Patel School of Global Sustainability

Energy Efficiency of Monolithic Domes

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Patel School of Global Sustainability

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Master of Arts Project Report

by

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Abstract

According to the U.S. Energy Information Administration (EIA), buildings in the U.S. consume 40 percent of energy, 72 percent of electricity, 13.6 percent of potable water and produce 39 percent of total carbon dioxide emissions (EIA). Energy consumption in buildings is driven by various aspects including heating, cooling, lighting and process loads. The Monolithic Dome Institute claims that their building structures obtain an average savings of 30 to 50 percent in cooling and heating operating costs when compared to conventional buildings. The Monolithic Dome's (MD) shape, the materials used and the placement of the materials are accredited with this claim (MDI).

Green buildings with third party certification, such as the US Green Building Council's (USGBC) LEED certification and the Green Building Council of Australia's (GBCA) Green Star (GS) certification, achieve energy efficiency using a variety of strategies. Energy efficiency is identified as the most important aspect of sustainable development in these point based systems and across the world mandatory energy standards are being implemented for buildings. Although significant weight is placed on obtaining energy points in systems like LEED, applicants need only meet several pre-requisites after which they can forego any further achievements in reducing energy consumption.

With energy identified as one of the most important resources to manage it's important to consider all the possible avenues in making buildings more energy efficient. This study looked at the modeled and actual energy consumption of a MD and compared it to the modeled energy consumption of a conventionally built building that followed ASHRAE Standard 90.1, Appendix G methods. Emphasis was placed on the methodologies and materials used during the construction phase and particularly on the building envelope and associated HVAC load used under the MD guidelines. The energy efficiency credits used in LEED were explored in an attempt to define how MDs could achieve these points and work even further to be considered green buildings. Although conclusive data was not obtained on how MDs compare to LEED buildings in energy efficiency, it was concluded that MDs are potentially more sustainable because of their longevity and adaptability to incorporate other green building strategies.

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Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

A/C	Air conditioner
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
CS	Core and Shell
EA	Energy and Atmosphere
EUI	Energy use intensity
FEMA	Federal Emergency Management Agency
GBCA	Green Building Council of Australia
GS	Green Star
HVAC	Heating, ventilation and air conditioning
IECC	International Energy Conservation Code
ISD	Independent School District
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
MD	Monolithic Dome
MDI	Monolithic Dome Institute
NBI	New Building Institute
NC	New Construction
R-value	Thermal resistance value
SPF	Spray polyurethane foam
SPFA	Spray Polyurethane Foam Alliance
USDOE	U.S. Department of Energy
USEIA	U.S. Energy Information Administration
USGBC	U.S. Green Building Council

1 Introduction

What makes the world go around? For some it's coffee. For a chemist it may be atoms. For a physicist it may be the concepts of force and energy. For an architect it could be drawings and designing. The most literal answer to this question is perhaps gravity. All living and non-living properties require energy or have an embodied energy associated with their function and production. In a physical and even political sense, energy allows the everyday functions in the world possible. Our society is dependent upon a source of energy to be operational in the aspects of transportation, functioning buildings, mechanical structures and so on and so forth. Many in the United States of America and abroad consider fossil fuels as the main source of energy and as a form of energy that has become extremely controversial and attached to negative connotations. Fossil fuels use hundreds of millions of fossils compacted and transformed from living matter into peat, then sedimentary rocks and finally our final and essential form of energy, coal, oil and natural gas. These resources are finite, as they require millions of years to create and when they are extracted from the ground at a faster pace than they can be replaced we are bound to run out.

1.1 Background

Perhaps the importance of energy and all the debates that revolve around its acquisition are the reason why so much importance is placed on energy efficiency in the building industry. Legislative policies that target building energy performance have been growing in number and potency. In the U.S., minimum building energy codes for commercial and residential buildings have been made mandatory for at least 37 states.[1] In places like New York City, legislative action is making certain energy standards mandatory. In a study conducted by the City of New York 75% of the city's total annual carbon emissions were attributed to buildings.[2] This finding along with increasing energy costs jolted the city into putting together an energy policy that requires annual

[1] (Energy Efficiency Program Administrators and Building Energy Codes, 2009)
[2] (Skolnik, 2011)

benchmark reports for energy and water use of city buildings over 10,000 square feet and privately owned buildings over 50,000 square feet.[3]

According to the U.S. Energy Information Administration (USEIA), buildings in the U.S. consume 40 percent of energy, 72 percent of electricity, and 13.6 percent of potable water and produce 39 percent of total carbon dioxide emissions.[4] The U.S. Department of Energy (USDOE) has worked in collaboration with the International Energy Conservation Code (IECC) and the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) to maintain and develop a set of residential and commercial energy codes that are used across the world. In the U.S. alone, eight states have not yet adopted these state-wide energy codes for commercial buildings and nine states have not adopted state-wide residential building codes (see *Figure 1*).[5]

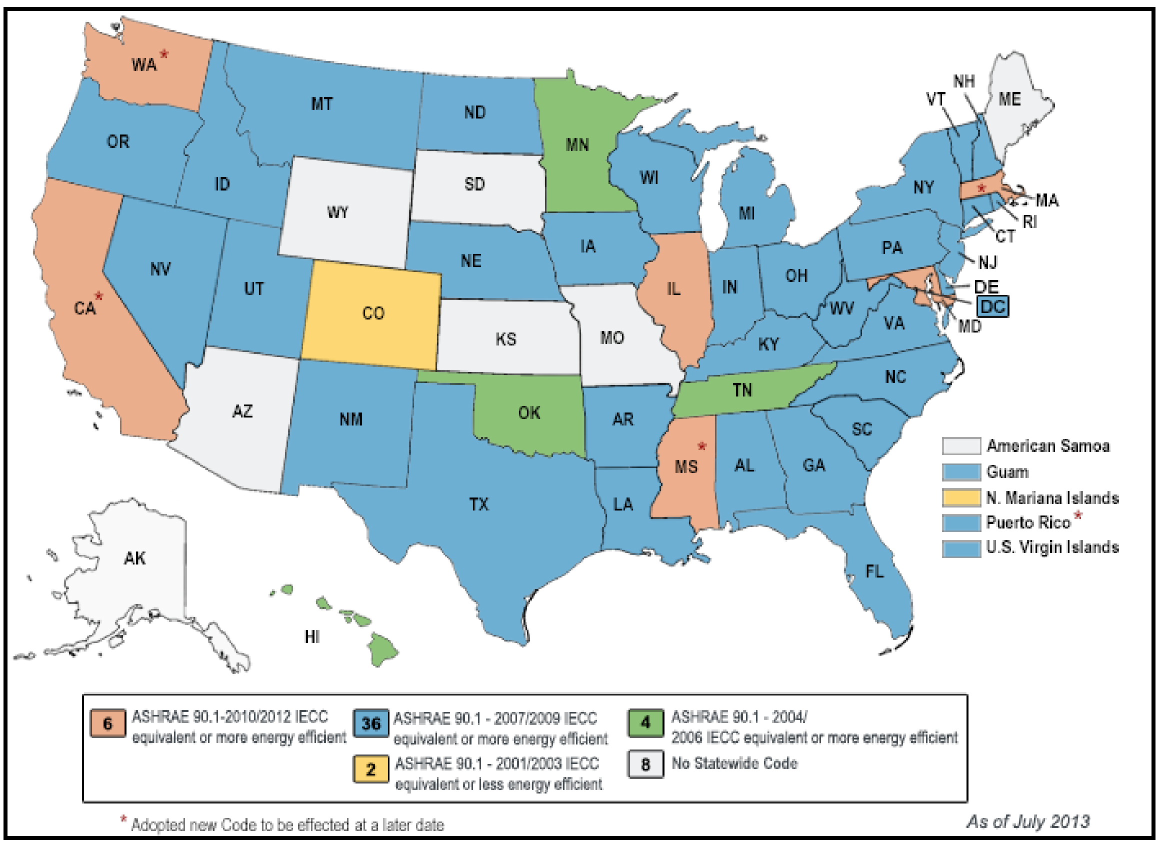

Figure 1: Current commercial building energy code adoption status in the U.S.[6]

[3] (Skolnik, 2011)
[4] (EIA)
[5] (USDOE, 2013)
[6] (USDOE, 2013)

It’s no wonder why third party green building certification systems place the most weight out of all their categories on the energy efficiency of the building. The United States Green Building Council’s (USGBC) certification system LEED or Leadership in Energy and Environmental Design and the Green Building Council of Australia’s (GBCA) Green Star (GS) certification system, for example, both have similar categories used to measure a building’s ability to perform efficiently. Credits in each category generally overlap in both systems and categories include the sustainability of the building’s location, water efficiency, energy and atmosphere, materials/resources and indoor environmental quality of the building. Energy efficiency is identified as the most important aspect of sustainable development in both of these point based systems.

Certification with systems such as LEED and GS take a holistic approach in creating a paradigm shift for buildings that can create energy instead of consume it, conserve potable water instead of using it to flush toilets (a waste of good drinking water) and reverse the effects of carbon emissions instead of emitting carbon dioxide. Holistic approaches tend to achieve a little bit of a lot and not a whole lot of any one thing, however. When emphasis is placed in one goal we tend to exert more energy and time on that one goal, as opposed to focusing on five or six goals where time and energy must be dispersed among all the categories. There is nothing inherently wrong with taking a holistic approach, but importance must be placed on insuring that all aspects of the approach are being worked on at a satisfactory level.

Another set of building procedures that is followed by the Monolithic Dome Institute (MDI) and other Monolithic Dome (MD) builders takes a different approach to construction of buildings that inherently provides excellent energy efficiency in both the commercial and residential realm. MDs come in various shapes and sizes and are as adaptable as conventional buildings to any type of building use (see *Figure 2*). The MDI claims that their building structures obtain an average savings of 30 to 50 percent in cooling and heating operating costs when compared to conventional buildings because of their superior insulation capabilities. The MD’s shape, the materials used and the placement of the materials are accredited with this claim.[7]

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[7] (MDI, 4 Reasons to Consider the Monolithic Dome)

Figure 2: Rendering of a Monolithic Dome as an ice arena by architect, Rick Crandall.[8]

The insulation material used in MDs is spray polyurethane foam (SPF), a super insulating, vapor deterrent and airflow minimizing material that is applied with a pumping system using a hose and a spray gun. SPF is used in many different application types, including commercial and residential wall, ceiling and roof, industrial insulation such as pipes and tanks, cold storage facilities, walk-in coolers, climate controlled buildings and flotation for water vessels, and some higher density SPF has even been used for structural support in the wings of airplanes.[9] The remaining cross section of a MD is comprised of an exterior PVC-coated nylon or polyester fabric, called the Airform, rebar and shotcrete. A real conundrum exists between the expected thermal resistance value (R-value) and the actual thermal performance of this combination of building materials and how they are used in a MD.

The MD takes a less holistic approach in the design of a building when it comes to addressing the various categories in third party green building certification systems, like LEED and GS. Four of the main characteristics marketed as the best features of the MD are energy efficiency, lowered construction and maintenance costs, the longer life-span of the building and the survivability of the structures.[10] In addition, MDs are rated by the Federal Emergency Management Agency (FEMA) as tornado, earthquake, termite, mold and fire proof and hurricane resistant and real testimonies to this effect exist.

Energy efficiency being as important as it is demands that we turn the spotlight on MDs, but this construction and design system is focusing on one aspect of sustainable development, which is the building envelope and subsequent HVAC (heating, ventilation

[8] (MDI, Monolithic Dome Institute)
[9] (Foametix, Engineering and Foam)
[10] (MDI, 4 Reasons to Consider the Monolithic Dome)

and air conditioning) loads to help to increase energy efficiency. Here again, focusing on one aspect leaves little room to work on other important criteria of sustainable development, such as reducing use of potable water, building on sites that are not considered sensitive or preserved ecosystems, allowing for natural ventilation of indoor space to improve air quality and so on and so forth. These other important factors are very much attainable in a MD, but just as in LEED and GS efforts must be made to obtain each goal at a level that is satisfactory.

1.2 Problem Statement

Turning the spotlight onto MDs requires that we answer some basic and fundamental questions. Although the technology is not new (MDs have been built the same way since their inception in 1975) the unfamiliarity with this building process and skepticism over the MD's energy savings leaves many to wonder what the true savings in cost would be and how they compare to even the best conventionally constructed green buildings. Those that have never seen or heard of a MD are also left to wonder about the social aspects: what the indoor environment is like, how to accommodate furnishings and living space with curved walls, what are the aesthetic qualities, and other understandable inquiries. General contractors, architects and other stakeholders may wonder about the physical aspects: what is the construction process, what type of equipment and training to use that equipment is necessary, who supplies the materials, et cetera. Still others who are experts in the green building industry must be cognizant of the fact that a MD's energy efficiency alone does not make up for other factors that are important for sustainable development: what is the indoor air quality like, does the life cycle analysis of the building materials result in a net positive carbon footprint, where in the MD is the ever more important topic of potable water being addressed.

Little exists in the way of peer reviewed and conclusive data on the energy efficiency of MDs, which creates a barrier in the understanding and integration of the building process. Part of the reason behind the lack of scientific literature on the energy efficiency is the traditional methods of using a building envelope's R-value and how this piece of information becomes a major corner stone when a building's energy consumption is modeled with professional software. Concepts of thermal performance and thermal battery are harder to put into single values and don't take into account reduced energy efficiency because of airflow, heat flow and moisture accumulation.

Finally, the question remains of how MDs compare in energy efficiency to green buildings with third party certification, such as LEED. Under the Energy and Atmosphere category, LEED certified building applicants have the option to meet minimally compliant prerequisites or to maximize energy efficiency points by modeling their building to perform 10% or 48% better than a minimally compliant building per the ASHRAE Standard 90.1-2007 Appendix G methodology. Giving this option to building applicants results in green buildings that may or may not be maximizing the energy efficiency of their building, whereas in the MD construction process, energy efficiency is built into the building envelope and high standards become the norm.

1.3 Objectives

This study entails the research and understanding of the metrics and strategies utilized under LEED 2009 for Core and Shell Development (CS) and LEED 2009 for New Construction and Major Renovations (NC) and the MD construction processes to address energy efficiency. By using an existing MD case study, differences in the modeled energy consumption and actual energy consumption of a MD are realized. Additionally, a greater understanding of the modeled energy consumption of a MD and a baseline building that follows ASHRAE Standard 90.1-2007, Appendix G - Performing Rating Method is gained. From the ASHRAE model, a 10% and 48% improved performance is also compared to the performance of the MD. Ultimately, a deeper understanding of what strategies used in each system are the most effective for high energy efficiency of the building envelope are gained and further implications on how to incorporate these strategies into LEED and MDs are discussed.

1.4 Research Questions

Specifically, the energy efficiency of the building envelope and HVAC systems in MD and LEED certified buildings are compared. Both the lowest level (10%) and highest levels (48%) of improvement over ASHRAE Standard 90.1, Appendix G methods are evaluated to assess and compare their energy efficiency to that of a replicate

MD building. This aspect of the study will result in understanding whether or not the energy efficiency achieved in a MD is significant enough to solicit its incorporation of building materials and processes into green certified buildings to maximize energy efficiency achievements in the sustainable development industry. Additional existing MD utility bills are reviewed to help clarify or reaffirm the findings of the energy models and to clarify any discrepancies between the modeled consumption and the actual trends of other existing MDs.

1.5 Significance and Justification

If energy is such an integral part of sustainable development, perhaps there is something to be learned from each system that can be integrated into the other to maximize efforts in the sustainability industry. MD builders and owners both testify to the MD’s ability to maintain constant temperatures for extended periods of time and to obtain energy savings of up to 70% in heating and cooling costs when compared to conventionally built structures with similar characteristics. Implications of such significant savings in energy consumption give MDs the potential to become one of the most green and sustainably designed structures in the world. With green building schemes like LEED placing energy efficiency as the category with the most points available, thus signifying the category’s prominence, all available avenues claiming to aid in this effort should be systematically explored.

1.6 Scope of this Report

The implications and theories mentioned in this report have been discussed with credible experts in the field and are backed by experienced professionals. Having said this, the field of energy efficiency in buildings is one that requires many years of experience in and previous knowledge of HVAC systems, energy modeling, construction processes and energy consumption as it relates to the building, all of which the researcher does not have a strong background in. Hence, the breadth of knowledge obtained in these specific areas relied heavily on literature review, meetings with professionals in the industry and courses. The necessary parameters for the study were reviewed during a three month period.

The limitations in educational background and time constraints also affected the physical aspect of the study, which endured several limitations. The original goal was to obtain sufficient data to conduct 15 to 20 energy modeling case studies for each of the systems mentioned (MD, LEED and GS). Issues relating to legalities, privacy of certain building parameters and the time frame in which the study was conducted all placed limitations on obtaining this data, triggering a reduction in quantity to one case study.

Furthermore, the accuracy of the energy model completed on the MD is estimated to be around 70% because several parameters had to be omitted or estimated based on generalities, when the information required was not available or could not be directly modeled in the modeling software. The affected parameters were:

1. MD square footage totaled 10,628 square feet and the actual size is 11,979 square feet.
2. Acrylic block glass wall on architectural plan was omitted from the model.
3. Heat pump standard efficiencies were inputted as indicated in ASHRAE Standard 90.1-2007, as they were not specified on the engineer's drawings (same in ASHRAE and MD models).
4. Lighting schedule inputted at 100% use during occupied hours (same in ASHRAE and MD models).
5. Airflow infiltration was omitted as a variable and inputted as zero for both models as the building was designed to have a positive pressure.
6. Electric consumption due to water heaters was omitted as it could not be directly modeled in the modeling software.

2 Literature Review

This section of the report will cover relevant information that is currently available on the subject matter that was obtained from various existing literature resources, publications, and courses, professionals in the industry, interviews and the like. Topics will be divided into three main subsections for Monolithic Domes, LEED buildings and lastly, a section on how Monolithic Domes compare to LEED energy efficiency credits. Information on the general methods of construction of Monolithic Domes will be covered, as well as their energy efficiency measures and related costs. Similarly, information on the performance of LEED buildings will be covered, as well as the credits that are geared toward improving energy efficiency.

2.1 Monolithic Dome Construction

The unique exterior characteristics of a MD resemble the unique structural characteristics that give them their famed claim in energy savings and a long lifespan. The MD's disaster resistant design allows for the assertion that their lifespan can be measured in centuries. Some of the basis for this claim is perhaps the resemblance in structure to Italy's Pantheon church, located in Rome. It has stood for almost two thousand years and is also structured around a pre-established form, made of concrete and reinforced for tension with ropes (instead of rebar, as in MDs).[11] Concrete itself is a super strong material with capabilities to withstand constant pressure and stress. For this reason it is used in our roadways, for example, which are able to withstand constant heavy loads on a daily basis and remain intact and stable for years.

The concrete dome concept utilized in Rome's Pantheon church has lived on through time and into the 1900's. Other forms of the MD shape can be found throughout history, including the very basic form of an igloo. The curved wall shape and the compacted and re-frozen snow melt can be attributed for the surprising and exceptional strength of these homes, which are still in use today. Igloos, of course, have nowhere near the strength found in concrete curved walls as in the MD. A more recent example of a similar design to the MD is the geodesic dome, developed by Buckminster Fuller. Geodesic domes are spherical in shape and were essentially designed as an overlapping triangular face using various types of materials. However, the interlocking mechanism in this type of structure caused problems with water leaks and structural integrity and repairs over time proved this construction method to be costly and inefficient.

The MD construction process is simple and straight forward and defied some of the common structural issues associated with dome buildings in previous history. It also helps to know that the MDI professionals are readily available for questions and advice to any and all inquirers. Five basic steps complete the building envelope from pouring the

[11] (MDI, The Pantheon, Rome, 126 AD)

concrete base foundation to waiting for walls to dry to deliver the building to its new owner. The process begins by forming the foundation of the building using steel reinforced concrete. The concrete is reinforced with rebar (reinforcing steel bars) and vertical bars embedded in the foundation are later attached to the dome structure itself (the wall and roof). Extra rebar is placed in the foundation along marked areas for doors and/or windows that may reach all the way down to the foundation. As in conventional building methods, conduits, piping, water and sewer lines must be planned and built into the foundation ahead of time. The parameters regarding the foundation that would need special attention would be sites located in flood plains, slopes or on moving ground.[12] In these scenarios an integrated foundation with the dome structure may be necessary and/or additional steps may be recommended. The completed foundation for a basic one dome structure is illustrated in *Figure 3*.

Figure 3: Typical cement foundation for a Monolithic Dome.[13]

Once the foundation has set and dried, a specially designed and fitted patented Airform is attached, which is manufactured at the MDI in Italy, Texas. The Airform is specially fabricated to specific dimensions based on the building model and is made of a PVC-coated nylon or polyester fabric. Attaching the Airform can be accomplished in various ways, but the most widely used mechanism is a metal strap that runs along the perimeter of the foundation (see *Figure 4*). The metal strap has predrilled holes where

[12] (MDI, The Foundation: Using an integrated floor system)
[13] (MDI, Monolithic Dome Institute)

concrete screws are drilled in along with the Airform. Once attached the Airform must be inflated for the duration of the construction process. This is done with an inflator fan or fans depending on the size of the dome, which is placed at predetermined air tubes built into the Airform fabric. Particular weather conditions, such as strong winds and rains, can make the inflation process hazardous and inefficient, so careful consideration must be given to the locations' weather patterns. The Airform becomes the outer surface of the building and remains so for its lifespan.

Figure 4: Airform being attached to the cement foundation.[14]

The dome is built from the inside of the inflated Airform; therefore, an airlock door mechanism must be put into place where workers can come in and out of the dome without allowing the air pressure to escape. *Figure 5* illustrates the airlock and air tubes properly installed. Any door or windows that are part of the design must be placed into the inflated Airform before moving on to the next step. This can be done several ways, including augmentations in the Airform that are framed with pressure treated wood.

The third step is applying the SPF. SPF is a super insulating material that inherently provides a barrier to airflow and enhanced moisture control. The floor and vertical bars in the dome should be covered well so that no vapor seeps up from the concrete into the dome and to protect the ground from spray back SPF or shotcrete.

[14] (MDI, Monolithic Dome Institute)

Choosing a trusted and experienced SPF spraying company or individual with good quality and consistency of the chemicals used in the SPF is important.

Figure 5: Airlock entrance and fan blowers properly installed.[15]

As well, different SPF suppliers have different specifications and rules for their product that should be followed. The SPF density recommended by the MDI is two pounds, using a total of 3 inches. There is a technique and rhythm involved in doing this correctly and safety hazards must be mitigated properly. Apart from this, the SPF is sprayed a few layers at a time, allowing for the contraction/expansion of the chemicals, and the resulting surface on the inside of the dome resembles the illustration in *Figure 6*. Before the last layer is sprayed, rebar hangers are embedded in the dried SPF walls. This allows the last layer of SPF to seal in the hangers to provide the strength needed to support the rebar.

After the SPF has set and dried the next step is to hang rebar in specified horizontal and vertical patterns that provide much of the structural integrity of the dome. Rebar does several things in the design of the MD. It provides an ally for tension on the dome to be dispersed, which can come in the form of snow, wind, falling trees, weight of the ground if it's buried, etc.; it also helps temperature fluctuations to be more evenly distributed throughout the building envelope.[16] Markings are placed on the dried SPF

[15] (MDI, Monolithic Dome Institute)
[16] (MDI, Steel Rebar Placement in a Monolithic Dome)

that designate the space between and alignment of the rebar. Extra rebar is placed in the more vulnerable areas where windows and/or door have been carved out to provide extra structural support. At the culmination of this step the dome resembles that of *Figure 7*.

Figure 6: Finished interior surface of wall after SPF is sprayed.

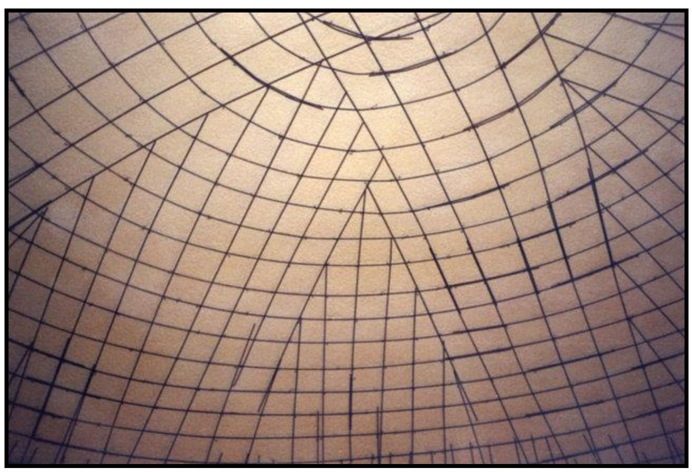

Figure 7: Rebar reinforcement ready for shotcrete.[17]

The final step in the construction process involves embedding the rebar in concrete. More specifically, a mix of sand, water and cement, called shotcrete, is used to slowly form layers of concrete to reach a total average depth of about 3 inches. It's sprayed on the walls at a particular angle and distance from the wall to cover all the space and holes

[17] (MDI, Monolithic Dome Institute)

between the SPF layer and the hanging rebar. As in the SPF spraying process, the application must be done meticulously and carefully to ensure the proper and even coverage is achieved. Once several layers of shotcrete have been applied and the rebar is fully embedded, the construction process is complete. After the appropriate drying time, the fan blowers can be shut off. The final version of the building envelope resembles a typical shotcrete sprayed wall, as shown in *Figure 8*. The construction process is complete (see *Figure 9* for a cross section depiction) and the interior of the MD can be finished using any of the typical materials and processes used in conventional buildings. The exterior of the Airform should be coated and can be coated with a large variety of traditional materials.

Figure 8: Finished interior wall surface.

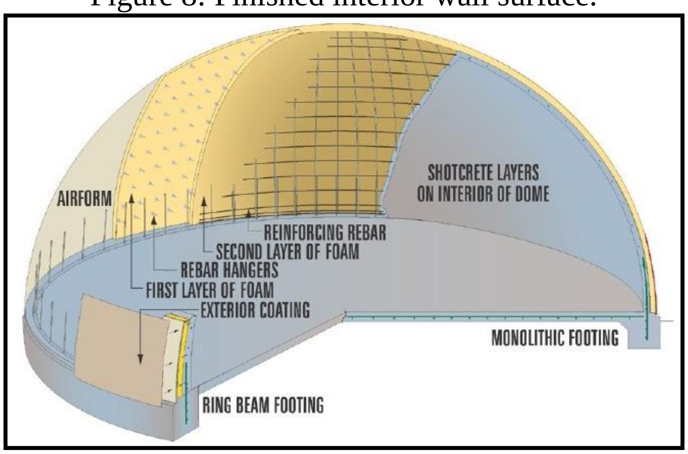

Figure 9: Depiction of all the layers in a Monolithic Dome.[18]

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[18] (MDI, Monolithic Dome Institute)

2.1.1 Pictures of Existing Monolithic Domes

All pictures were acquired from the Monolithic Dome Institute website with their permission and can be found using the search box tool on the main page: http://www.monolithic.com/.

Figure 10: Residential 2,700 square foot dome.

Figure 11: Residential 2,900 square foot dome.

Figure 12: Interior kitchen of a Monolithic Dome.

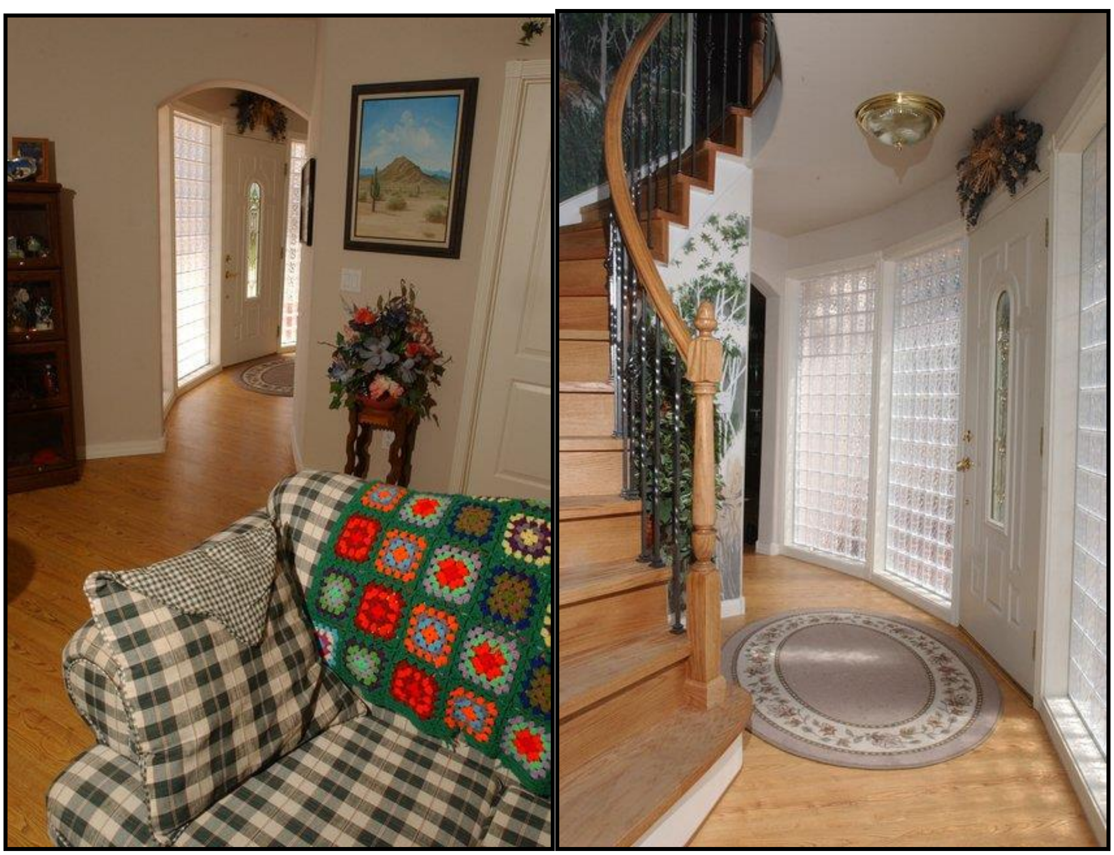

Figure 13: Other interior views of the Monolithic Dome in Figure 11.

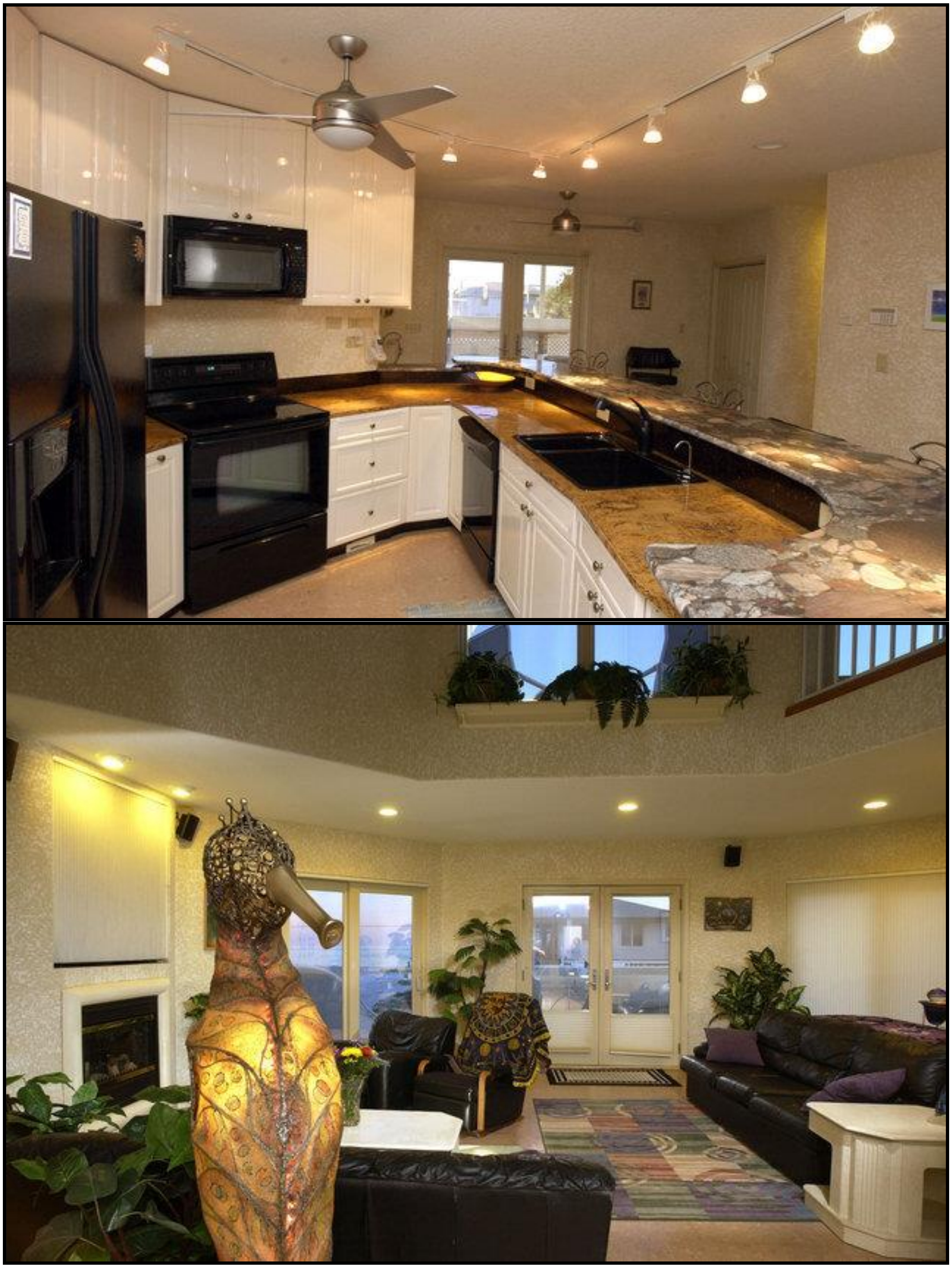

Figure 14: Interior of a Monolithic Dome home.

Figure 15: Interior of same Monolithic Dome home in Figure 13.

Figure 16: Children's Reading Center consists of five Monolithic Domes and funded primarily through an USDA loan.

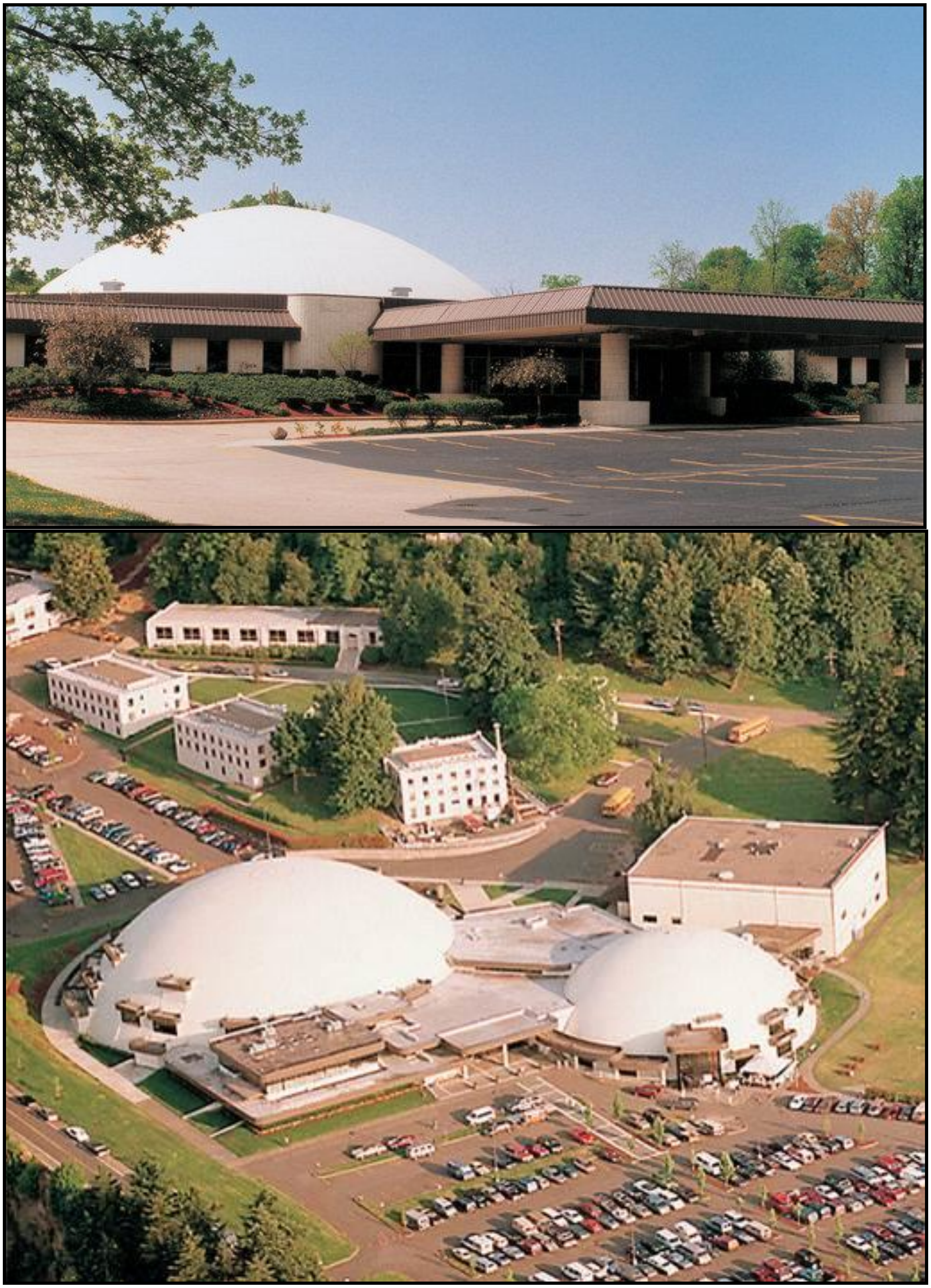

Figure 17: City Bible Church in Portland, Oregon with two Monolithic Domes.

Figure 18: Interior of school in Pattonsburg, Missouri with four Monolithic Domes.

Figure 19: Xanadu Island Resort in Belize, which has lived through several hurricanes.

Figure 20: Back porch view and bedroom of the Xanadu Island Resort.

Figure 21: Restroom in the Xanadu Island Resort.

2.1.2 Cost and Energy Efficiency of a Monolithic Dome

When we talk about the cost to build something, it's important to take a holistic approach that details the different aspects that will create or save money, which results in a net cost or savings analysis. The cost to build a MD is similar to, if not less than, a building of similar use, size, and location and built with the same materials. In fact, as the size of the building increases above approximately 2,000 square feet the construction becomes exponentially less expensive simply because of the reduced material needed for a dome versus square shaped structure, as well as the efficiency in the construction method.

Although it's hard to put a set price on a MD because of the many existing variables, certain specific numbers have been used to try and give people a general idea. The State of Arizona has the highest proportion of MD schools, and conventionally built school buildings in Arizona cost about 18% more than the MDs that have been built there already.[19] In 1994, Payson Elementary School in Arizona cost $64 per square foot compared to the average state-wide cost of $84 per square foot at that time.[20] MD schools around the year 2000 cost about $80 per square foot and a home could cost between $75 and $100 per square foot.[21] Still another report from 2010 states "…the rule of thumb in estimating the final cost of an average, finished Monolithic Dome home is $110 per square foot (2006 pricing) of floor area. This includes everything but your furniture and land."[22]

Prices will fluctuate between contractors, SPF suppliers, annual market inflations and such, but the longevity, energy savings and other characteristics associated with owning a MD will remain the same. Many of the savings associated with a MD that offset the initial cost to build one relate to its ability to reduce energy consumption for the life of the building. Energy costs are reduced because of the design of the building envelope. SPF is one of the best insulating materials currently available on the market. Its superior performance in maintaining constant temperatures adds to the design quality of using a spray type application. This application method results in a leak proof and

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19 (MDI, 4 Reasons to Consider the Monolithic Dome)
20 (MDI, How Much Does a Monolithic Dome Cost?)
21 (MDI, 4 Reasons to Consider the Monolithic Dome)
22 (MDI, How Much Does a Monolithic Dome Cost?)

seamless barrier from outside elements to the inside of the building. Thermographs taken in Canada by Rob Phillips of a MD and another nearby facility demonstrate the domes' ability to block air leaks. *Figure 22* shows a picture taken in daylight of the MD studied. The thermographs show how in 25 degrees below zero weather, the MD's indoor heat only leaks through where the door is located (see *Figure 23*), compared to the nearby metal building, which shows warm air leaking even through the insulated walls (see *Figure 24*).[23]

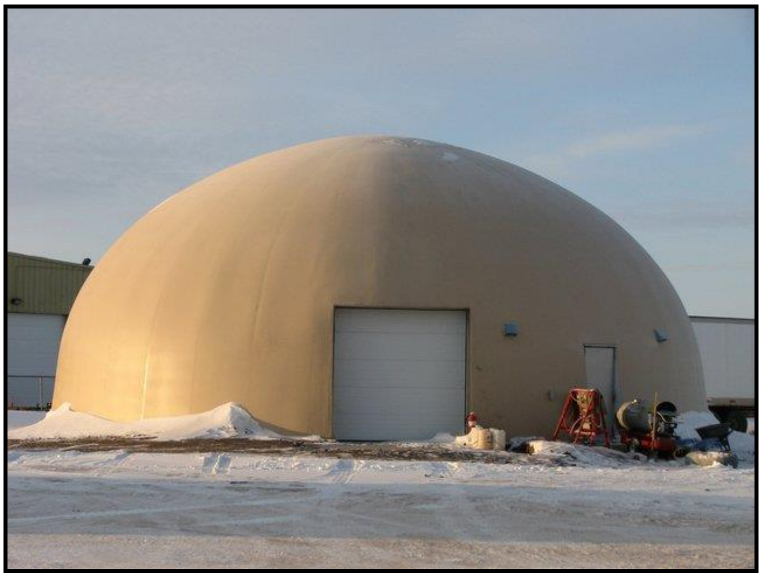

Figure 22: Picture of MD used in thermograph study.[24]

This SPF insulation, combined with a three inch concrete wall that's adhered to the inside of the insulation doubles the effects of insulation. Concrete itself acts as a heat sink, holding and maintaining temperature fluctuations for days. A MD home in below freezing weather can be without heat for several days while maintaining comfortable indoor temperatures; such was the testament of a MD homeowner whose heater stopped working during an ice storm and didn't notice it until four days later. This ability to maintain its temperature also equates to a smaller need in tonnage for the air conditioning (A/C) system. In fact, MDI asserts that whatever tonnage a conventional building requires in its A/C system, a MD of similar size can use a quarter of that.

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[23] (MDI, Thermographs of Dome in Canada)
[24] (MDI, Thermographs of Dome in Canada)

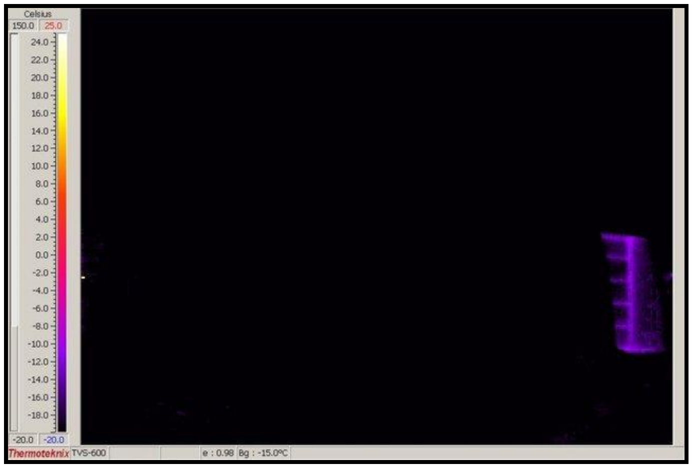

Figure 23: Thermograph of MD in freezing weather showing zero air leaks through the wall.[25]

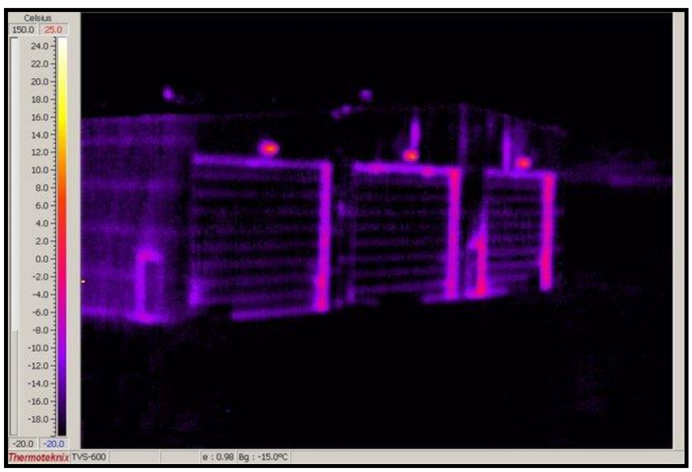

Figure 24: Thermograph of insulated conventionally built building with air leaks through the wall.[26]

The energy savings associated with heating and cooling results in an average of 30-50% reduction in costs.[27] In the long run this figure results in the realized potential to save thousands of dollars per year on electricity. This has been proven in several already existing MDs. A 34,000 square foot MD church built near Houston, Texas is one such dome. The average monthly heating and cooling cost is $1,500 and the dome cost about

25 (MDI, Thermographs of Dome in Canada)
26 (MDI, Thermographs of Dome in Canada)
27 (MDI, 4 Reasons to Consider the Monolithic Dome)

$1.2 million to construct.[28] The MDI took a conservative approach in computing a 30 year predicted annual energy savings study. Over a 30 year span and with a 2% rate of inflation, the church would save $2,028,404; even more, by placing the annual savings into an investment account with an interest of 7% they would save $5,800,893 by the 30th year, which is enough to pay off their entire dome by the 13th year.[29]

Other savings associated with owning a MD relate to the reduced costs in maintenance of the exterior, reduced cost in insurance premiums for the building and never having to rebuild in the case of a flood, fire, hurricane, tornado, and termite or mold infestation. FEMA's near disaster proof rating of MDs and the real life experiences of MD owners present credibility behind this claim. The MDI website has reports of domes having endured fires, hurricanes and tornados and remaining intact. One such story is of a MD home in Pensacola Beach, Florida that was built directly on the coast. An account of the weather conditions was kept of September 17, 2004 when Hurricane Ivan, category 3, made landfall with the "Dome of a Home" right in the middle of the hurricane's path.[30] All residents were under orders to evacuate, but the MD owners received approval to stay. Accounts of the home owners as well as MSNBC news broadcast team documenting the events from inside the home reported that all seemed quiet in the dome while the wind and water pounded on it from the outside and only minor damages were incurred as expected.[31] All other conventional buildings in the area had to be re-constructed.

Still others have repeatedly testified to the MD's ability to maintain constant and comfortable temperatures while saving on energy bills. Dr. David Del Bosque, the superintendent of the Avalon Independent School District (ISD) in Avalon, Texas stated, "It's everything that they claim it to be!" The Avalon MD was built in 2003 for about $1.2 million and received special funding from the state for its construction. State officials have the keys to the dome so that it can be opened up to the public in inclement weather. Another superintendent, Mr. Earl Jarrett from Spur ISD in Texas, spoke of the three domes on site there. Mr. Jarrett stated that after upgrading all their HVAC systems,

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[28] (South, 2012)
[29] (MDI, How Much Does a Monolithic Dome Cost?)
[30] (Sigler)
[31] (Sigler)

updating old buildings and adding the three domes (nearly doubling their square footage) they are saving about 40% in electricity costs.

2.2 Energy Efficiency Criteria in LEED

Energy efficiency is addressed in LEED in various categories, but more specifically in the Energy and Atmosphere (EA) category. Credits under this category are the most affective at encouraging LEED building applicants to dramatically reduce their energy consumption. The LEED for New Construction (NC) and Major Renovations and LEED for Core and Shell (CS) Development rating systems have a total number of possible points of 35 and 37, respectively, in the EA category. In this category, and to receive any level of certification under the USGBC, a prerequisite for Minimum Energy Performance must be followed. The other credit under the EA category that affects energy efficiency in both the NC and CS ratings systems is the Optimize Energy Performance credit.

The Minimum Energy Performance prerequisite is meant to create a baseline performance for LEED buildings to exceed. It can be obtained using three available options:

1. Whole building energy simulation
    a. Demonstrate a 10% or 5% improvement in the proposed building performance rating for new construction and major renovations, respectively, from the baseline comparison of a building simulation model that follows Appendix G of ANSI/ASHRAE/IESNA Standard 90.1-2007
2. Comply with measures in ASHRAE's Advanced Energy Design Guide
    a. Applicable to office buildings (less than 20000 sq. ft.), retail buildings (less than 20,000 sq. ft.) or warehouse/self-storage buildings (less than 50,000 sq. ft.)
3. Comply with measures in New Building Institute's Advanced Buildings Core Performance Guide

The Optimize Energy Performance credit is meant to further reduce energy consumption of the building, which again has three available options that are framed around the same options in the prerequisite. The option with the most available points (Option 1 - Whole Building Energy Simulation) gives a certain amount of points associated with an increased percentage of improved performance above the ASHRAE Standard 90.1 requirements (see *1*). Three to twenty one points are available in Option 1 under LEED for CS and one to nineteen points under LEED for NC.

Table1: Points given based on improved performance over ASHRAE Standard 90.1.[32]

New Buildings	Existing Building Renovations	Points
12%	8%	3
14%	10%	4
16%	12%	5
18%	14%	6
20%	16%	7
22%	18%	8
24%	20%	9
26%	22%	10
28%	24%	11
30%	26%	12
32%	28%	13
34%	30%	14
36%	32%	15
38%	34%	16
40%	36%	17
42%	38%	18
44%	40%	19
46%	42%	20
48%	44%	21

Other categories with credits that have the potential to alter the energy efficiency of a building are: (1) Sustainable Sites (Heat Island Effect – Roof), (2) Indoor Environmental Quality (Controllability of Systems – Thermal Comfort and Thermal Comfort – Design) and (3) Water Efficiency (Water Use Reduction prerequisite and credit).

[32] (USGBC, 2009)

1. Sustainable Sites, Heat Island Effect for Roof – The three options to achieve points in this credit are (1 point):
    a. Using roofing material with a solar reflective index equal to or greater than 78 for a roof with a slope less than or equal to 15%, and 29 for a roof with a slope greater than 15%, for a minimum of 75% of the total roof area
    b. Using a vegetated roof that covers at least 50% of the total roof area
    c. Using a combination of options a and b that meet the following criteria[33]:

$$\frac{\text{Area Roof Meeting Minimum SRI}}{0.75} + \frac{\text{Area of Vegetated Roof}}{0.5} \geq \text{Total Roof Area}$$

2. Indoor Environmental Quality
    a. The Controllability of Systems credit requires that a minimum of 50% of the building occupants have access to individualized controls for their ambient room temperature and follows criteria on thermal comfort from ASHRAE's Standard 55-2004 (1 point)
    b. The Thermal Comfort Design follows ASHRAE's Standard 55-2004 parameters on HVAC systems (1 point)

3. Water Efficiency - Both the prerequisite and the credit require a percentage reduction in water use from which points are assigned (see *Table 2*), compared to a baseline model, which is calculated based on the following criteria[34]:

[33] (USGBC, 2009)
[34] (USGBC, 2009)

Commercial Fixtures, Fittings, and Appliances	Current Baseline (Imperial units)	Current Baseline (Metric units)
Commercial toilets	1.6 gallons per flush (gpf)* Except blow-out fixtures: 3.5 (gpf)	6 liters per flush (lpf) Except blow-out fixtures: 13 lpf
Commercial urinals	1.0 (gpf)	4 lpf
Commercial lavatory (restroom) faucets	2.2 gallons per minute (gpm) at 60 pounds per square inch (psi), private applications only (hotel or motel guest rooms, hospital patient rooms) 0.5 (gpm) at 60 (psi)** all others except private applications 0.25 gallons per cycle for metering faucets	8.5 liters per minute (lpm) at 4 bar (58 psi), private applications only (hotel or motel guest rooms, hospital patient rooms) 2.0 lpm at 4 bar (58 psi), all others except private applications 1 liter per cycle for metering faucets
Commercial prerinse spray valves (for food service applications)	Flow rate ≤ 1.6 (gpm) (no pressure specified; no performance requirement)	Flow rate ≤ 6.1 lpm (no pressure specified; no performance requirement)

Residential Fixtures, Fittings, and Appliances	Current Baseline (Imperial units)	Current Baseline (Metric units)
Residential toilets	1.6 (gpf)***	6 liters per flush (lpf) Except blow-out fixtures: 13 lpf
Residential lavatory (bathroom) faucets	2.2 (gpm) at 60 psi	4 lpm 8.5 lpm at 4 bar (58 psi), private applications only (hotel or motel guest rooms, hospital patient rooms) 2.0 lpm at 4 bar (58 psi), all others except private applications 1 liter per cycle for metering faucets
Residential kitchen faucet		
Residential showerheads	2.5 (gpm) at 80 (psi) per shower stall****	Flow rate ≤ 6.1 lpm (no pressure specified; no performance requirement)

* EPAct 1992 standard for toilets applies to both commercial and residential models.

** In addition to EPAct requirements, the American Society of Mechanical Engineers standard for public lavatory faucets is 0.5 gpm at 60 psi (2.0 lpm at 4 bar (58 psi)) (ASME A112.18.1-2005). This maximum has been incorporated into the national Uniform Plumbing Code and the International Plumbing Code.

*** EPAct 1992 standard for toilets applies to both commercial and residential models.

**** Residential shower compartment (stall) in dwelling units: The total allowable flow rate from all flowing showerheads at any given time, including rain systems, waterfalls, bodysprays, bodyspas and jets, must be limited to the allowable showerhead flow rate as specified above (2.5 gpm) per shower compartment, where the floor area of the shower compartment is less than 2,500 square inches (1.5 square meters). For each increment of 2,500 square inches (1.5 square meters) of floor area thereafter or part thereof, an additional showerhead with total allowable flow rate from all flowing devices equal to or less than the allowable flow rate as specified above must be allowed. Exception: Showers that emit recirculated nonpotable water originating from within the shower compartment while operating are allowed to exceed the maximum as long as the total potable water flow does not exceed the flow rate as specified above.

Table 2: Points awarded for improved performance above the baseline standards for water efficiency.

Percentage Reduction	Points
20%	Prereq.
30%	2
35%	3
40%	4

2.2.1 Energy Performance of LEED Buildings

Depending on the intent and focus of the project applicant, very few or a lot of the total points possible to reduce energy consumption could be obtained. Much debate and literature exists on whether the number of points obtained or the LEED certification level obtained indicates how efficient a building is performing. Theoretically, obtaining a higher level of certification would imply the building is more efficient. Similarly, a building that receives LEED certification may be expected to perform more efficiently than a building that follows standard building codes (depending on the standards for that region).

A study conducted in 2008 by the New Building Institute (NBI), with support from the US Environmental Protection Agency (USEPA) and funded by the USGBC, gathered data on 121 LEED certified buildings that used the NC, version 2 rating tool. The study concluded that LEED buildings are performing as expected, which is about 25-30% better than the national average and that as the level of certification increased, so did the efficiency of performance, albeit not by a significant margin (see *Figure 25*).[35] However, the study also concluded that the measured energy use intensity (EUI) and projected/simulated energy use for over half the buildings studied differed by more than 25% (see *Figure 26*).[36]

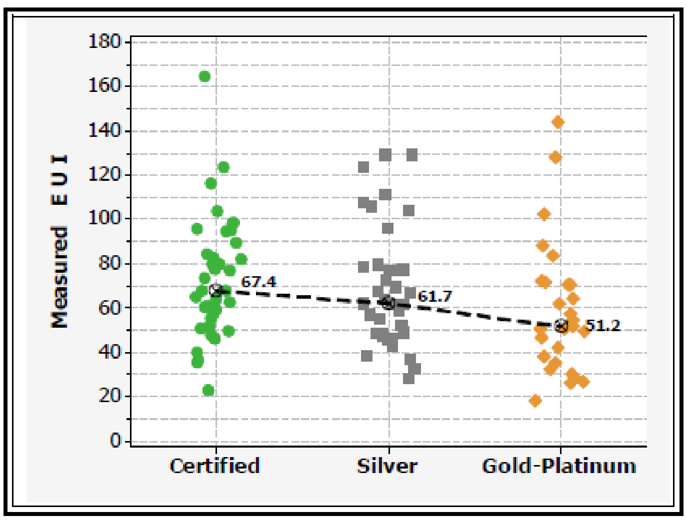

Figure 25: Results of LEED energy performance study showing a slight correlation in improved efficiency as certification level increases.[37]

Another study completed in 2006 looked at commercial LEED certified buildings' energy performance, narrowing in on the modeled versus actual results of 21 case studies. The authors in this study were associated with the USGBC, the USEPA, the USDOE or Lawrence Berkeley National Laboratory. Some of the findings from this study confirm the Turner and Frankel study. Among other conclusions, the study found that for 18 of

[35] (Turner & Frankel, 2008)
[36] (Turner & Frankel, 2008)
[37] (Turner & Frankel, 2008)

the studied buildings with simulated and actual energy use data on file, the actual consumption was lower than the simulated by 1% with a standard deviation of 46%.[38] They also found that the number of points achieved in the Optimize Energy Performance credit was not strongly correlated to the building's energy use (see *Figure 27*).[39] The smaller quantity of case study samples in this study should be noted, as it was also in the study itself.

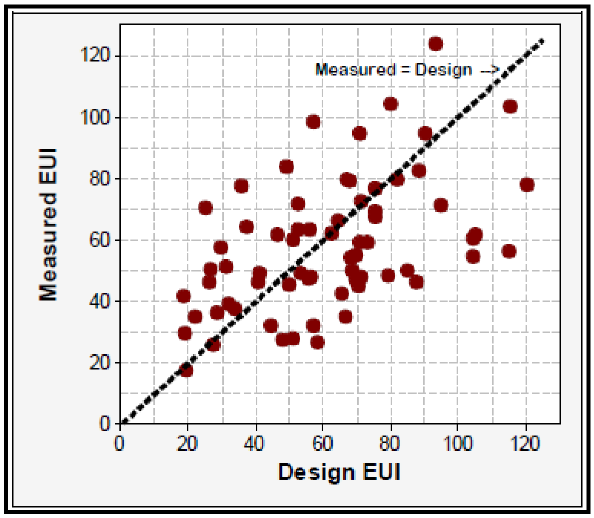

Figure 26: Graph from LEED energy performance study showing over half the buildings deviate more than 25% from their designed EUI.[40]

In this final study discussed, the National Research Council Canada (NRCC) Institute for Research in Construction conducted a re-analysis of data supplied by the NBI and USGBC from their 2008 Turner and Frankel report.[41] Data on measured energy use of 100 LEED certified commercial and institutional buildings was compared to standard US commercial buildings and the study concluded that, although LEED buildings used 18-39% less energy per floor area, 28-35% of LEED buildings used more energy than the conventional commercial buildings.[42] As in the Diamond, Opitz and

[38] (Diamond, Opitz, Hicks, Von Neida, & Herrera, 2006)
[39] (Diamond, Opitz, Hicks, Von Neida, & Herrera, 2006)
[40] (Turner & Frankel, 2008)
[41] (Newsham, Mancini, & Birt, 2009)
[42] (Newsham, Mancini, & Birt, 2009)

Hicks' study, the NRCC found that the energy performance of the studied buildings had little correlation with the certification level or the number of points obtained.[43]

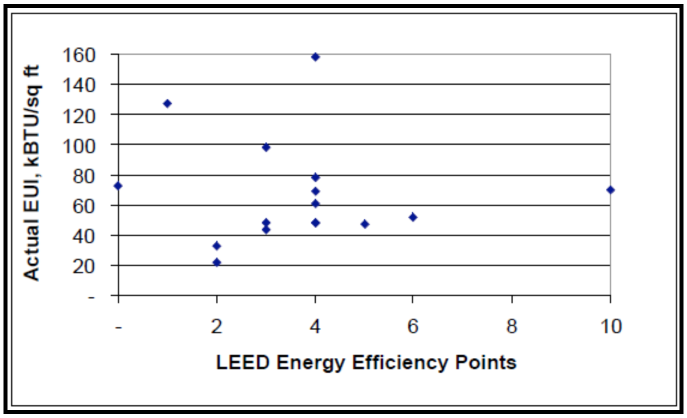

Figure 27: Graph showing no strong correlation between performance and number of points obtained.[44]

From these three studies, one can gain an understanding of the conflicts and difficulties related to accurately measuring a building's performance, as well as simulating performance and making the modeled energy consumption match the actual energy consumption. Certain variables will always be unpredictable to a certain extent, as building occupants accommodate their surroundings to their comfort levels, building designs are tweaked before the building is built and installed components of the building perform differently than what they were engineered for. Despite these variances, certain common ground can be found in that third party certification systems like LEED bring much needed attention to the importance of building sustainably and in many cases, these buildings take large strides in that very direction.

2.3 LEED Energy Credits in a Monolithic Dome

Without changing a thing in the way that a MD is constructed there are several opportunities to gain points under the LEED NC and CS ratings systems. The energy performance of MD relates directly to the building envelope and HVAC design and these approaches have a place in the LEED rating process. Further actions can be taken, as in

43 (Newsham, Mancini, & Birt, 2009)
44 (Diamond, Opitz, Hicks, Von Neida, & Herrera, 2006)

conventional structures, to achieve points in various credits. A review of Section 2.2 on Energy Efficiency Criteria of a LEED Building sheds light on the credits that MDs may be able to obtain.

- ✓ **Sustainable Sites: Heat Island Effect – Roof**

  A MDs exterior can be covered on the outside with almost any type of material or coating. This would include using a material with a solar reflective index and/or a green roof (see *Figure 28*).

Figure 28: Thick growing vines covering the roof of a Monolithic Dome.[45]

- ✓ **Water Efficiency: Water Use Reduction Prerequisite and Credit**

  Water fixtures and systems can be installed in a MD as in any other conventional structure. In fact, MDs can be built as storage tanks for anything from explosive chemicals to water (see *Figure 29*).

[45] (MDI, Monolithic Dome Institute)

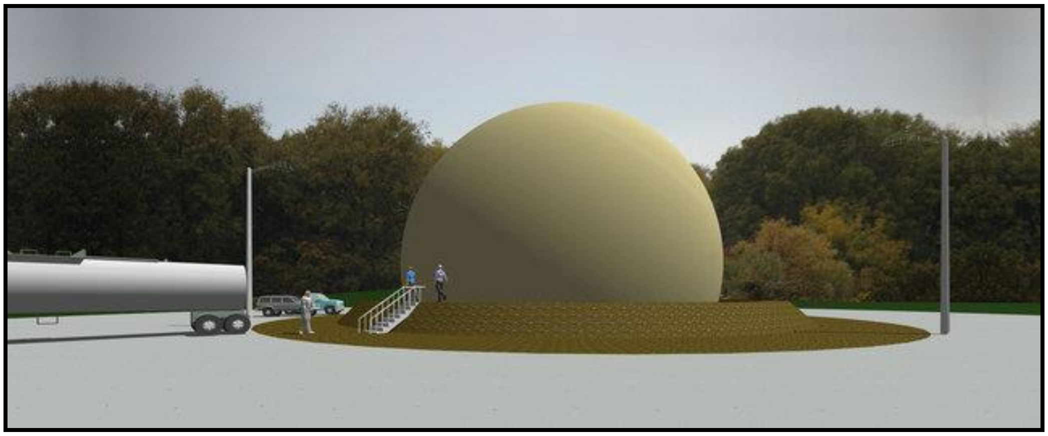

Figure 29: Monolithic Dome used as a storage tank.[46]

- ✓ **Energy and Atmosphere: Minimum Energy Performance Prerequisite and Optimize Energy Performance Credit**

  MDs have been proven to reduce energy costs by at least 30% of conventionally built structures. The question would be how the ASHRAE Standard 90.1 baseline simulation would compare to the MD. Under LEED NC parameters and assuming that conventional buildings follow ASHRAE Standard 90.1, the capabilities of the MD would be able to at least get 10 points. If no other quality of the MD is counted as energy efficient, simply using SPF in the building would certainly help achieve these points. "When Foametix is installed in your structure, it provides the building with a sealed envelope, allowing the designer to downsize HVAC systems and supply the required ventilation. When Foametix is used with a whole building concept, it can help achieve the 10 possible points."[47]

- ✓ **Indoor Environmental Air Quality: Thermal Comfort (Controllability of System and Design Credits)**

  The MD design provides for excellent constant temperatures throughout the structure. Furthermore, individual thermal comfort controls can be installed just as in conventional structures. Here again, SPF can "…help a building comply with ASHRAE Standard 55-2004 by insulating and air sealing the building, which

46 (MDI, Monolithic Dome Institute)
47 (Foametix, LEED Certification)

allows for controlled ventilation strategies that enhance uniform temperatures, moisture control and reduction of pollutants."[48]

3 Methodology

A week long workshop put on by the MDI was attended in their Texas headquarters. The workshop covered the entire MD construction process and consisted of a combination of lecture and hands on practical experiences. The main topics covered were polyurethane foam, rebar and concrete, design and layout and equipment needed to build a dome. Experiences included the actual spraying of SPF and shotcrete, installing the rebar inside the dome and visiting a variety of existing residential and non-residential MDs. After the completion of the workshop, an additional week was spent discussing the intent of the research with MDI professionals. In this way, documents and insight relating to the energy efficiency of MDs was gathered, contact details for MD owners and architects was obtained and interviews were conducted, both in person and through telephone conversations. As a result of the cooperation from the MDI staff, the data required to perform energy models and review the actual energy consumption of existing MDs was obtained for use in this study.

On-line and in person courses were taken pertaining to LEED to gain a general understanding of the categories and credits required for the certification process. Previous knowledge of LEED and the USGBC was obtained through several graduate level college courses. Literature review and consultations with industry professionals in the field aided in the assertions made regarding LEED building energy performance. The data required to conduct energy modeling or compare energy consumption of LEED buildings to MDs was not readily available by the USGBC.

3.1 Energy Modeling

The software used to conduct the models was Trace 700 Version 6.2.10 by Trane and it was used under the direct supervision and review of an industry professional with current experience with the software and with an educational background in engineering. One MD was chosen for the energy modeling aspect of the research, whose architectural

[48] (Foametix, LEED Certification)

plans and energy consumption data was available. The Avalon ISD, located in Avalon, Texas (ASHRAE climate zone 3A) is a gymnasium and multi-purpose facility that was built in 2003. The 124 by 25 foot dome has a 12 foot stem wall, measures 11,979 square feet and seats approximately 720 people. The energy efficiency of a MD comes from the design of the building envelope and the reduced capacity needed for the A/C unit. Although other measures could be taken after the building envelope is constructed to increase the overall efficiency and sustainability of the building, the focus of the model was placed on the building envelope and HVAC efficiency and capacity.

The other simulated model was of a conventional building that follows Appendix G of ASHRAE Standard 90.1-2007 methods for the building envelope and HVAC efficiency and capacity with all other parameters remaining the same as the MD. *Table 3* shows the building envelope parameters that varied between both models. *Table 4* shows the key HVAC parameters inputted that varied between both models, with the Proposed Design column pertaining to the MD and the Baseline Design to the ASHRAE model.

Table 3: Input parameters for the building envelope in each energy model.

	Monolithic Dome	**ASHRAE Standard 90.1**
Roof Construction:		
Thickness	7.25 in.	6 in.
Heat Capacity	4.83 Btu/hr.ft.degrees F	0.2 Btu/hr.ft.degrees F
R-Value	58.8	20.8
Material	Concrete + insulation	Min roof non-residential Zone 2-8
Reflectivity	0.1	0.3
Wall Construction:		
Thickness	7.25 in.	6.28
Heat Capacity	4.83 Btu/hr.ft.degrees F	2.25 Btu/hr.ft.degrees F
R-Value	58.8	11.8
Material	Concrete + insulation	Min wall non-residential Zone 3

Table 4: Input parameters for HVAC systems used in each model.

Input Parameter	Proposed Design Input	Baseline Design Input
HVAC System Type	AC-6 Packaged Terminal Air Conditioner Supply vol: 264 cfm Fan power: 0.13 kW	AC-6 Packaged Terminal Air Conditioner Supply vol: 353 cfm Fan power: 0.11 kW
HVAC System Type	AC-5 Packaged Terminal Air Conditioner Supply vol: 213 cfm Fan power: 0.13 kW	AC-5 Packaged Terminal Air Conditioner Supply vol: 294 cfm Fan power: 0.09 kW
HVAC System Type	AC-3 Packaged Terminal Air Conditioner Supply vol: 120 cfm Fan power: 0.07 kW	AC-3 Packaged Terminal Air Conditioner Supply vol: 158 cfm Fan power: 0.05 kW
HVAC System Type	AC-2 Packaged Terminal Air Conditioner Supply vol: 231 cfm Fan power: 0.08 kW	AC-2 Packaged Terminal Air Conditioner Supply vol: 275 cfm Fan power: 0.08 kW
HVAC System Type	AHU-2 Single Zone Supply vol: 4204 cfm Fan power: 1.79 kW	AHU-2 Single Zone Supply vol: 4335 cfm Fan power: 3.47 kW
HVAC System Type	AC-4 Packaged Terminal Air Conditioner Supply vol: 145 cfm Fan power: 0.07 kW	AC-4 Packaged Terminal Air Conditioner Supply vol: 177 cfm Fan power: 0.05 kW
HVAC System Type	AC-1 Packaged Terminal Air Conditioner Supply vol: 234 cfm Fan power: 0.08 kW	AC-1 Packaged Terminal Air Conditioner Supply vol: 300 cfm Fan power: 0.09 kW
HVAC System Type	AHU-1 Single Zone Supply vol: 4275 cfm Fan power: 1.79 kW	AHU-1 Single Zone Supply vol: 4588 cfm Fan power: 3.68 kW
Cooling Equipment	Plant: HP-2 Type: 90.1-10 Min ACHP SS/SP Elec 65-135 MBh Category: Air-cooled unitary Clg Cap: 7.5 tons Engy Rate: 11 Packaged EER HR Cap: 83 Mbh Engy Rate: 3.3 Packaged COP	Plant: AC-4 Type: 90.1-10 Min ACHP AllHeat SP < 65 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 11.1 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.26 Packaged
Cooling Equipment	Plant: AC-2 Type: Packaged Terminal Heat Pump Category: Air-cooled unitary Clg Cap: 15 Mbh Engy Rate: 9.8 Packaged EER HR Cap: 14 Mbh Engy Rate: 2.9 Packaged COP	Plant: AC-1 Type: 90.1-10 Min ACHP AllHeat SP < 65 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 11.1 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.26 Packaged
Cooling Equipment	Plant: AC-1 Type: Packaged Terminal Heat Pump Category: Air-cooled unitary Clg Cap: 15 Mbh Engy Rate: 9.8 Packaged EER HR Cap: 14 Mbh Engy Rate: 2.9 Packaged COP	Plant: HP-1 Type: 90.1-10 Min ACHP SS/SP Elec 135-240 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 10.6 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.2 Packaged

Input Parameter	Proposed Design Input	Baseline Design Input
Cooling Equipment	Plant: AC-6 Type: Packaged Terminal Heat Pump Category: Air-cooled unitary Clg Cap: 15 Mbh Engy Rate: 9.8 Packaged EER HR Cap: 14 Mbh Engy Rate: 2.9 Packaged COP	Plant: AC-5 Type: 90.1-10 Min ACHP AllHeat SP < 65 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 11.1 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.26 Packaged
Cooling Equipment	Plant: AC-5 Type: Packaged Terminal Heat Pump Category: Air-cooled unitary Clg Cap: 15 Mbh Engy Rate: 9.8 Packaged EER HR Cap: 14 Mbh Engy Rate: 2.9 Packaged COP	Plant: AC-2 Type: 90.1-10 Min ACHP AllHeat SP < 65 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 11.1 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.26 Packaged
Cooling Equipment	Plant: AC-4 Type: Packaged Terminal Heat Pump Category: Air-cooled unitary Clg Cap: 15 Mbh Engy Rate: 9.8 Packaged EER HR Cap: 14 Mbh Engy Rate: 2.9 Packaged COP	Plant: HP-2 Type: 90.1-10 Min ACHP SS/SP Elec 135-240 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 10.6 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.2 Packaged
Cooling Equipment	Plant: AC-3 Type: Packaged Terminal Heat Pump Category: Air-cooled unitary Clg Cap: 15 Mbh Engy Rate: 9.8 Packaged EER HR Cap: 14 Mbh Engy Rate: 2.9 Packaged COP	Plant: AC-6 Type: 90.1-10 Min ACHP AllHeat SP < 65 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 11.1 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.26 Packaged
Cooling Equipment	Plant: HP-1 Type: 90.1-10 Min ACHP SS/SP Elec 65-135 MBh Category: Air-cooled unitary Clg Cap: 7.5 tons Engy Rate: 11 Packaged EER HR Cap: 83 Mbh Engy Rate: 3.3 Packaged COP	Plant: AC-3 Type: 90.1-10 Min ACHP AllHeat SP < 65 MBh Category: Air-cooled unitary Clg Cap: 115 % Plant Capacity Engy Rate: 11.1 Packaged EER HR Cap: 125 % Plant Capacity Engy Rate: 3.26 Packaged
Heat Rejection Parameters	Type: 90.1 Min Air Cooled Condenser HR Type: Air-cooled condenser Energy Consumption: 0.055290 kW/ton Quantity: 2	Type: 90.1 Min Air Cooled Condenser HR Type: Air-cooled condenser Energy Consumption: 0.055290 kW/ton Quantity: 8
Heat Rejection Parameters	Type: Condenser fan for Heat Pump HR Type: Air-cooled condenser Energy Consumption: 0.120000 kW/ton Quantity: 6	
Heating Equipment	Plant: AC-6 Heat Type: Default electric resistance Category: Electric resistance Capacity: 14 Mbh Energy Rate: 100 Percent efficient	Plant: AC-5 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient
Heating Equipment	Plant: AC-3 Heat Type: Default electric resistance Category: Electric resistance Capacity: 14 Mbh Energy Rate: 100 Percent efficient	Plant: HP-1 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient
Heating Equipment	Plant: HP-2 Heat Type: Default electric resistance Category: Electric resistance Capacity: 83 Mbh Energy Rate: 100 Percent efficient	Plant: AC-3 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient
Heating Equipment	Plant: AC-5 Heat Type: Default electric resistance Category: Electric resistance Capacity: 14 Mbh Energy Rate: 100 Percent efficient	Plant: AC-1 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient
Heating Equipment	Plant: AC-2 Heat Type: Default electric resistance Category: Electric resistance Capacity: 14 Mbh Energy Rate: 100 Percent efficient	Plant: HP-2 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient

Input Parameter	Proposed Design Input	Baseline Design Input
Heating Equipment	Plant: HP-1 Heat Type: Default electric resistance Category: Electric resistance Capacity: 83 Mbh Energy Rate: 100 Percent efficient	Plant: AC-6 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient
Heating Equipment	Plant: AC-4 Heat Type: Default electric resistance Category: Electric resistance Capacity: 14 Mbh Energy Rate: 100 Percent efficient	Plant: AC-4 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient
Heating Equipment	Plant: AC-1 Heat Type: Default electric resistance Category: Electric resistance Capacity: 14 Mbh Energy Rate: 100 Percent efficient	Plant: AC-2 Heat Type: Default electric resistance Category: Electric resistance Capacity: 125 % Plant Capacity Energy Rate: 100 Percent efficient

The resulting energy consumption of the ASHRAE model was used to calculate how a minimally compliant LEED building that performs 10% better and a maximally compliant LEED building (performing 48% better) than the ASHRAE model would each compare to the MD. These percentages are based on the EA prerequisite for energy performance of all LEED buildings to model a building that is at least 10% better than ASHRAE Standard 90.1-2007 and the maximum points allotted (21) under the Optimize Energy credit for a 48% better than ASHRAE Standard 90.1-2007, Appendix G – Performing Rating Method. The other obtainable credits that relate to energy efficiency were not used in the comparison because they do not majorly and directly contribute to the energy consumption of the building envelope and HVAC systems.

4 Results

This section is divided into the results for the energy modeling conducted, the actual versus modeled energy use of the Avalon MD and another section presenting the data obtained on the electrical consumption of seven existing Monolithic Domes. These Monolithic Domes are located in Italy, Texas, where they were manufactured and where they are currently being used for residential and construction type work relating to the production of Monolithic Domes.

4.1 Comparison of ASHRAE and Monolithic Dome Energy Models

The modeled total building energy consumption of the MD was 208 10^6 Btu's per year and that of the ASHRAE model was 276 10^6 Btu's per year (see *Table 5*). The breakdown of this usage between lighting, space heating and cooling, heat rejection and conditioned fans is outlined in *Table 5*. The lighting parameter resulted in the same energy consumption, as this variable was excluded from the comparison. The space cooling parameter showed the most significant savings in energy consumption, with the MD model using 27.6% less energy. The second parameter with the most significant savings was for conditioned fans. In this parameter, the MD model consumed 43.9% less energy.

Based on these simulated energy consumption levels the MD would perform 24.5% better than a conventionally built structure that followed ASHRAE Standard 90.1-2007. Similarly, the models illustrate a 24.5% annual energy cost savings using the MD design. The ASHRAE model costs $6,044 while the MD costs $4,563 per year to operate. This would translate into annual savings of $1,481.

Table 5: Modeled Energy Consumption of ASHRAE and Monolithic Dome.

Project Name: Avalon							Date: July 31, 2013
City: Avalon, Texas		Weather Data: Dallas, Texas (8760)					
Note: The percentage displayed for the "Proposed/ Base %" column of the base case is actually the percentage of the total energy consumption. * Denotes the base alternative for the ECB study.		* Alt-2 AHSRAE 90 1			Alt-1 Monolithic Dome		
		Energy 10^6 Btu/yr	Proposed / Base %	Peak kBtuh	Energy 10^6 Btu/yr	Proposed / Base %	Peak kBtuh
Lighting - Conditioned	Electricity	80.8	29	40	80.8	100	40
Space Heating	Electricity	8.8	3	390	0.4	4	139
Space Cooling	Electricity	117.1	42	126	84.8	72	63
Heat Rejection	Electricity	9.9	4	10	9.1	92	8
Fans - Conditioned	Electricity	59.0	21	26	33.1	56	14
Total Building Consumption		**275.6**			**208.1**		

Based on the performance calculated in the ASHRAE model, a minimally compliant LEED building that consumed 10% less energy would have an annual energy consumption of 248 10^6 BTU. This equates to an improved performance by the Monolithic Dome of 16%. Similarly, a LEED building that had a 48% improved performance over the ASHRAE model would consume 143 10^6 BTU or perform 31.3% better than the MD.

4.2 Modeled and Actual Energy for the Avalon Monolithic Dome

The modeled energy consumption of the Avalon MD was lower than the actual energy consumption by 25.2%, with the actual average for the 2009-2010 and 2011-2012 school year being 278^6 Btu per year (see *Table 6*). Similarly, the energy cost of the modeled Avalon MD was lower than the actual cost by 29.4% (see *Table 6*).

Table 6: Modeled Versus Realized Energy Consumption and Cost for Avalon Monolithic Dome.

	Energy (10^6 Btu/yr.)	**Cost/yr.**
Modeled	208	$4,563
Realized	278	$6,461
% Difference	25.2%	29.4%

4.3 Energy Cost Records for Existing Monolithic Domes

The actual energy cost for seven MDs located in Italy, Texas was obtained from the MDI (see *Table 7*). The electricity consumption from a range of three years was used to calculate the average energy cost of these MDs with varying size and functionality. One of the largest inconsistencies found with these results was the Visitor dome, which measures 315 square feet and uses an average of $2,518 in electrical costs every year. The next up in size is the Design dome, which has a similar function but is almost four times the size of the Visitor dome, costs about the same. Another interesting point to make is the average annual energy cost of the Main MD, which measures 3,219 square feet and costs $9,866. It costs about the same to operate the Bruco MD, a manufacturing facility four times the size.

Perhaps one of the biggest inconsistencies in cost is between the DBS and Main domes. The DBS dome is a residential space occupied 24/7 and measuring 1,800 square feet, whiles the Main dome offices is only 419 square feet larger, but costs $4,488 more annually (see *Table 7*). It should be noted that the Main dome is used as the headquarters offices for the MDI and is therefore occupied with anywhere from 15-20 people during normal business hours.

Table 7: Average Energy Cost for a 3 Year Span of Seven Monolithic Domes.

Name	Function	Size (sq. ft.)	Average Energy Cost/Year (3 years)
Visitor	Visitor ctr/lobby	315	$2,518
Design	Offices	1,256	$2,579
Pumpkin	Manufacturing	1,256	$3,160
Training	Office/Conference	2,664	$3,899
DBS	Residential	2,800	$4,278
Main	Offices	3,219	$9,866
Bruco	Manufacturing	14,000	$10,924
Avalon	Multi. Purpose/Gym	11,979	$6,461 (2 yr. avg.)

5 Discussion of Results

The main interpretations of significant value to the discussion revolve around the accuracy of the energy models for the MD and ASHRAE comparison, as well as the modeled versus actual energy consumption of the Avalon MD. Results indicate that the modeled MD performs better than a building following ASHRAE Standard 90.1, as well as a building performing 10% better than ASHRAE Standard 90.1. However, a conclusion cannot be explicitly made about the energy savings in a MD based on the energy model, if the energy model doesn't accurately represent the actual energy consumption of a MD. This section will be divided into two main subsections, the first of which will cover the difference in modeled versus actual energy consumption of the Avalon MD and how buildings that follow ASHRAE Standard 90.1 compare to the MD model and the second, the notable characteristics found in the energy costs obtained on the seven existing MDs.

5.1 Modeled and Actual Energy Consumption Results

The resulting figures from the Trace Software energy models would indicate that the MD would perform around 25% better than a conventionally built structure. This improvement in performance fails to support the MDI claim that MDs perform 30-50% better than conventional buildings. However, the understanding of how a "conventionally" designed building is defined poses varying perspectives on the degree of improved efficiency obtained. If the conventional building parameters are defined around ASHRAE Standard 90.1-2007, Appendix G parameters, as it was in this study, than the assertion could perhaps be made that indeed MDs perform around 25% better. If instead the conventionally built structure follows less stringent standards, it may be easier to obtain improved efficiencies of 30-50%, as claimed by the MDI.

Furthermore, a minimally certified LEED building that achieved no other points related to energy efficiency, except to increase performance by 10% over ASHRAE Standard 90.1, would still be 16% less efficient than a MD. This improved performance does not extend over to a LEED certified building that obtained the maximum points for a 48% improved efficiency over ASHRAE Standard 90.1.

In making these assertions based on the modeled energy consumption, a discussion must be had on how the modeled results did not resemble the actual energy consumption of the Avalon MD. This realization places several barriers to the comparison of the actual difference in performance between MDs and LEED buildings for several reasons. For one, actual performance data on a LEED building was not available for use in this study. Therefore, the actual performance of a conventionally built LEED building, comparable in size, material, functionality and location, cannot be compared to the actual performance data obtained for the Avalon MD. The results available in this study allow for a comparison of the actual Avalon MD consumption to the modeled ASHRAE building energy consumption. As mentioned in the Literature Review section of this report, energy modeling of LEED buildings following ASHRAE standards can be inaccurate by as much as 25% from their designed EUI (see *Figure 26*). An appropriate comparison is not possible without actual data on a comparable building that performs 10% or 48% better than ASHRAE Standard 90.1. Therefore, comparing the actual Avalon MD data to the ASHRAE model would not lead to conclusive or trusted results in this study.

An attempt to understand why the modeled consumption for the Avalon MD did not accurately portray the actual energy consumption is important. Based on the literature review regarding energy modeling of MDs, we would expect that modeled results would be higher than actual energy use. In this case, we would be having a lengthy discussion about energy modeling software limitations in accurately portraying the energy savings achieved with the MD's thermal storage battery, reduced airflow leaks and efficient moisture control barrier. All of these parameters greatly help to reduce the MD's energy consumption.

However, this study resulted in the opposite affect and several parameters are predicted as the cause of this result. One such parameter could be the height of the main usable space inputted in the energy modeling software, which has a bearing on the amount of space being conditioned by HVAC systems and consequently, the efficiency modeled. The architectural plans of the Avalon MD depicted a suspended cloud ceiling height for this section and this was the height used for that space. The software may or may not calculate the space between the suspended cloud ceiling and the actual ceiling of the building as space that needs to be conditioned; therefore, if this space was not calculated into the energy model a higher efficiency than what's realized would result.

In addition, during the process of measuring, calculating and inputting data about the Avalon MD into the Trace software small improvises were made that were assumed to vary the result by an insignificant margin. Although the study as a whole took three months, the energy modeling aspect had only three weeks and depended upon the available time and schedule of others. The small improvises combined may have caused a bigger than expected impact in the results of the Avalon MD model. The three main improvised parameters were:

1. The replacement of the existing acrylic block glass wall, which measures around 80 by 8 feet, with the standard MD wall made of 7 inches total concrete and insulation.
2. The difference in calculations for the total square footage of the MD was about 1,000 square feet. The modeled Avalon MD was therefore smaller than the actual building by this margin.
3. The energy cost, which was lower in the Avalon model by around 29%, may have been affected by the entered utility parameters. A copy of the electricity bill obtained for Avalon MD was used to obtain this information, but specific and miscellaneous fees were not included in the model.

If we were to assume that the ASHRAE model was accurate, than the actual performance of the Avalon MD is about the same as the ASHRAE model, with the ASHRAE model consuming 275^6 Btu per year and the Avalon MD consuming 278^6 Btu per year. In this scenario there would be no yearly cost savings in energy consumption with the MD. However, the other benefits of owning a MD would still make this type of construction more appealing to the long-term perspective thinker. From a cost perspective alone, because a MD does not have to be rebuilt over time from normal wear and tear or from natural disaster occurrences, there are direct cost savings as well as indirect. The indirect cost savings come in the form of reduced insurance premiums and savings in time not spent rebuilding.

From a green building perspective and as visited in Section 2.3 LEED Energy Credits in a Monolithic Dome, MDs are adaptable to meet the other standards usually addressed in certification systems such as LEED. Above and beyond what obtaining LEED credits would do, the conventional construction process creates a great deal more waste than that of the MD because of the application process used for the shotcrete and SPF in the walls and ceiling of the building. Virtually no waste is created. The shotcrete used for the MD building envelope can also be mixed with fly ash, a by-product of burning coal in power plants. In fact, the MDI supports the use of fly ash in their structures for several reasons, including the improved workability of the concrete while pumping during the construction process and the increased strength of the finished product because of the stronger chemical bonds created.[49]

Beyond looking at the technical economic and environmental aspects of building a MD there are also the social aspects. From a bird's eye view the MD may seem irregular and un-inviting, but the reality for those that have examined existing residential and non-residential buildings is that they can be just as beautiful, comfortable or unique as the owner wants the building to be. As part of the study, at least 15 MDs were visited and examined from the outside and inside. From experience and testimony given by these MD owners, the atmosphere is quiet, comfortable and above all, a sense of mental security is felt immediately upon entering the building because of the proven safety against almost unavoidable natural disasters. In regions around the world where

[49] (Copeland, 2003)

earthquakes are common and entire villages are destroyed over the course of minutes, MDs offer a valuable advantage that no amount of monetary cost should overlook. In coastal communities that are pounded by hurricane force winds annually, again bringing destruction to communities and adding to the region's financial burden and ability to prosper as a nation, MDs may offer a housing solution that is permanent and trusted. These types of issues are especially relevant in an age where climate change is increasing the possibility of these types of occurrences.

5.2 Energy Cost of Existing Monolithic Domes

The resulting utility bills analysis of the seven existing MDs posed some interesting results. These MDs were built on site for the use of friends and staff of the MDI. Having spoken to the staff and seen and been inside of these buildings, the usage schedule may help explain some of the inconsistencies. For instance the Visitor dome, which seems to use too much energy (see *Table 7*), is left unlocked all day and people can come in and out of the dome unsupervised. It's a possibility that the door is left open or not shut well or perhaps the A/C unit is not kept at a constant temperature, causing the unit to overwork at times to make up for lost cooling time.

Another notable inconsistency in these results is between the DBS and Main domes. The large difference in cost between these two domes can be attributed to several factors. For one, the Main dome is usually occupied by three or four times more people than the DBS dome in a given day, with each person assigned to a desktop computer, telephone, et cetera. This facility functions as the main headquarters office for MDI and therefore, the occupants in the dome are using a lot more energy throughout the day to work on their computer, make coffee, heat up their lunch, print and scan documents and other related office activities. In addition to the occupancy schedule and type, the design of the dome was a bit of a project. The front/entrance was built with tall windows that absorb and bring into the facility a lot of heat throughout the day. As one of the first domes built on site, the owner expressed some regret in regards to electrical consumption in making this design decision, although the dome itself still functions well and comfortably for its' occupants.

One of the astonishing elements of the utility bills is how well the Bruco dome performs compared to the other MD utility bills. The Bruco dome is four times bigger than the second largest dome (Main) and only uses $1,058 more per year (see *Table 7*). This could be attributed to the fact that the Main dome is occupied by more people and has computers and machines that are left on for longer periods of time during the day. The Bruco dome may have five to ten people in it at one time and the ventilation resulting from large factory doors may perhaps contribute to keeping the building cooler during the summer in combination with the performance of the building envelope, which is supposed to reduce the heat transfer from the outside to the inside.

It should be noted that all seven of these MDs, as well as the case study Avalon MD, are located in Climate Zone 3A which is classified by ASHRAE definition as warm and humid. The results of the study may have been different depending on the climate zone the building was tested in. This is a common regarding equal performance whether in an extremely cold climate, hot and dry or hot and humid climate. To this effect the MDI has reported that their buildings work just as well at maintaining constant temperatures whether in extremely hot or cold climates. However, in constant and extremely hot and humid climates (categorized by ASHRAE as Zone 1) the MD's close family member, known as the Ecoshell, is recommended. The Ecoshell does not have the SPF used in MDs, but it remains structurally strong with approximately two inches of shotcrete and an imbedded rebar cage.[50] Ecoshells, however, cannot provide all the benefits claimed for the MD.

6 Closing Remarks and Recommendations

The MD is a type of structure that has the potential to become one of the most sustainable buildings of the century. From the perspective of endurance and longevity, its persistence and strength to endure and not burn or decay over time elicits a great deal of attention for the sustainable development industry. Knowing the time, cost and resources, both human and in materials, which are required to rebuild residences and communities makes this issue of strength and longevity in a building even more prominent. Besides it's longevity, its ability to adapt to and be modified to fit into other

[50] (MDI, The Ecoshell vs. The Monolithic Dome, 2009)

conventional standards of building makes the structure versatile and open to be continually improved upon and personalized. MDs work as both commercial and residential buildings and although not without its skeptics, engineers and designers can testify to their ability to even be used as high-rise buildings. This is another positive quality for the sustainability aspect, as high density development starts to become a necessity with an exponential and irrepressible global population growth.

Although this study focused on how the energy credits of LEED can be incorporated into the MD construction process, other categories under the LEED rating system can also be examined through the lens of the MD. For instance, in the Sustainable Sites category a quick overlook reveals that MDs have the potential to meet the prerequisite for reduced construction pollution as well as receive points based on the location and characteristics of the site chosen. In the Materials and Resources category, many of the credits listed are obtainable with the MD, to include the use of regional materials, the recycled content used in both SPF (castor oil) and shotcrete (flyash) and for certification of existing buildings under LEED, the building reuse credits would certainly apply.

Perhaps one of the most unique characteristics is the peace of mind that comes with being inside of a MD. How many other buildings, particularly residential, can ensure its tenants survivability against tornadoes, earthquakes and fires? This characteristic is also the basis for the huge cost savings achieved over the life of the building, which includes the ability to insure the building at a much lower premium. Several major aspects stand out from a cost perspective. For example, conventional construction requires that a roof be replaced about every 15 years, which for a house that's about 1,300 square feet can cost about $6,000 depending on the materials used. Aside from the cost of recoating the exterior of a MD, there are no other maintenance fees associated with the building envelope for the life of the building. The MD essentially requires a one-time construction fee and related embodied energy after which decades can go by before having to invest any significant money, time or energy again. One of the major recommendations for continuing studies on MDs would be to conduct a Life Cycle Cost (LCC) analysis to be able to comprehensively understand the long term savings associated with this type of building structure.

Despite the fact that cost savings when compared to LEED buildings following ASHRAE Standard 90.1 were not explicitly proven in this study, the other known characteristics of a MD should make this type of construction more appealing than what it currently seems to be in the market. A shift in our perception of the perfect house or building must occur to move past the weariness of unfamiliar walls and into the unavoidable future where sustainability becomes the number one priority.

The USGBC has historically been an organization to consider feedback from its stakeholders and supporters and their mission has been to transform the way communities are designed to support a more sustainable future and instill more responsibility. With such a powerful statement and honest motivations to improve our built environment, MDs are deserving of a more thorough analysis into what they could contribute to the sustainable building industry.

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