>STL. Grade</th>
<th>$M_u$ (lb-ft)</th>
<th>$S_{req}$ (in³)</th>
<th>$I_{req}$ (in⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
<td>Tampa, FL</td>
<td>Other</td>
</tr>
<tr>
<td>Yielding</td>
<td>33</td>
<td>603.68</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>322.56</td>
<td>0.15</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Table D-49, Properties of Potential Members

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size</th>
<th>Properties of Potential Members</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
</tr>
<tr>
<td>2505117-68</td>
<td>1.375</td>
<td>2.5</td>
</tr>
<tr>
<td>Member Designation</td>
<td>$2.78F_y$ (Kip/in$^2$)</td>
<td>$0.56F_y$ (Kip/in$^2$)</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>250S137-68</td>
<td>91.7</td>
<td>18.5</td>
</tr>
</tbody>
</table>
**Table D-51, Distortional Buckling Variable Calculations**

| Member Designation | \(b_{ef} \) (in) | \(d_{ef} \) (in) | \(x_{ef} \) (in) | \(y_{ef} \) (in) | \(h_{o} \) (in) | \(A_{o} \) (in\(^2\)) | \(J_{o} \) (in\(^4\)) | \(I_{o} \) (in\(^4\)) | \(k_{o} \) (in\(^4\)) | \(L_{o} \) (in) | \(L_{m} \) (in) | \(k_{o\times m} \) (Kip\(\cdot\)in\(^3\)) | \(k_{o\times w} \) (Kip\(\cdot\)in\(^3\)) | \(k_{p} \) (Kip\(\cdot\)in\(^3\)) | \(k_{p\times e} \) (Kip\(\cdot\)in\(^3\)) | \(k_{p\times w} \) (Kip\(\cdot\)in\(^3\)) |
|-------------------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 250S137-68        | 1.30            | 0.34            | 0.52            | -0.04           | -0.79          | 0.12            | 0.000199        | 0.001           | 0.021           | 0.002          | 0              | 7.07           | 48              | 4.33            | 1.36            | 0              | 0.019           | 0.001          |
### Table D-52, Local Distortional Buckling Check (AISI 100 §C3.1.4)

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>$M_y$ (Kip-in)</th>
<th>$M_{crd}$ (Kip-in)</th>
<th>$\lambda_d$</th>
<th>$h/t$</th>
<th>$b/t$</th>
<th>$h/b$</th>
<th>$F_d$ (Kip/in$^2$)</th>
<th>$\Phi M_n$ (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250S137-68</td>
<td>10.2</td>
<td>88.2</td>
<td>0.34</td>
<td>35.1</td>
<td>19.3</td>
<td>1.8</td>
<td>285.4</td>
<td>849.8</td>
</tr>
</tbody>
</table>

### D.2.2.2 Axial Design

#### D.2.2.2.1 Member 1 in Figure 4-11

<table>
<thead>
<tr>
<th>Designation</th>
<th>Load Combination</th>
<th>$P_u$ (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grav</td>
<td>$1.2D + 1.6L + 0.5(Lr</td>
<td></td>
</tr>
<tr>
<td>Grav-Lat</td>
<td>$1.2D + 1.0W + L + 0.5(Lr</td>
<td></td>
</tr>
</tbody>
</table>
### Table D-54, Properties of Potential Members

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>Member Size (b, h, Thk)</th>
<th>Properties of Potential Members (g, h, S1, S2, A, G, J, Cw, K, L, ( \sigma_y ), ( \sigma_m ), ( \sigma_t ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S162-97</td>
<td>1.625 x 4 x 0.1017</td>
<td>( 1.54 ), ( 0.572 ), ( -1.18 ), ( 2.02 ), ( 0.892 ), ( 0.907 ), ( 0.782 ), ( 0.00261 ), ( 0.839 )</td>
</tr>
<tr>
<td>400S250-68</td>
<td>2.5 x 4 x 0.0713</td>
<td>( 1.64 ), ( 0.929 ), ( -2.11 ), ( 2.83 ), ( 0.775 ), ( 0.932 ), ( 0.693 ), ( 0.00117 ), ( 2.23 )</td>
</tr>
<tr>
<td>600S137-68</td>
<td>1.375 x 6 x 0.0713</td>
<td>( 2.2 ), ( 0.443 ), ( -0.768 ), ( 2.37 ), ( 1.03 ), ( 1.03 ), ( 0.64 ), ( 0.00108 ), ( 0.93 )</td>
</tr>
<tr>
<td>360S137-68</td>
<td>1.375 x 3.634 x 0.0713</td>
<td>( 1.4 ), ( 0.461 ), ( -0.940 ), ( 1.76 ), ( 0.405 ), ( 0.400 ), ( 0.47 ), ( 0.000787 ), ( 0.303 )</td>
</tr>
<tr>
<td>Member Designation</td>
<td>$\lambda_c$</td>
<td>$F_n$ (Kip/in$^2$)</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>400S162-97</td>
<td>1.08</td>
<td>20.3</td>
</tr>
<tr>
<td>400S250-68</td>
<td>1.00</td>
<td>21.6</td>
</tr>
<tr>
<td>600S137-68</td>
<td>1.06</td>
<td>20.5</td>
</tr>
<tr>
<td>362S137-68</td>
<td>1.25</td>
<td>17.2</td>
</tr>
</tbody>
</table>
### Table D-56, Distortional Buckling Variable Calculations

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>bₛ (in)</th>
<th>dₛ (in)</th>
<th>xₛ (in)</th>
<th>yₛ (in)</th>
<th>lₛ (in)</th>
<th>Aₛ (in²)</th>
<th>Iₛ (in⁴)</th>
<th>Iₛ (in⁴)</th>
<th>Iₑ (in⁴)</th>
<th>Cₑ (in²)</th>
<th>Lₑ (in)</th>
<th>Lₑ (in)</th>
<th>kₑₛ₀ (K/in²)</th>
<th>kₑₑₛ₀ (K/in²)</th>
<th>kₑₑₑ (K/in²)</th>
<th>kₑₑₑₑ (K/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S162-97</td>
<td>1.52</td>
<td>0.45</td>
<td>0.59</td>
<td>0.05</td>
<td>0.84</td>
<td>0.20</td>
<td>0.000827</td>
<td>0.003</td>
<td>0.050</td>
<td>0.006</td>
<td>9.73</td>
<td>18.05</td>
<td>7.53</td>
<td>1.94</td>
<td>0.025</td>
<td>0.011</td>
</tr>
<tr>
<td>400S250-88</td>
<td>2.41</td>
<td>0.59</td>
<td>0.08</td>
<td>0.06</td>
<td>1.15</td>
<td>0.22</td>
<td>0.000365</td>
<td>0.004</td>
<td>0.135</td>
<td>0.012</td>
<td>18.05</td>
<td>7.53</td>
<td>2.61</td>
<td>0.67</td>
<td>0.018</td>
<td>0.002</td>
</tr>
<tr>
<td>600S137-68</td>
<td>1.30</td>
<td>0.34</td>
<td>0.52</td>
<td>0.04</td>
<td>0.79</td>
<td>0.12</td>
<td>0.000199</td>
<td>0.001</td>
<td>0.021</td>
<td>0.002</td>
<td>9.73</td>
<td>18.05</td>
<td>2.61</td>
<td>0.45</td>
<td>0.010</td>
<td>0.027</td>
</tr>
<tr>
<td>362S137-68</td>
<td>1.30</td>
<td>0.34</td>
<td>0.52</td>
<td>0.04</td>
<td>0.79</td>
<td>0.12</td>
<td>0.000199</td>
<td>0.001</td>
<td>0.021</td>
<td>0.002</td>
<td>8.58</td>
<td>11.13</td>
<td>1.13</td>
<td>0.74</td>
<td>0.013</td>
<td>0.008</td>
</tr>
</tbody>
</table>
### Table D-57, Local Distortional Buckling Check (AISI 100 §C4.1.2, §C4.2)

<table>
<thead>
<tr>
<th>Member Designation</th>
<th>λ&lt;sub&gt;d&lt;/sub&gt;</th>
<th>P&lt;sub&gt;crd&lt;/sub&gt; (Kip)</th>
<th>h/t</th>
<th>b/t</th>
<th>h/b</th>
<th>F&lt;sub&gt;d&lt;/sub&gt; (Kip/in²)</th>
<th>Φ&lt;sub&gt;P&lt;/sub&gt; (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400S162-97</td>
<td>0.33</td>
<td>238.0</td>
<td>39.3</td>
<td>16.0</td>
<td>2.5</td>
<td>312.3</td>
<td>21374.1</td>
</tr>
<tr>
<td>400S250-68</td>
<td>5.45</td>
<td>0.8</td>
<td>56.1</td>
<td>35.1</td>
<td>1.6</td>
<td>1.1</td>
<td>14867.7</td>
</tr>
<tr>
<td>600S137-68</td>
<td>0.63</td>
<td>52.9</td>
<td>84.2</td>
<td>19.3</td>
<td>4.4</td>
<td>82.7</td>
<td>31711.4</td>
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<td>362S137-68</td>
<td>0.42</td>
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<td>186.9</td>
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### D.2.2.3 Combined Loading

#### D.2.2.3.1 Member 1 in Figure 4-11

### Table D-58, Combined Compression and Bending Interaction for Tampa, FL (AISI 100 §C5.2.2)

<table>
<thead>
<tr>
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<th>Member Size</th>
<th>C&lt;sub&gt;mx&lt;/sub&gt;</th>
<th>C&lt;sub&gt;my&lt;/sub&gt;</th>
<th>P&lt;sub&gt;e&lt;/sub&gt; (Kip)</th>
<th>α</th>
<th>Portions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
<td>Thk (in)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Axial</td>
<td>Flexure</td>
<td>Total</td>
</tr>
<tr>
<td>400S162-97</td>
<td>1.625</td>
<td>4</td>
<td>0.1017</td>
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<td>1</td>
<td>57.2</td>
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<tr>
<td>400S250-68</td>
<td>2.5</td>
<td>4</td>
<td>0.0713</td>
<td>1</td>
<td>1</td>
<td>58.1</td>
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<tr>
<td>600S137-68</td>
<td>1.375</td>
<td>6</td>
<td>0.0713</td>
<td>1</td>
<td>1</td>
<td>97.6</td>
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### Table D-59, Combined Compression and Bending Interaction for Other Locations (AISI 100 §C5.2.2)

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<th>Member Size</th>
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<th>C&lt;sub&gt;my&lt;/sub&gt;</th>
<th>P&lt;sub&gt;e&lt;/sub&gt; (Kip)</th>
<th>α</th>
<th>Portions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
<td>Thk (in)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>Axial</td>
<td>Flexure</td>
<td>Total</td>
</tr>
<tr>
<td>362S137-68</td>
<td>1.375</td>
<td>3.625</td>
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### Table D-60, Recommended Members

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<th>Member Designation</th>
<th>Member Size</th>
<th>Location of Applicability</th>
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<tr>
<td></td>
<td>b (in)</td>
<td>h (in)</td>
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<td>600S137-68</td>
<td>1.375</td>
<td>6</td>
</tr>
<tr>
<td>362S137-68</td>
<td>1.375</td>
<td>3.625</td>
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</tbody>
</table>
Table D-61, Tilting and Bearing Strength Capacities

<table>
<thead>
<tr>
<th>Member</th>
<th>Selected CFS Stud</th>
<th>$t_1$ (in)</th>
<th>$t_{CL}$ (in)</th>
<th>$t_{tot}$ (in)</th>
<th>$t_2/t_1$</th>
<th>$P_{ns}$ (lb/screw)</th>
<th>$\Phi P_{ns,\text{int}}$ (lb/screw)</th>
<th>$\Phi P_{ns,\text{edge}}$ (lb/screw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600S137-68</td>
<td>0.0713</td>
<td>0.0713</td>
<td>0.143</td>
<td>1.0</td>
<td>1568</td>
<td>784</td>
<td>457</td>
</tr>
<tr>
<td>1</td>
<td>362S137-68</td>
<td>0.0713</td>
<td>0.0713</td>
<td>0.143</td>
<td>1.0</td>
<td>1568</td>
<td>784</td>
<td>457</td>
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</tbody>
</table>
### Table D-62, Recommended Connection

<table>
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<tr>
<th>Selected CFS Stud</th>
<th>Selected Clip Angle</th>
<th>Self Drilling Screws</th>
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<tbody>
<tr>
<td>600S137-68</td>
<td>SSC2.25</td>
<td>(2) #10</td>
</tr>
<tr>
<td>362S137-68</td>
<td>SSC4.25</td>
<td>(2) #10</td>
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### D.2.3 Aluminum Frame

#### Table D-63, Member Description

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<th>Description</th>
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<tr>
<td>1</td>
<td>Vertical</td>
</tr>
<tr>
<td>2</td>
<td>Same as member (1)</td>
</tr>
<tr>
<td>3</td>
<td>Horizontal, Top</td>
</tr>
<tr>
<td>4</td>
<td>Horizontal, Bottom</td>
</tr>
<tr>
<td>5</td>
<td>Horizontal, Middle</td>
</tr>
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</table>

#### Table D-64, Aluminum and Steel Mechanical Properties

Source: 2010 ADM Table A.3.4

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$F_{tu}$ kip/in$^2$</th>
<th>$F_{ty}$ kip/in$^2$</th>
<th>$F_{cy}$ kip/in$^2$</th>
<th>$F_{sue}$ kip/in$^2$</th>
<th>$F_{sy}$ kip/in$^2$</th>
<th>$E$ kip/in$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6063</td>
<td>22</td>
<td>16</td>
<td>16</td>
<td>13</td>
<td>9.6</td>
<td>10100</td>
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<td>6061</td>
<td>38</td>
<td>35</td>
<td>35</td>
<td>24</td>
<td>21</td>
<td>10100</td>
</tr>
<tr>
<td>A307</td>
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<td>45</td>
<td>27</td>
<td>27</td>
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</tbody>
</table>

#### Table D-65, Buckling Constants

Source: 2010 ADM Table B.4.2

<table>
<thead>
<tr>
<th>Member Type</th>
<th>Load Type</th>
<th>Intercept, $B_o$</th>
<th>Slope, $D_o$</th>
<th>Intersection, $C_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns and Beam Flanges</td>
<td>Axial Compression</td>
<td>17.3</td>
<td>0.07</td>
<td>98.9</td>
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<td>Flat Elements</td>
<td>Axial Compression</td>
<td>19.5</td>
<td>0.09</td>
<td>93.3</td>
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<tr>
<td></td>
<td>Bending</td>
<td>28.3</td>
<td>0.18</td>
<td>102.8</td>
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<tr>
<td></td>
<td>Shear</td>
<td>12.2</td>
<td>0.04</td>
<td>117.9</td>
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<tr>
<td>Curved Elements</td>
<td>Axial Compression</td>
<td>19.2</td>
<td>0.53</td>
<td>See Plot Curves</td>
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<tr>
<td></td>
<td>Bending</td>
<td>28.8</td>
<td>1.51</td>
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#### Table D-66, Post Buckling Constants

Source: 2010 ADM Table B.4.3

<table>
<thead>
<tr>
<th>Element of Section</th>
<th>$k_1$</th>
<th>$k_2$</th>
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<tbody>
<tr>
<td>Flat in compression (T5 to T9)</td>
<td>0.35</td>
<td>2.27</td>
</tr>
<tr>
<td>Flat in Flexure</td>
<td>0.50</td>
<td>2.04</td>
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</tbody>
</table>
### Table D-67, $\Phi$ Factors for Respective Load Type
*Source: 2010 ADM*

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Yield</th>
<th>Rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>0.90</td>
<td>0.75</td>
</tr>
<tr>
<td>Compression</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Shear</td>
<td>0.90</td>
<td>0.75</td>
</tr>
<tr>
<td>Shear (Connections)</td>
<td>1.00</td>
<td>0.75</td>
</tr>
<tr>
<td>Torsion</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Flexure</td>
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<td>0.90</td>
</tr>
</tbody>
</table>

### Table D-68, $\Phi$ Factors for Respective Connection Type
*Source: 2010 ADM*

<table>
<thead>
<tr>
<th>Connection Type</th>
<th>Yield</th>
<th>Rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welds</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Bolts (Tension, Shear)</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Bolts (Bearing/Tearout)</td>
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<td>0.75</td>
</tr>
<tr>
<td>Screws (Tension)</td>
<td>0.50</td>
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</tr>
<tr>
<td>Screws (Shear)</td>
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<td>0.50</td>
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<tr>
<td>Adhesives</td>
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<td>N/A</td>
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</tbody>
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### D.3.3.1 Flexural Design

#### D.3.3.1.1 Member 1 in Figure 4-11

### Table D-69, Potential Dimensional and Strength Limits

<table>
<thead>
<tr>
<th>Limit State</th>
<th>$c_0/c_c$</th>
<th>$m_1 \times h/t$</th>
<th>$m_2 \times h/t$</th>
<th>$M_u$ (lb-ft)</th>
<th>$S_{req}$ (in$^3$)</th>
<th>$I_{req}$ (in$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding</td>
<td>(-1, 1)</td>
<td>40.9</td>
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<td>2414.7</td>
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<td>1.7 0.9 (Tampa, FL</td>
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</table>
### Table D-70, Initial Member Sizing

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<th>Member Size</th>
<th>Thk.</th>
<th>b (in)</th>
<th>h (in)</th>
<th>b/t</th>
<th>h/t</th>
<th>A&lt;sub&gt;AL&lt;/sub&gt; (in&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>S&lt;sub&gt;AL&lt;/sub&gt; (in&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>I&lt;sub&gt;AL&lt;/sub&gt; (in&lt;sup&gt;4&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8&quot;</td>
<td>2.25</td>
<td>3.25</td>
<td>18.0</td>
<td>26.0</td>
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<td>1.2</td>
<td>1.9</td>
<td>1.1</td>
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<tr>
<td></td>
<td></td>
<td>4.5</td>
<td></td>
<td>36.0</td>
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<td>1.9</td>
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<td>1.4</td>
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<td>54.0</td>
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<td>3.5</td>
<td>11.9</td>
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</tr>
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<td>3/16&quot;</td>
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### Table D-71, Web Element Calculation Variables

<table>
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<th>Thk.</th>
<th>b (in)</th>
<th>h (in)</th>
<th>c&lt;sub&gt;c&lt;/sub&gt; (in)</th>
<th>c&lt;sub&gt;o&lt;/sub&gt; (in)</th>
</tr>
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<tbody>
<tr>
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### Table D-72, Tension and Compression Load Acting at Bottom and Top of Assembly

<table>
<thead>
<tr>
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<th>Thk.</th>
<th>b (in)</th>
<th>h (in)</th>
<th>Tension (Kip) Tampa, FL</th>
<th>Other</th>
<th>Compression (Kip) Tampa, FL</th>
<th>Other</th>
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### Table D-73, Element Local Failure Check - Strength Capacity

<table>
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<tr>
<th>Elem. Desig.</th>
<th>Dimensions</th>
<th>S1</th>
<th>S2</th>
<th>Tension (Kip)</th>
<th>Compression (Kip)</th>
<th>Satisfies Strength</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Thk (in)</td>
<td>Width (in)</td>
<td></td>
<td>Yield</td>
<td>Rupture</td>
<td>Yield</td>
</tr>
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<td>Comp. Flange</td>
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<td>Varies</td>
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<td></td>
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</table>

### Table D-74, Recommended Member 1 Dimensional Size

<table>
<thead>
<tr>
<th>Location</th>
<th>Size</th>
<th>ΦM_u (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>2-1/4x5-1/2x3/16 C</td>
<td>5188.3</td>
</tr>
<tr>
<td>Other</td>
<td>2-1/4x4-1/2x3/16 C</td>
<td>3818.2</td>
</tr>
</tbody>
</table>

### D.2.3.1.2 Member 5 in Figure 4-11

#### Table D-75, Potential Dimensional and Strength Limits

<table>
<thead>
<tr>
<th>Limit State</th>
<th>c_0/c_c</th>
<th>m_1 x h/t</th>
<th>m_2 x h/t</th>
<th>M_u (lb-ft) Tampa, FL</th>
<th>S_{req} (in^2) Tampa, FL</th>
<th>I_{req} (in^4) Tampa, FL</th>
<th>Other Tampa, FL</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding</td>
<td>(-1, 1)</td>
<td>40.9</td>
<td>603.7</td>
<td>322.6</td>
<td>0.4</td>
<td>1.3</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(∞, -1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

#### Table D-76, Initial Member Sizing

<table>
<thead>
<tr>
<th>Member Size</th>
<th>Thk.</th>
<th>b (in)</th>
<th>h/t</th>
<th>A_{AL} (in^2)</th>
<th>S_{AL} (in^3)</th>
<th>I_{AL} (in^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>1.5</td>
<td>3.25</td>
<td>24.0</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.25</td>
<td></td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>1.5</td>
<td>3.25</td>
<td>12.0</td>
<td>1.1</td>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.25</td>
<td></td>
<td>0.7</td>
<td>0.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

279
### Table D-77, Web Element Calculation Variables

<table>
<thead>
<tr>
<th>Member Size</th>
<th>b (in)</th>
<th>h (in)</th>
<th>(c_c) (in)</th>
<th>(c_o) (in)</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>1.5</td>
<td>3.25</td>
<td>-1.625</td>
<td>1.625</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.25</td>
<td>-1.125</td>
<td>1.125</td>
<td></td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>1.5</td>
<td>3.25</td>
<td>-1.625</td>
<td>1.625</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>-0.75</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

### Table D-78, Tension and Compression Load Acting at Bottom and Top of Assembly

<table>
<thead>
<tr>
<th>Member Size</th>
<th>b (in)</th>
<th>h (in)</th>
<th>Tampa, FL</th>
<th>Other</th>
<th>Tampa, FL</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>1.5</td>
<td>3.25</td>
<td>2.2</td>
<td>1.2</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.25</td>
<td>3.2</td>
<td>1.7</td>
<td>3.2</td>
<td>1.7</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>3.25</td>
<td>2.2</td>
<td>1.2</td>
<td>2.2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>4.8</td>
<td>2.6</td>
<td>4.8</td>
<td>2.6</td>
<td></td>
</tr>
</tbody>
</table>

### Table D-79, Element Local Failure Check - Strength Capacity

<table>
<thead>
<tr>
<th>Elem. Desig.</th>
<th>Dimensions</th>
<th>S1</th>
<th>S2</th>
<th>Tension (Kip)</th>
<th>Compression (Kip)</th>
<th>Satisfies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thk (in)</td>
<td>Width (in)</td>
<td></td>
<td></td>
<td>Yield</td>
<td>Rupture</td>
</tr>
<tr>
<td>Comp. Flange</td>
<td>1/16</td>
<td>1.5</td>
<td>25.6</td>
<td>49.8</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/8</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Tens. Flange</td>
<td>1/16</td>
<td>1.5</td>
<td>1.4</td>
<td>1.5</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/8</td>
<td>1.5</td>
<td>2.7</td>
<td>3.1</td>
<td>Yes</td>
<td></td>
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</table>

### Table D-80, Recommended Member 5 Dimensional Size

<table>
<thead>
<tr>
<th>Location</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>1-1/2x3-1/4x1/8 C</td>
</tr>
<tr>
<td>Other</td>
<td>1-1/2x3-1/4x1/16 C</td>
</tr>
</tbody>
</table>

### D.2.3.1.3 Member 3, 4 in Figure 4-11

<table>
<thead>
<tr>
<th>Designation</th>
<th>Load Combination</th>
<th>(M_u) (lb-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grav</td>
<td>1.2D + 1.6L + 0.5(Lr</td>
<td></td>
</tr>
<tr>
<td>Grav-Lat</td>
<td>1.2D + 1.0W + L + 0.5(Lr</td>
<td></td>
</tr>
</tbody>
</table>
## Table D-82, Moment Capacities of Wood Sections

<table>
<thead>
<tr>
<th>Section</th>
<th>Depth (in)</th>
<th>Width (in)</th>
<th>Density</th>
<th>Linear Foot Weight (lb/ft)</th>
<th>Moment Capacity of Wood Sections (lb-ft)</th>
<th>Modification Factor x (C-NDM, 2005)</th>
<th>( f_r ) (psi)</th>
<th>( f_u ) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5</td>
<td>3.5</td>
<td>0.575</td>
<td>28.5</td>
<td>11.1</td>
<td>1.05</td>
<td>1.5</td>
<td>0.85</td>
</tr>
</tbody>
</table>

## Table D-83, Properties of Potential Members

<table>
<thead>
<tr>
<th>Potential Dimensional and Strength Lumber (2010 AOM §6.1)</th>
<th>( C_m ) (in)</th>
<th>( m_k ) x ( b_k )</th>
<th>( m_k ) Lat</th>
<th>( b_k ) Galv</th>
<th>( S_m ) (in²)</th>
<th>( S_m ) Galv</th>
<th>( f_m ) (psi)</th>
<th>( f_m ) Galv</th>
<th>( f_m ) Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4&quot; x 1/2&quot;</td>
<td>0.3</td>
<td>40.9 x 0.7</td>
<td>960.2</td>
<td>465.2</td>
<td>0.7</td>
<td>0.7</td>
<td>18%</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td>1/2&quot; x 1/2&quot;</td>
<td>0.7</td>
<td>40.9 x 0.7</td>
<td>960.2</td>
<td>465.2</td>
<td>0.7</td>
<td>0.7</td>
<td>18%</td>
<td>18%</td>
<td>18%</td>
</tr>
</tbody>
</table>
Table D-84, Initial Member Sizing and Global Bending Axis Location

<table>
<thead>
<tr>
<th>Member Size</th>
<th>Thk.</th>
<th>b (in)</th>
<th>h (in)</th>
<th>b/t</th>
<th>h/t</th>
<th>A_{AL} (in^2)</th>
<th>S_{AL} (in^3)</th>
<th>x_{cm} (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>1.5</td>
<td>7.5</td>
<td>120.0</td>
<td>24</td>
<td>1.1</td>
<td>0.7</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>56.0</td>
<td>24</td>
<td>0.6</td>
<td>0.3</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>1.5</td>
<td>4.0</td>
<td>32.0</td>
<td>12</td>
<td>1.3</td>
<td>0.7</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>16.0</td>
<td>12</td>
<td>0.8</td>
<td>0.4</td>
<td>5.7</td>
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</tbody>
</table>

Table D-85, Web Element Calculation Variables

<table>
<thead>
<tr>
<th>Member Size</th>
<th>Thk.</th>
<th>b (in)</th>
<th>h (in)</th>
<th>c_c (in)</th>
<th>c_o/c_c</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>1.5</td>
<td>7.5</td>
<td>1.5</td>
<td>-3.3</td>
<td>-1.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>1.5</td>
<td>-4.3</td>
<td>-1.3</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>1.5</td>
<td>4.0</td>
<td>1.5</td>
<td>-3.3</td>
<td>-1.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>1.5</td>
<td>-4.2</td>
<td>-1.4</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Table D-86, Tension and Compression Load Acting at Bottom and Top of Assembly

<table>
<thead>
<tr>
<th>Member Size</th>
<th>Thk.</th>
<th>b (in)</th>
<th>h (in)</th>
<th>Tension (Kip)</th>
<th>Compression (Kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>1.5</td>
<td>9.25</td>
<td>1.5</td>
<td>4.4</td>
<td>2.8</td>
</tr>
<tr>
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<td>3.5</td>
<td>1.5</td>
<td>4.4</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>1.5</td>
<td>7.5</td>
<td>1.5</td>
<td>4.4</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>1.5</td>
<td>4.4</td>
<td>3.6</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table D-87, Element Local Failure Check - Strength Capacity

<table>
<thead>
<tr>
<th>Elem. Desig.</th>
<th>Dimensions</th>
<th>S_1</th>
<th>S_2</th>
<th>Tension (Kip)</th>
<th>Compression (Kip)</th>
<th>Satisfies Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thk (in)</td>
<td>Width (in)</td>
<td>Si</td>
<td>S2</td>
<td>Yield</td>
<td>Rupture</td>
</tr>
<tr>
<td>Comp. Flange</td>
<td>1/16</td>
<td>7.5</td>
<td>25.6</td>
<td>49.8</td>
<td>6.8</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>1/16</td>
<td>3.5</td>
<td>2.2</td>
<td>6.8</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>1/8</td>
<td>4</td>
<td>3.6</td>
<td>3.6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>1/8</td>
<td>2.0</td>
<td>3.6</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Tens. Flange</td>
<td>1/16</td>
<td>7.5</td>
<td>6.8</td>
<td>7.7</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>1/16</td>
<td>3.5</td>
<td>3.2</td>
<td>3.6</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>1/8</td>
<td>4</td>
<td>7.2</td>
<td>8.3</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>1/8</td>
<td>2.0</td>
<td>3.6</td>
<td>4.1</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
### Table D-88, Recommended Member 3 Dimensional Size

<table>
<thead>
<tr>
<th>Location</th>
<th>Load Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>Grav</td>
<td>1-1/2x2x1/8, 1-1/2x3.25x1/8 C</td>
</tr>
<tr>
<td></td>
<td>Grav-Lat</td>
<td>1-1/2x2x1/8, 1-1/2x3.25x1/8 C</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>Grav</td>
<td>1-1/2x2x1/8, 1-1/2x4.25x1/8 C</td>
</tr>
<tr>
<td></td>
<td>Grav-Lat</td>
<td>1-1/2x2x1/8, 1-1/2x4.25x1/8 C</td>
</tr>
<tr>
<td>Detroit, MI</td>
<td>Grav</td>
<td>1-1/2x2x1/8, 1-1/2x4.75x1/8 C</td>
</tr>
<tr>
<td></td>
<td>Grav-Lat</td>
<td>1-1/2x2x1/8, 1-1/2x4.75x1/8 C</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>Grav</td>
<td>1-1/2x2x1/8, 1-1/2x4.25x1/8 C</td>
</tr>
<tr>
<td></td>
<td>Grav-Lat</td>
<td>1-1/2x2x1/8, 1-1/2x4.25x1/8 C</td>
</tr>
</tbody>
</table>

### D.2.3.2 Axial Design

#### D.2.3.2.1 Member 1 in Figure 4-11

### Table D-89, Required Axial Capacity per Load Case

<table>
<thead>
<tr>
<th>Designation</th>
<th>Load Combination</th>
<th>$P_u$ (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grav</td>
<td>1.2D + 1.6L + 0.5(Lr</td>
<td></td>
</tr>
<tr>
<td>Grav-Lat</td>
<td>1.2D + 1.0W + L + 0.5(Lr</td>
<td></td>
</tr>
</tbody>
</table>

### Table D-90, Potential Dimensional and Strength Limits (1) (2010 ADM §E.3)

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Demand Factor</th>
<th>$\tau_b$</th>
<th>$KL_x/\tau_b$ (in)</th>
<th>$KL_y/\tau_b$ (in)</th>
<th>$C_c$</th>
<th>$F_{cy}$ (Kip/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding</td>
<td>$P_r/P_y \leq 0.5$</td>
<td>1</td>
<td>96</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P_r/P_y &gt; 0.5$</td>
<td>0.75</td>
<td>128</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexural Buckling</td>
<td>$P_r/P_y \leq 0.5$</td>
<td>1</td>
<td>96</td>
<td>48</td>
<td>98.9</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>$P_r/P_y &gt; 0.5$</td>
<td>0.75</td>
<td>128</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torsional Buckling</td>
<td>$P_r/P_y \leq 0.5$</td>
<td>1</td>
<td>96</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P_r/P_y &gt; 0.5$</td>
<td>0.75</td>
<td>128</td>
<td>64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table D-91, Potential Element Strength Limits Based on Uniform Compression

<table>
<thead>
<tr>
<th>Case</th>
<th>Limit State</th>
<th>$b/t$</th>
<th>$F_{c,min}$</th>
<th>$F_{c,max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only One Edge is Supported</td>
<td>Yielding</td>
<td>8.2</td>
<td>18.7</td>
<td>11.7</td>
</tr>
<tr>
<td></td>
<td>Inelastic Buckling</td>
<td>8.2</td>
<td>15.9</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>Elastic Buckling</td>
<td>18.7</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Post-Buckling</td>
<td>15.9</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>Both Edges are Supported</td>
<td>Yielding</td>
<td>25.6</td>
<td>49.8</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>Inelastic Buckling</td>
<td>25.6</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Post-Buckling</td>
<td>49.8</td>
<td>12.7</td>
<td></td>
</tr>
</tbody>
</table>
### Table D-92, Required Capacities for the Elements

<table>
<thead>
<tr>
<th>Member Size</th>
<th>b/t</th>
<th>h/t</th>
<th>P_u (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Grav</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>2.25</td>
<td>4.5</td>
<td>18.0</td>
</tr>
<tr>
<td>3/16&quot;</td>
<td>5.5</td>
<td>5.5</td>
<td>12.0</td>
</tr>
</tbody>
</table>

### Table D-93, Capacity of Member's Elements per 2010 ADM §E.4.2, §B.5.4.2

<table>
<thead>
<tr>
<th>Member Size</th>
<th>S1</th>
<th>S2</th>
<th>F_c (Kip/in²)</th>
<th>ΦP_n (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b</td>
<td>h</td>
<td>b</td>
<td>h</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>2.25</td>
<td>4.5</td>
<td>11.7</td>
<td>52.8</td>
</tr>
<tr>
<td>3/16&quot;</td>
<td>5.5</td>
<td>5.5</td>
<td>11.7</td>
<td>14.0</td>
</tr>
</tbody>
</table>

### Table D-94, Buckling Capacity

<table>
<thead>
<tr>
<th>Member Size</th>
<th>r (in)</th>
<th>KL/τr (in)</th>
<th>F_c (Kip/in²)</th>
<th>ΦP_n (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>2.25</td>
<td>4.5</td>
<td>1.6</td>
<td>0.94</td>
</tr>
<tr>
<td>3/16&quot;</td>
<td>5.5</td>
<td>5.5</td>
<td>1.9</td>
<td>0.93</td>
</tr>
</tbody>
</table>

### D.2.4 Basic Fastening Transparent PC Sheathing and Panel to Foundation Design

#### D.2.4.1 Bolts and Screws

### Table D-95, Required Load per Panel

<table>
<thead>
<tr>
<th>Designation</th>
<th>Load Combination</th>
<th>Shear (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
</tr>
<tr>
<td></td>
<td>In-PL</td>
<td>Out-of-PL</td>
</tr>
<tr>
<td>Grav</td>
<td>1.2D + 1.6L + 0.5(Lr</td>
<td></td>
</tr>
<tr>
<td>Grav-Lat</td>
<td>1.2D + 1.0W + L + 0.5(Lr</td>
<td></td>
</tr>
</tbody>
</table>

### Table D-96, Anchor Bolt Quantity Required per Panel (2010 ADM §J.3, §E3.4)

<table>
<thead>
<tr>
<th>Bolt Diameter (in)</th>
<th>ΦR₁,AL (lb/bolt)</th>
<th>ΦR₁,STL (lb/bolt)</th>
<th>nₛ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AL</td>
<td>STL</td>
<td>AL</td>
</tr>
<tr>
<td>0.25</td>
<td>766</td>
<td>861.5</td>
<td>6</td>
</tr>
<tr>
<td>0.375</td>
<td>1723</td>
<td>1938.3</td>
<td>3</td>
</tr>
<tr>
<td>0.5</td>
<td>3063</td>
<td>3445.9</td>
<td>2</td>
</tr>
<tr>
<td>Screw Diameter (in)</td>
<td>Moment (lb-ft)</td>
<td>$\Phi R_{1,AL}$ (lb/screw)</td>
<td>$\Phi R_{1,STL}$ (lb/screw)</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td></td>
<td>Tampa, FL</td>
<td>Other</td>
<td></td>
</tr>
<tr>
<td>0.138</td>
<td>11876</td>
<td>3750</td>
<td>84</td>
</tr>
<tr>
<td>0.164</td>
<td></td>
<td></td>
<td>123</td>
</tr>
<tr>
<td>0.19</td>
<td></td>
<td></td>
<td>168</td>
</tr>
</tbody>
</table>
Appendix E

Direct Cost Analysis and Constructability

E.1 Direct Cost Analysis

Table E-1, Average Cost of Items Not in R.S. Means

<table>
<thead>
<tr>
<th>Material</th>
<th>Average Cost of Items Not in R.S. Means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost (1)</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Cellular PC (3 mm)</td>
<td>1.95</td>
</tr>
<tr>
<td>Cellular PC (10 mm)</td>
<td>2.18</td>
</tr>
<tr>
<td>Cellular PC (16 mm)</td>
<td>3.50</td>
</tr>
<tr>
<td>Cellular PC (25 mm)</td>
<td>5.05</td>
</tr>
<tr>
<td>Granular Asphalt</td>
<td>15.58</td>
</tr>
<tr>
<td></td>
<td>387.63</td>
</tr>
<tr>
<td>Self-Drilling Screws (1&quot;)</td>
<td>0.16</td>
</tr>
<tr>
<td>Self-Drilling Screws (3/4&quot;)</td>
<td>0.15</td>
</tr>
<tr>
<td>Self-Drilling Screws (1&quot;)</td>
<td>0.17</td>
</tr>
<tr>
<td>Hold Down Bolts</td>
<td>13.40</td>
</tr>
<tr>
<td>Bearing Plate</td>
<td>0.98</td>
</tr>
</tbody>
</table>

E.1.1 Quantity Take-Offs

Table E-2, Quantity Take-Off for Light Gauge (1") in Tampa, FL

<table>
<thead>
<tr>
<th>Material</th>
<th>Line Number</th>
<th>Density (lb/in²)</th>
<th>ft</th>
<th>ft²</th>
<th>ft³</th>
<th>Lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated Glass (1/4&quot;)</td>
<td>88856100020</td>
<td>0.191</td>
<td>30.1</td>
<td>903</td>
<td>109.3</td>
<td></td>
</tr>
<tr>
<td>Cellular PC (25 mm)</td>
<td>0.0045</td>
<td>88.3</td>
<td>57.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellular PC (16 mm)</td>
<td>0.0045</td>
<td>27.7</td>
<td>9.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyurethane Foam (&lt; 2&quot;)</td>
<td>007212900530</td>
<td>0.00145</td>
<td>9.4</td>
<td>3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>0.043</td>
<td>52.0</td>
<td>99.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint Gasket (1/8&quot; x 3/8&quot;)</td>
<td>79116104400</td>
<td>0.734</td>
<td>33.2</td>
<td>0.4</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Silicone Sealant (Gallon)</td>
<td>79213240100</td>
<td>0.296</td>
<td>15.7</td>
<td>16.2</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>055813303130</td>
<td>0.296</td>
<td>15.7</td>
<td>16.2</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Aluminum (Custom Extrusions)</td>
<td>051423054000</td>
<td>0.997</td>
<td>11.3</td>
<td>0.05</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Fiber-Glass Reinforced Polystyrene</td>
<td>065710101000</td>
<td>0.994</td>
<td>11.3</td>
<td>0.05</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>4&quot; Deep Studs (17 Gauge)</td>
<td>054113301370</td>
<td>4</td>
<td>68.9</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (1&quot;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>82</td>
</tr>
<tr>
<td>Self-Drilling Screws (3/4&quot;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>106</td>
</tr>
<tr>
<td>Anchor Bolts (1 Long, 1/2&quot; Dia)</td>
<td>031519100040</td>
<td>2</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Hold Down Bolts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Bearing Plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Bolts w/ Washer and Nuts (4&quot; Long, 1/4&quot;)</td>
<td>050523100590</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
### Table E-3, Quantity Take-Off for Light Gauge (2) in Tampa, FL

<table>
<thead>
<tr>
<th>Material</th>
<th>Line Number</th>
<th>Density (lb/in³)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminted Glass (1/4&quot;)</td>
<td>88856100620</td>
<td>0.101</td>
<td>30.1</td>
</tr>
<tr>
<td>Cellular PC (25mm)</td>
<td></td>
<td>0.0045</td>
<td>829</td>
</tr>
<tr>
<td>Cellular PC (16mm)</td>
<td></td>
<td>0.0045</td>
<td>30.0</td>
</tr>
<tr>
<td>Polyurethane Foam (&lt; 1&quot;)</td>
<td>072129100310</td>
<td>0.00145</td>
<td>1.8</td>
</tr>
<tr>
<td>Polyurethane Foam (&lt; 2&quot;)</td>
<td>072129100320</td>
<td>0.00145</td>
<td>6.8</td>
</tr>
<tr>
<td>PC</td>
<td></td>
<td>0.043</td>
<td>32</td>
</tr>
<tr>
<td>Joint Gasket (1/8&quot; x 3/8&quot;)</td>
<td>79116104400</td>
<td>0.29</td>
<td>15.7</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>055813039130</td>
<td>0.097</td>
<td>0.11</td>
</tr>
<tr>
<td>Aluminum (Custom Extrusions)</td>
<td>051423070400</td>
<td>0.097</td>
<td></td>
</tr>
<tr>
<td>Fiber-Glass Reinforced Polyester Thermal</td>
<td>065210101000</td>
<td>0.0044</td>
<td>21.1</td>
</tr>
<tr>
<td>4&quot; Deep Studs (17 Gauge)</td>
<td>054113304370</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>Self-Drilling Screws (1&quot;)</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (3/4&quot;)</td>
<td></td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (1/2&quot;)</td>
<td></td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Anchor Bolts (1 Long, 1/2&quot; Dia)</td>
<td>031519100340</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Hold/Tie Downs</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Bearing Plate</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Bolts w/ Washer and Nuts (4&quot; Long, 1/4&quot;)</td>
<td>050523100590</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

### Table E-4, Quantity Take-Off for Light Gauge (1) in Washington D.C. and Albuquerque, NM

<table>
<thead>
<tr>
<th>Material</th>
<th>Line Number</th>
<th>Density (lb/in³)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminted Glass (1/4&quot;)</td>
<td>88856100620</td>
<td>0.101</td>
<td>30.1</td>
</tr>
<tr>
<td>Cellular PC (25mm)</td>
<td></td>
<td>0.0045</td>
<td>829</td>
</tr>
<tr>
<td>Cellular PC (16mm)</td>
<td></td>
<td>0.0045</td>
<td>30.0</td>
</tr>
<tr>
<td>Polyurethane Foam (&lt; 1&quot;)</td>
<td>072129100310</td>
<td>0.00145</td>
<td>1.8</td>
</tr>
<tr>
<td>Polyurethane Foam (&lt; 2&quot;)</td>
<td>072129100320</td>
<td>0.00145</td>
<td>6.8</td>
</tr>
<tr>
<td>PC</td>
<td></td>
<td>0.043</td>
<td>32</td>
</tr>
<tr>
<td>Joint Gasket (1/8&quot; x 3/8&quot;)</td>
<td>79116104400</td>
<td>0.29</td>
<td>15.7</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>055813039130</td>
<td>0.097</td>
<td>0.11</td>
</tr>
<tr>
<td>Aluminum (Custom Extrusions)</td>
<td>051423070400</td>
<td>0.097</td>
<td></td>
</tr>
<tr>
<td>Fiber-Glass Reinforced Polyester Thermal</td>
<td>065210101000</td>
<td>0.0044</td>
<td>21.1</td>
</tr>
<tr>
<td>4&quot; Deep Studs (19 Gauge)</td>
<td>054113304370</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>Self-Drilling Screws (1&quot;)</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (3/4&quot;)</td>
<td></td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (1/2&quot;)</td>
<td></td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Anchor Bolts (1 Long, 1/2&quot; Dia)</td>
<td>031519100340</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Hold/Tie Downs</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Bearing Plate</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Bolts w/ Washer and Nuts (4&quot; Long, 1/4&quot;)</td>
<td>050523100590</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Table E-5, Quantity Take-Off for Light Gauge (1) in Detroit, MI

<table>
<thead>
<tr>
<th>Material</th>
<th>Line Number</th>
<th>Density (lb/ft³)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated Glass (1/4&quot;)</td>
<td>88856100020</td>
<td>0.101</td>
<td>50.1</td>
</tr>
<tr>
<td>Cellular PC (25mm)</td>
<td></td>
<td>0.0045</td>
<td>60.5</td>
</tr>
<tr>
<td>Granular Aerogel</td>
<td></td>
<td>0.0072</td>
<td>4.7</td>
</tr>
<tr>
<td>Polyurethane Foam (&lt;2&quot;)</td>
<td>072129100320</td>
<td>0.00145</td>
<td>15.9</td>
</tr>
<tr>
<td>PC</td>
<td></td>
<td>0.043</td>
<td>32.0</td>
</tr>
<tr>
<td>Joint Gasket (1/8&quot; x 3/8&quot;)</td>
<td>79116104400</td>
<td></td>
<td>23.2</td>
</tr>
<tr>
<td>Silicone Sealant (Gallon)</td>
<td>079213204100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>055813050130</td>
<td>0.29</td>
<td>15.7</td>
</tr>
<tr>
<td>Aluminum (Custom Extrusions)</td>
<td>051423050400</td>
<td>0.097</td>
<td>0.05</td>
</tr>
<tr>
<td>Fiber-Glass Reinforced Polyester Thermal</td>
<td>065210101000</td>
<td>0.094</td>
<td>11.3</td>
</tr>
<tr>
<td>6&quot; Deep Studs (19 Gauge)</td>
<td>054113304200</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Self-Drilling Screws (1&quot;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (3/4&quot;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (1/2&quot;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anchor Bolts (1'L, 1/2&quot; Dia)</td>
<td>031519100040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hold Down Screws</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing Plate</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Bolts w/ Washer and Nuts (4&quot; Long, 1/4&quot;)</td>
<td>050523100090</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table E-6, Quantity Take-Off for Heavy Gauge (1) in Tampa, FL

<table>
<thead>
<tr>
<th>Material</th>
<th>Line Number</th>
<th>Density (lb/ft³)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated Glass (1/4&quot;)</td>
<td>88856100020</td>
<td>0.101</td>
<td>30.1</td>
</tr>
<tr>
<td>Cellular PC (25mm)</td>
<td></td>
<td>0.0045</td>
<td>88.9</td>
</tr>
<tr>
<td>Cellular PC (16mm)</td>
<td></td>
<td>0.0043</td>
<td>28.4</td>
</tr>
<tr>
<td>Polyurethane Foam (&lt;2&quot;)</td>
<td>072129100320</td>
<td>0.00145</td>
<td>12.8</td>
</tr>
<tr>
<td>PC</td>
<td></td>
<td>0.043</td>
<td>32</td>
</tr>
<tr>
<td>Joint Gasket (1/8&quot; x 3/8&quot;)</td>
<td>79116104400</td>
<td></td>
<td>23.2</td>
</tr>
<tr>
<td>Silicone Sealant (Gallon)</td>
<td>079213204100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>055813050130</td>
<td>0.29</td>
<td>15.7</td>
</tr>
<tr>
<td>Aluminum (Custom Extrusions)</td>
<td>051423050400</td>
<td>0.097</td>
<td>0.05</td>
</tr>
<tr>
<td>Fiber-Glass Reinforced Polyester Thermal</td>
<td>065210101000</td>
<td>0.094</td>
<td>11.3</td>
</tr>
<tr>
<td>6&quot; Deep Studs (15 Gauge)</td>
<td>054113304410</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Self-Drilling Screws (1&quot;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (3/4&quot;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-Drilling Screws (1/2&quot;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anchor Bolts (1'L, 1/2&quot; Dia)</td>
<td>031519100040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hold Down Screws</td>
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### Table E-7, Quantity Take-Off for Heavy Gauge (1) in Washington D.C. and Albuquerque, NM

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<th>ft³</th>
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### Table E-8, Quantity Take-Off for Heavy Gauge (1) in Detroit, MI

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### Table E-9, Quantity Take-Off for Structural Aluminum in Tampa, FL

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### Table E-10, Quantity Take-Off for Structural Aluminum in Washington D.C. and Albuquerque, NM

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Table E-11, Quantity Take-Off for Structural Aluminum in Detroit, MI

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<td>Bolts w/ Washer and Nuts (1&quot; Long, 1/4&quot;)</td>
<td>050323100200</td>
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Table E-12, Quantity Take-Off for Original Wall System (RGWPS)

<table>
<thead>
<tr>
<th>Material</th>
<th>Line Number</th>
<th>Density (lb/ft^3)</th>
<th>ft</th>
<th>ft^2</th>
<th>ft^3</th>
<th>lb</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGU</td>
<td>084413100350</td>
<td>0.0005</td>
<td>32</td>
<td>32</td>
<td>10.4</td>
<td>198.0</td>
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<tr>
<td>Joint Gasket</td>
<td>079116104400</td>
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<td>96</td>
<td></td>
<td></td>
<td>615.6</td>
<td></td>
</tr>
<tr>
<td>5&quot;x5&quot; HSS Section</td>
<td>051223175100</td>
<td>0.29</td>
<td>0.5</td>
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<td>0.1</td>
<td>0.1</td>
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<tr>
<td>1/4&quot; Connecting Plate</td>
<td>051223950300</td>
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<td>0.002</td>
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<td>Custom Connectors</td>
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Table E-13, Quantity Take-Off for Traditional Wood Frame in Tampa, FL

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<th>Line Number</th>
<th>Density (lb/ft^3)</th>
<th>ft</th>
<th>ft^2</th>
<th>ft^3</th>
<th>lb</th>
<th>n</th>
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<tbody>
<tr>
<td>Vinyl Siding</td>
<td>074633104300</td>
<td>0.0197</td>
<td>32</td>
<td>1024.0</td>
<td>5.7</td>
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<tr>
<td>Vapor Retarder</td>
<td>072351000100</td>
<td>0.022</td>
<td>32</td>
<td>1024.0</td>
<td>44.8</td>
<td>44.8</td>
<td></td>
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<tr>
<td>OSB Plywood (7/16&quot; Thk)</td>
<td>061535003400</td>
<td>0.0222</td>
<td>32</td>
<td>1024.0</td>
<td>44.8</td>
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<tr>
<td>2x6 Wood Studs</td>
<td>061110403165</td>
<td>0.0191</td>
<td>31.25</td>
<td>1000.0</td>
<td>59.1</td>
<td>59.1</td>
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<tr>
<td>FiberGlass Batt (R-13)</td>
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<td>0.0006</td>
<td>32</td>
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<td>0.0056</td>
<td>32</td>
<td>1024.0</td>
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<td>Hold/Tie Down</td>
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<td>Bearing Plate</td>
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Table E-14, Quantity Take-Off for Traditional Wood Frame in Washington D.C. and Albuquerque, NM

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<th>Material</th>
<th>Line Number</th>
<th>Density (lb/ft³)</th>
<th>ft²</th>
<th>ft³</th>
<th>lb</th>
<th>n</th>
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<tr>
<td>Vinyl Siding</td>
<td>074633104000</td>
<td>0.0197</td>
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<tr>
<td>Vapor Retarder</td>
<td>072510100480</td>
<td>0.0197</td>
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<td>5.7</td>
<td></td>
</tr>
<tr>
<td>OSB/Plywood (7/16” Thk)</td>
<td>061626100840</td>
<td>0.0222</td>
<td>32</td>
<td></td>
<td>44.8</td>
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</tr>
<tr>
<td>2x6 Wood Studs</td>
<td>061110406165</td>
<td>0.0191</td>
<td>31.25</td>
<td></td>
<td>50.1</td>
<td></td>
</tr>
<tr>
<td>Fiberglass Batt (R-19)</td>
<td>072116200160</td>
<td>0.0006</td>
<td>32</td>
<td></td>
<td>17.1</td>
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</tr>
<tr>
<td>Gypsum Wallboard (1/2” Thk)</td>
<td>092910300320</td>
<td>0.0306</td>
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<td>70.4</td>
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<tr>
<td>Nails (#8)</td>
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<td></td>
<td>70.4</td>
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</tr>
<tr>
<td>Anchor Bolts (1’ Long, 1/2” Dia)</td>
<td>031510900040</td>
<td>0.0306</td>
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<td>70.4</td>
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<tr>
<td>Hold/Tie Downs</td>
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Table E-15, Quantity Take-Off for Traditional Wood Frame in Detroit, MI

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<th>lb</th>
<th>n</th>
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<tbody>
<tr>
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<tr>
<td>Vapor Retarder</td>
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<td>0.0197</td>
<td>32</td>
<td></td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>OSB/Plywood (7/16” Thk)</td>
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<td>0.0222</td>
<td>32</td>
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<td>44.8</td>
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</tr>
<tr>
<td>2x6 Wood Studs</td>
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<td>0.0191</td>
<td>31.25</td>
<td></td>
<td>50.1</td>
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</tr>
<tr>
<td>Fiberglass Batt (R-21)</td>
<td>072116200160</td>
<td>0.0006</td>
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<td></td>
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<tr>
<td>Gypsum Wallboard (1/2” Thk)</td>
<td>092910300320</td>
<td>0.0306</td>
<td>32</td>
<td></td>
<td>70.4</td>
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<tr>
<td>Nails (#8)</td>
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<td>0.0306</td>
<td>32</td>
<td></td>
<td>70.4</td>
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<td>Hold/Tie Downs</td>
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<td>Bearing Plate</td>
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Table E-16, Direct Cost Estimate for Light Gauge (1) in Tampa, FL

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<tr>
<th>Light Gauge (1) in Tampa, FL</th>
<th>Cost Code</th>
<th>Material</th>
<th>Labor Cost</th>
<th>Number of Crews</th>
<th>Labor Cost</th>
<th>Material Cost</th>
<th>Unit Crew Size</th>
<th>Unit Cost</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Windows Glazing and Gaskets</td>
<td>$293.00</td>
<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>2</td>
<td>$3.15</td>
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</tr>
<tr>
<td>Interior Glass (14.3%)</td>
<td>$293.00</td>
<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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</tr>
<tr>
<td>Insulation</td>
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<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
<td></td>
</tr>
<tr>
<td>Windows Glazing and Gaskets</td>
<td>$293.00</td>
<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
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<td>$2.02</td>
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<tr>
<td>Interior Glass (14.3%)</td>
<td>$293.00</td>
<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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</tr>
<tr>
<td>Insulation</td>
<td>$293.00</td>
<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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</tr>
<tr>
<td>Metal</td>
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<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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</tr>
<tr>
<td>Metal</td>
<td>$293.00</td>
<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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</tr>
<tr>
<td>Metal</td>
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<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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<tr>
<td>Metal</td>
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<td>$0.20</td>
<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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<td>$0.20</td>
<td>$50.50</td>
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<td>$125.71</td>
<td>$420.59</td>
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<td>$2.02</td>
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<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
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<td>$2.02</td>
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<td>Metal</td>
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<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
<td>1</td>
<td>$2.02</td>
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<tr>
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<td>$50.50</td>
<td>1</td>
<td>$125.71</td>
<td>$420.59</td>
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<td>$2.02</td>
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<td>Subtotals</td>
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<td>$2.02</td>
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</table>

[1] Values referenced from E.S. Moses 2015
[2] Labor is assumed to be 40%
[3] Material is assumed to be 10%
[4] Waste factor is assumed to be 5%
[5] Waste factor is assumed to be 15%
[6] Open shop labor
[7] O&P is assumed to be 10%
Table E-17, Direct Cost Estimate for Light Gauge (2) in Tampa, FL

<table>
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<th>Cost Code</th>
<th>Item</th>
<th>Units</th>
<th>Quantity</th>
<th>Material Unit Cost (UD)</th>
<th>Material Cost</th>
<th>Labor Unit Cost (UD)</th>
<th>Unit Output per Crew</th>
<th>Unit Crew Size</th>
<th>Number of Crews</th>
<th>Labor Cost</th>
<th>Equipment Unit Cost</th>
<th>Equipment Cost</th>
<th>Total w/ Waste Factor</th>
<th>Notes</th>
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<tr>
<td><strong>Window Glazing and Gaskets</strong></td>
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</tr>
<tr>
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<tr>
<td>0991694400</td>
<td>Joint Gasket (1/8&quot; x 1/8&quot;)</td>
<td>ft²</td>
<td>20.1</td>
<td>$11.02</td>
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<td>$24.31</td>
<td>90.00</td>
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<tr>
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<td>10.0</td>
<td>$7.71</td>
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<td>ft³</td>
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<td>$0.56</td>
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<td>ft³</td>
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Table E-18, Direct Cost Estimate for Heavy Gauge (1) in Tampa, FL

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Table E-19, Direct Cost Estimate for Aluminum Frame in Tampa, FL

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<th>Unit Crew Size</th>
<th>Number of Crews</th>
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Table E-20, Direct Cost Estimate for Light Gauge (1) in Washington D.C. and Albuquerque, NM

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<th>Labor Unit Cost</th>
<th>Daily Output per Crew</th>
<th>Unit Crew Size</th>
<th>Number of Crews</th>
<th>Labor Cost</th>
<th>Equipment Unit Cost</th>
<th>Equipment Cost</th>
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Subtotals: $3,377.04, $299.32, $1,442.81, $3,976.96, $168.81, $3.82, $1,532.78

Sales Tax (8%): $20.21

Overhead & Profit (10%): $357.97, $3.64

Total: $1,191.99, $655.83, $4.12, $1,545.06
Table E-21, Direct Cost Estimate for Heavy Gauge (1) in Washington D.C. and Albuquerque, NM

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<th>Number of Crews</th>
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<th>Total w/ Waste Factor</th>
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</tbody>
</table>

Subtotal | $5,552.92 | $181.82 | $0.00 | [5] |
Sales Tax (9%) | $204.18 | | | |
Overhead & Profit (10%) | $225.41 | $78.18 | | [9] |
Subtotal | $5,090.52 | $266.00 | $0.82 | [9] |
Contingencies (10%) | $590.95 | $58.09 | $0.10 | [10] |
Adjustments | $0.00 | $0.00 | $0.00 | | |
Total | $5,460.47 | $266.00 | $1.90 | $5,710.00 | [5] |
Table E-22, Direct Cost Estimate for Aluminum Frame in Washington D.C. and Albuquerque, NM

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<th>Quantity</th>
<th>Material Unit Cost</th>
<th>Material Cost</th>
<th>Labor Unit Cost</th>
<th>Labor Cost</th>
<th>Equipment Unit Cost</th>
<th>Equipment Cost</th>
<th>Notes</th>
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<td>$12.23</td>
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<td>1</td>
<td>$181.44</td>
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<tr>
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Subtotals: $1,261.83 $854.83 $0.79 $4,019.91

Sales Tax (9%): $113.50

Overhead & Profit (10%): $64.75

Subtotal: $1,261.83 $854.83 $0.79 $4,019.91

Contingency (10%): $394.32 $394.32 $394.32 $394.32

Adjustments: $0.00 $0.00 $0.00 $0.00

Total: $1,956.83 $949.15 $1.38 $5,413.81
Table E-23, Direct Cost Estimate for Light Gauge (1) in Detroit, MI

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Table E-24, Direct Cost Estimate for Heavy Gauge (1) in Detroit, MI

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| Insulation  |                              |       |          |                           |               |                        |            |                             |                |                 |                | $109.61             |       |
|             | Cellulose PC (2% max)          | ft²   | 80.0     | $4.71                     | $377.68       |                        |            |                             |                |                 |                | $83.79              |       |
|             | Blown Aluminum                 | ft²   | 5.1      | $5.79                     | $31.77        |                        |            |                             |                |                 |                | $111.79             | [3]   |
|             | Polyurethane Foam (2'')        | ft³   | 7.7      | $0.19                     | $1.38         | $0.28                  | $31.28     | 300.00                      | 5              | 1               | $2.13           | $20.24              | $12.60 | [4]   |
|             | Fiber Glass Reinforced Polyester| ft³   | 11.3     | $7.56                     | $84.83        |                        |            |                             |                |                 |                | $133.32             |       |

| Metal       | Stainless Steel                | ft    | 15.0     | $12.20                    | $183.00       | $24.27                 | $364.27    | 24.00                       | 2              | 1               | $252.22        | $1,220.22           |       |
|             | Aluminum (Oxygen Extraction)   | lb    | 8.2      | $1.22                     | $10.10        | $1.47                  | $11.65     | 110.00                      | 7              | 3               | $73.05          | $329.78             |       |
|             | 1/2 Deep Due Studs (12 Gauge)  | ft    | 4.0      | $3.82                     | $15.28        | $2.09                  | $16.08     | 90.00                       | 2              | 1               | $27.18          | $61.25              |       |
|             | Self-Drilling Screw (1"")     | n     | 15.9     | $0.18                     | $2.80         |                        |            |                             |                |                 |                | $2.76               | [3]   |
|             | Self-Drilling Screw (3/8")    | n     | 86.9     | $0.13                     | $11.62        |                        |            |                             |                |                 |                | $0.87               | [3]   |
|             | Self-Drilling Screw (5/8")    | n     | 86.9     | $0.13                     | $11.62        |                        |            |                             |                |                 |                | $0.87               | [3]   |
|             | Anchor Bolt (1" Long, 1/4"")  | n     | 2.0      | $1.09                     | $2.18         | $0.58                  | $1.83      | 30.00                       | 1              | 1               | $3.18           | $23.82              |       |
|             | Threaded Rods                   | n     | 4.0      | $1.00                     | $4.00         |                        |            |                             |                |                 |                | $12.32              |       |
|             | Bearing Race                   | n     | 6.0      | $0.71                     | $4.26         |                        |            |                             |                |                 |                | $4.40               | [3]   |
|             | Bolts w/ Washers & Nuts (4" Long, 3/4"") | n     | 2.0      | $0.16                     | $3.20         | $0.82                  | $2.66      | 20.00                       | 1              | 1               | $3.38           | $7.70               |       |

| Misc.       | 2" STP (5") Temp. Beams        | 1000 ft| 5.00    | $203.66                   | $1,018.30     | $1,64.29               | $164.29    |                             |                |                 |                | $1,213.44           |       |
|             | Laborers                        | Week  | 8.48    | $1.59                     | $13.40        | $1.59                  | $13.40     |                             |                |                 |                | $21.90              |       |

| Subtotals   |                                    |       |          |                           |               |                        |            |                             |                |                 |                | $854.87             |       |
| Sales Tax (9%)|                              |       |          |                           |               |                        |            |                             |                |                 |                | $77.64              |       |
| Overhead & Profit (10%) |                           |       |          |                           |               |                        |            |                             |                |                 |                | $83.44              |       |
| Subtotal    |                                    |       |          |                           |               |                        |            |                             |                |                 |                | $939.31             |       |
| Company Tax (10%) |                           |       |          |                           |               |                        |            |                             |                |                 |                | $93.93              |       |
| Adjustments |                                    |       |          |                           |               |                        |            |                             |                |                 |                | $0.00               |       |

| Total       |                                    |       |          |                           |               |                        |            |                             |                |                 |                | $1,033.79           |       |
Table E-25, Direct Cost Estimate for Aluminum Frame in Detroit, MI

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Notes:
- [1] ~ [8] indicate specific notes or references related to each entry.
Table E-26, Direct Cost Estimate for Wood Frame in Tampa, FL

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<th>Material</th>
<th>Material Cost</th>
<th>Labor Unit</th>
<th>Labor Daily</th>
<th>Unit Rate</th>
<th>Number of</th>
<th>Labor Cost</th>
<th>Equipment Unit</th>
<th>Equipment Total w/ Waste</th>
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<tr>
<td>074651104000</td>
<td>Vinyl Siding</td>
<td>ft²</td>
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<td>ft²</td>
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<td>1</td>
<td>$2.24</td>
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<td>$7.28</td>
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| 061368100000 | OSB (17/32"
        | ft²   | 32.0     | $0.30    | $9.48        | $0.82      | 1400.00     | 2         | 1         | $10.24     |                | $23.34                   |       |
| 092910000500 | Gypsum Wellboard (1/2"
        | ft²   | 32.0     | $0.37    | $11.84       | $0.47      | 9405.00     | 2         | 1         | $15.04     |                | $27.37                   |       |
| 072111010000 | Fiberglass Batt (E-13)  | ft²   | 31.3     | $0.32    | $10.00       | $0.22      | 1350.00     | 1         | 1         | $6.18      |                | $17.38                   |       |
| 060531100520 | Nails (1d Common)        | lb    | 1.0      | $1.50    | $1.56        |            |             |           |           |            |                | $1.64                    |       |
| 013111010540 | Anchor Bolts (1/" Long 1/2"
        | n     | 3.0      | $1.26    | $3.78        | $1.69      | 1311.00     | 1         | 1         | $3.78      |                | $6.42                    |       |
| 013111010540 | Hold Down Screws         | n     | 1.0      | $8.60    | $8.60        |            |             |           |           | $8.60      |                | $8.60                    |       |
| 013111010540 | Beam Plate               | n     | 1.0      | $8.71    | $8.71        |            |             |           |           | $8.71      |                | $8.71                    |       |
| 013110400665 | 2x6 Wood Studs           | 1000 ft | 0.031 | $58.32   | $1.83        |            |             |           |           | $11.79     |                | $31.92                   |       |
| 013110300100 | 2x6 SPF (F) Temp. Insulg     | 1000 ft | 0.028 | $88.22   | $2.91        |            |             |           |           | $164.39    |                | $266.51                   |       |
| 012113201900 | Labor                    | Week  | 0.142   | $1,150.00 | $12.89       | $0.00      |             |           |           | $164.39    |                | $266.51                   |       |
|            | **Subtotal**             |       | $120.38 | $240.39   | $0.00        | $370.93    |             |           |           |            |                |                          |       |
|            | **Sales Tax (9%)**       |       |          |           | $7.76        |            |             |           |           |            |                |                          | [5]   |
|            | **Gross Profit (39%)**   |       |          |           | $12.70       | $3.01      |             |           |           |            |                |                          | [5]   |
|            | **Subtotal**             |       | $130.44 | $246.10   | $0.00        | $377.55    |             |           |           |            |                |                          |       |
|            | **Contingency (10%)**    |       |          |           | $15.07       | $15.41     | $0.00       | $15.41   |           |            |                |                          |       |
|            | **Adjustments**          |       |          |           | $0.00        | $0.00      | $0.00       | $0.00    |           |            |                |                          |       |
|            | **Total**                |       | $165.81 | $266.51   | $0.00        | $437.32    |             |           |           |            |                |                          |       |
Table E-27, Direct Cost Estimate for Wood Frame in Washington D.C. and Albuquerque, NM

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<th>Material Cost</th>
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<th>Number of</th>
<th>Labor Cost</th>
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**Insulation**

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<th>Number of</th>
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**Metal**

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**Misc.**

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Table E-28, Direct Cost Estimate for Wood Frame in Detroit, MI

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Subtotal: $320.86
Sales Tax (9%): $8.45
Overhead & Profit (10%): $14.90
Subtotal: $343.21
Contingency (20%): $68.64
Adjustments: $0.00
Total: $412.81
Table E-29, Direct Cost Estimate for Original Wall System (RGWPS)

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Chicago.


