THERMAL ENVELOPE SUBSTITUTION:
ENERGY AND COST IMPLICATIONS OF USING
STRUCTURAL INSULATED PANELS IN THE
MANUFACTURED HOUSING INDUSTRY

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ABSTRACT

Thermal Envelope Substitution: Energy and Cost Implications of Using Structural Insulated Panels in the Manufactured Housing Industry

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Currently 10% of all single family homes produced in the U.S. are manufactured homes with 75% of these households making less than \$50,000 in annual income (Manufactured Housing Survey). Manufactured homes typically use twice as much primary energy per square foot than site built homes yet there is no agenda within the industry or its governing bodies to address this excess energy consumption. The research presented in this thesis compares the thermal envelope performance of the typical wood stud framing used in the manufactured home industry to the thermal envelope of structural insulated panels (SIPs). This comparison examines the energy savings a SIP manufactured home could create for a home owner while speculating on the financial and technical feasibility of using SIPs in the manufactured housing industry. Ultimately, the comparison reveals the short comings of the Manufactured Homes Construction and Safety Standards (HUD Code) regarding thermal envelope requirements and energy use intensity.

These short comings are revealed when the energy use of HUD compliant manufactured homes is scrutinized and compared to the energy use of a similar home built with SIPs for the thermal envelope. The continuous insulation and airtight qualities of the SIP home allow it to use 32%-46% less energy than the HUD compliant homes in the same locations. Manufactured homes require much more energy to heat and cool because the HUD code does not require a certain performance criteria be met for the airtightness of manufactured homes and the overall U-values it requires for the thermal envelopes of such homes is too high for the varying climate zones found in the U.S. If SIP panels were to be used for the thermal envelope of the manufactured housing industry, low income manufactured home owners could be saving \$300-\$700 annually in energy costs.

Unfortunately, the SIP industry cannot offer its product at a low enough price to compete with the economies of scale achieved by the manufactured housing industry when buying raw construction materials. The value of this research then, is the exposure of the manufactured home's inferior thermal envelope performance compared to more modern construction technologies and the speculation of how the manufactured housing industry might be able to incorporate a SIP thermal envelope without putting its customers at a monetary disadvantage.

ACKNOWLEDGMENTS

This research was inspired by all the high end green architecture providing energy efficiency to the few who realize its need and who can afford it, while the masses keep gobbling energy without enough knowledge to care. The solution to our energy consumption problems won't be solved by the enlightened few. Instead, they will be solved through widespread understanding, participation, and commitment of all industries and individuals.

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Champion Homes, Lindsay, CA

API Trailers, Santa Maria, CA

TABLE OF CONTENTS

LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
1) INTRODUCTION.....	1
1.1) The Problem	1
1.2) Background Studies	1
1.3) Research	1
2) THE MANUFACTURED HOUSING INDUSTRY.....	2
2.1) A Brief History Of Manufactured Housing	2
2.2) HUD Code	4
2.3) The Modern Product	6
2.4) Efficiencies of Factory Production	10
2.5) Champion Homes Factory Tour	11
2.6) Economies of Scale	17
2.7) Energy Consumption and Health Issues	18
2.8) The Stick Framed Envelope	20
3) ALTERNATIVE THERMAL ENVELOPE SYSTEM.....	21
3.1) Product Comparison	21
3.2) Structural Insulated Panels (SIPs)	24
3.3) SIPs for Manufactured Housing	26
4) HUD CODE COMPARISON.....	27
4.1) Energy Use Modeling	27
4.2) Thermal Performance Modeling	28
4.3) U-Value Component Calculations	30
4.4) Control Model 1	31
4.5) Control Model 2	34
4.6) Control Model 3	37
4.7) SIP Model 1	40
4.8) Design Builder Energy Model	43
4.9) Energy Use Comparison 1: El Paso, TX	45
4.10) Energy Use Comparison 1.1: New Orleans, LA	48
4.11) Energy Use Comparison 2: Phoenix, AZ	51
4.12) Energy Use Comparison 2.1: San Luis Obispo, CA	54
4.13) Energy Use Comparison 2.2: St. Louis, MO	57
4.14) Energy Use Comparison 3: Boise, ID	60
4.15) Energy Use Comparison 3.1: Minneapolis, MN	63
4.16) Energy Modeling Cost and Efficiency Comparison	66
4.17) Energy Sensitivity Comparison	68
5) ENERGY STAR COMPARISON.....	70
5.1) Energy Star Manufactured Housing	70
6) COST COMPARISON.....	72
6.1) SIP Cost vs. Stick Cost: Retail Price Comparison	72
7) CONCLUSIONS.....	74
7.1) Energy Use Comparison	74
7.2) Price Comparison & Appropriateness of SIPs for Manufactured homes	74
7.3) Further Research and Investigation	76
	vi

TABLE OF CONTENTS (CONTINUED)

8) REFERENCES.....	77
9) BIBLIOGRAPHY.....	79
10) APPENDICES.....	80
- Designing Energy Star Qualified Manufactured Housing	80

LIST OF TABLES

Table 1: Manufactured to Site Built Home Cost Comparison	10
Table 2: Site Built vs. Manufactured Home Construction	11
Table 3: 2030 Challenge Average Residential Site EUI's	21
Table 4: Control Model 1 Floor Component U-Value	35
Table 5: Control Model 1 Wall Components U-Value	36
Table 6: Control Model 1 Roof Component U-Value	36
Table 7: Control Model 1 Overall U-Value Calculation	37
Table 8: Control Model 2 Floor Component U-Value	38
Table 9: Control Model 2 Wall Components U-Value	39
Table 10: Control Model 2 Roof Component U-Value	39
Table 11: Control Model 2 Overall U-Value Calculation	40
Table 12: Control Model 3 Floor Component U-Value	41
Table 13: Control Model 3 Wall Components U-Value	42
Table 14: Control Model 3 Roof Component U-Value	42
Table 15: Control Model 3 Overall U-Value Calculation	43
Table 16: SIP Model 1 Floor Component U-Value	44
Table 17: SIP Model 1 Wall Components U-Value	45
Table 18: SIP Model 1 Roof Component U-Value	45
Table 19: SIP Model 1 Overall U-Value Calculation	46
Table 20: Gas and Electric Energy Rate Costs	70
Table 21: HUD Code vs. SIPs Cost and Efficiency Comparison	71

LIST OF FIGURES

Fig. 1: 1928 Pierce Arrow Housecar	4
Fig. 2: 1922 Zagelmeyer Tent Trailer	4
Fig. 3: Maximum Allowable Overall U-Values	7
Fig. 4: Champion Homes Zone 3 Model	9
Fig. 5: Manufactured Housing Demographics	11
Fig. 6: Champion Homes Factory Floor	12
Fig. 7: Champion Homes Trailer Chassis Fab.	13
Fig. 8: Champion Homes Ducting Fabrication	13
Fig. 9: Champion Homes Bulk Material Storage	13
Fig. 10: Champion Homes Floor Fabrication	14
Fig. 11: Champion Homes Flipping a Floor	14
Fig. 12: Champion Homes Laminate Flooring	14
Fig. 13: Champion Homes Wall Framing	15
Fig. 14: Champion Homes Electrical/Plumbing	15
Fig. 15: Champion Homes Cabinet Shop	15
Fig. 16: Champion Homes Exterior Wall	16
Fig. 17: Champion Homes Anchor Strapping	16
Fig. 18: Champion Homes Roof	16
Fig. 19: Champion Homes Exterior Paneling	17
Fig. 20: Champion Homes Excess Blocking	17
Fig. 21: Champion Homes Roof	17
Fig. 22: Champion Homes Installed Window	18
Fig. 23: Champion Homes Drywall Finishing	18
Fig. 24: Champion Homes Finish Painting	18
Fig. 25: THERM model of 2 x 4 framing	22
Fig. 26: 2 x 4 Wall Thermal Imaging	22
Fig. 27: Insulated Concrete Forms	24

LIST OF FIGURES (CONTINUED)

Fig. 28: The Vitruvian Building System	25
Fig. 29: A Structural Insulated Panel	26
Fig. 30: A SIP Home in Construction	26
Fig. 31: Insulfoam EPS Block Storage	28
Fig. 32: SIP Pneumatic Press	28
Fig. 33: SIP Custom Panel Fabrication	28
Fig. 34: Energy Model Floor Plan	32
Fig. 35: Energy Model Elevations	33
Fig. 36: Passive House U-value Calculator	34
Fig. 37: Control Model 1 Schematic Section	37
Fig. 38: Control Model 2 Schematic Section	40
Fig. 39: Control Model 3 Schematic Section	43
Fig. 40: SIP Model 1 Schematic Section	46
Fig. 41: Design Builder Axonometric	47
Fig. 42: Design Builder Model Energy Zones	47
Fig. 43: Control 1- El Paso Fuel Totals	49
Fig. 44: SIP 1- El Paso Fuel Totals	49
Fig. 45: Control 1- El Paso Fuel Breakdown	49
Fig. 46: SIP 1- El Paso Fuel Breakdown	49
Fig. 47: Control 1- El Paso Heating Design: Energy Loss Through Thermal Envelope	50
Fig. 48: SIP 1-El Paso Heating Design: Energy Loss Through Thermal Envelope	50
Fig. 49: Control 1- El Paso Cooling Design Day	51
Fig. 50: SIP 1- El Paso Cooling Design Day	51
Fig. 51: Control 1- New Orleans Fuel Totals	52
Fig. 52: SIP 1- New Orleans Fuel Totals	52
Fig. 53: Control 1- New Orleans Fuel Breakdown	52

LIST OF FIGURES (CONTINUED)

Fig. 54: SIP 1- New Orleans Fuel Breakdown	52
Fig. 55: Control 1- New Orleans Heating Design: Energy Loss Through Thermal Envelope	53
Fig. 56: SIP 1- New Orleans Heating Design: Energy Loss Through Thermal Envelope	53
Fig. 57: Control 1- New Orleans Cooling Design Day	54
Fig. 58: SIP 1- New Orleans Cooling Design Day	54
Fig. 59: Control 2- Phoenix Fuel Totals	55
Fig. 60: SIP 1- Phoenix Fuel Totals	55
Fig. 61: Control 2- Phoenix Fuel Breakdown	55
Fig. 62: SIP 1- Phoenix Fuel Breakdown	55
Fig. 63: Control 2- Phoenix Heating Design: Energy Loss Through Thermal Envelope	56
Fig. 64: SIP 1- Phoenix Heating Design: Energy Loss Through Thermal Envelope	56
Fig. 65: Control 2- Phoenix Cooling Design Day	57
Fig. 66: SIP 1- Phoenix Cooling Design Day	57
Fig. 67: Control 2- SLO Fuel Totals	58
Fig. 68: SIP 1- SLO Fuel Totals	58
Fig. 69: Control 2- SLO Fuel Breakdown	58
Fig. 70: SIP 1- SLO Fuel Breakdown	58
Fig. 71: Control 2- SLO Heating Design: Energy Loss Through Thermal Envelope	59
Fig. 72: SIP 1- SLO Heating Design: Energy Loss Through Thermal Envelope	59
Fig. 73: Control 2- SLO Cooling Design Day	60
Fig. 74: SIP 1- SLO Cooling Design Day	60
Fig. 75: Control 2- St. Louis Fuel Totals	61
Fig. 76: SIP 1- St. Louis Fuel Totals	61
Fig. 77: Control 2- St. Louis Fuel Breakdown	61

LIST OF FIGURES (CONTINUED)

Fig. 78: SIP 1- St. Louis Fuel Breakdown	61
Fig. 79: Control 2- St. Louis Heating Design: Energy Loss Through Thermal Envelope	62
Fig. 80: SIP 1- St. Louis Heating Design: Energy Loss Through Thermal Envelope	62
Fig. 81: Control 2- St. Louis Cooling Design Day	63
Fig. 82: SIP 1- St. Louis Cooling Design Day	63
Fig. 83: Control 3- Boise Fuel Totals	64
Fig. 84: SIP 1- Boise Fuel Totals	64
Fig. 85: Control 3- Boise Fuel Breakdown	64
Fig. 86: SIP 1- Boise Fuel Breakdown	64
Fig. 87: Control 3- Boise Heating Design: Energy Loss Through Thermal Envelope	65
Fig. 88: SIP 1- Boise Heating Design: Energy Loss Through Thermal Envelope	65
Fig. 89: Control 3- Boise Cooling Design Day	66
Fig. 90: SIP 1- Boise Cooling Design Day	66
Fig. 91: Control 3- Minneapolis Fuel Totals	67
Fig. 92: SIP 1- Minneapolis Fuel Totals	67
Fig. 93: Control 3- Minneapolis Fuel Breakdown	67
Fig. 94: SIP 1- Minneapolis Fuel Breakdown	67
Fig. 95: Control 3- Minneapolis Heating Design: Energy Loss-Through Thermal Envelope	68
Fig. 96: SIP 1- Minneapolis Heating Design: Energy Loss Through Thermal Envelope	68
Fig. 97: Control 3- Minneapolis Cooling Design Day	69
Fig. 98: SIP 1- Minneapolis Cooling Design Day	69
Fig. 99: Control 3- Minneapolis Fuel Totals .6 ACH Model	72
Fig. 100: Control 3- Minneapolis Fuel Totals .3 ACH Model	72
Fig. 101: Control 3- Minneapolis Fuel Totals .3 ACH Model	73

LIST OF FIGURES (CONTINUED)

Fig. 102: SIP 1- Minneapolis Fuel Totals	73
Fig. 103: Control 3- Minneapolis Heating Design: Energy Loss Through Thermal Envelope .3 ACH model	73
Fig. 104: SIP 1- Minneapolis Heating Design: Energy Loss Through Thermal Envelope	73
Fig. 105: Energy Star Manufactured Housing Climate Zone Map	75
Fig. 106: 4' x 8' Wall Section: SIPs v. Stick Framed	78

CHAPTER 1: INTRODUCTION

1.1) The Problem:

The manufactured housing industry provides very low cost single family housing across the nation at a fraction of the cost of site built homes. This industry's efficiencies in finances and manufacturing are contrasted by its product's lack of energy efficiency and thermal comfort. Poor energy efficiency of manufactured homes can be largely attributed to the mediocre performance of the wood stud framed thermal envelope used in such homes. The construction code for manufactured homes does not specify an airtightness requirement and also allow overall U-values that are too high for many regions of the United States. With 10% of all single family homes in the nation being manufactured homes, the industry has the potential to affect positive change in our nation's energy consumption. To demonstrate this potential, the wood stud framed thermal envelope used by the manufactured housing industry is compared to a thermal envelope created by structural insulated panels (SIPs).

1.2) Background Studies:

In order to provide a better understanding of manufactured housing and SIPs an introduction and a background is provided for each industry. Tours of a manufactured home factory and a Foam/SIP factory provide first hand information about each industry.

1.3) Research:

The energy efficiency of typical wood stud framed manufactured housing is modeled and compared to the energy efficiency of the same home built with SIPs. The energy comparison is conducted in multiple different climate zones as defined by the Manufactured Home Construction Safety and Standards act. The energy models are identical except for their thermal envelopes. Therefore, any differences seen between the results can be attributed to the changes in the thermal envelope.

CHAPTER 2: THE MANUFACTURED HOUSING INDUSTRY

2.1) A Brief History Of Manufactured Housing

After the American automotive boom of the early 20th century, the car became a part of the ordinary American lifestyle. The automobile allowed for a level of personal transportation that was unmatched by previous means. Beyond the practical aspects of fast and easy personal transportation, a new outlook on the recreation of travel became apparent. The automobile made it easy for car owners to take short camping trips to destinations that were previously out of reach given the time frame of a weekend. With an automobile, people could get places faster while carrying more home amenities with them like large tents, cots, food, cooking apparatus, and toiletries. By the mid 1920's it was "estimated that 10-15 million Americans were going car camping every year" (Sutter 223).

Soon automobile manufacturers and entrepreneurs caught on to the new car camping trend and launched products intended to make the camping experience more comfortable. This

Fig. 1: 1928 Pierce Arrow Housecar

Fig. 2: 1922 Zagelmeyer Tent Trailer

new market brought forth the first camping trailers and recreational vehicles (RV's). A few manufacturers began producing high end self contained auto campers (RV's) like the Pierce Housecar to the left. These types of camping enhancement vehicles were not as popular, and most companies producing models like this were brought down in the 1929 market crash. Camping trailers were sold with the most success as they could be attached to almost any vehicle and were much cheaper to buy than an RV. Most trailers utilized folding and pop-up strategies to maximize amenity while minimizing space and weight.

As industrial technology continued to improve through World War II and beyond, the RV and camping trailer industry was able to include even more amenity to its products. Trailer models that previously only had sleeping and eating amenities were now being produced with longer lengths that included bathrooms and electrical lighting. By the 1940's and 50's camping trailers had incorporated enough lifestyle amenity that many people began to see them as viable options for permanent residence.

While the style of American car camping evolved with technology, so did the campgrounds that serviced this recreation. Campgrounds began incorporating site fees for future improvements, water hook-ups, and electrical hook-ups. Campgrounds on the outskirts of many cities and in many rural areas that were once intended as recreational camping spots were now being turned into America's first mobile home parks and the social stigma of trailer living began to develop. By the 1970's mobile homes had become so popular as an affordable housing option that one mobile home was produced for every three site built homes (Manufactured Housing Association of Oklahoma).

With such a large boom in production and popularity, the national government implemented the National Manufactured Housing Construction and Safety Standards Act of 1974. This act created a national system for controlling the quality of manufactured homes produced in the U.S. More commonly known as the "HUD Code," this act is applicable to all manufactured houses regardless of where in the U.S. they are produced or placed (Briggs 51). The standards set forth in the HUD code create a strict set of performance based compliance standards that are intended to create a clear separation in quality between the pre-1974 "mobile homes" and the post HUD code "manufactured homes."

2.2) HUD Code

The HUD code sets forth performance based criteria for all aspects of manufactured home construction including design, construction, strength, durability, fire resistance, energy efficiency, ventilation, wind resistance and installation procedures (Manufactured Housing Association of Oklahoma). Unlike the local and state building codes for modular or site-built homes, the HUD Code is a national system that applies to all manufactured homes regardless of local jurisdiction. Due to this unique national system of code, “once designs of manufactured housing are approved, the same or similar designs can be replicated many times in the controlled factory environment” without the need for re-approval of the design and construction process (Briggs 70).

Enforcement of the HUD code is broken down into two separate enforcement agencies organized at the state level. Each state has the option to control these two enforcement agencies or allow private industry to provide such services. The first enforcing agency to review the process of a manufactured home’s development is the Design Approval Primary Inspection Agency (DAPIA). This agency reviews all new plans submitted for manufactured homes and ensures that these plans meet the performance based criteria for manufactured housing set forth by the HUD code. Once plans are approved by the DAPIA they can be reproduced over and over again without needing additional approval. The second enforcing agency is the Production Inspection Primary Inspection Agency (PIPIA). This agency ensures the factory production practices meet safety and quality regulations for factory construction set forth by HUD code.

The organization, performance criteria, and enforcement of the HUD code has allowed the manufactured housing industry to become what it is today. For the purposes of this thesis, however, only the thermal envelope performance criteria of the HUD code are scrutinized and applied.

HUD Code - Subpart F- Thermal Protection

"The HUD-Code has its own unique set of thermal requirements that were revised in 1994. They are expressed as a maximum overall U-value (U_o) for the entire building envelope (ceiling, walls, windows and floors but not including air infiltration) for each of three climate zones. The HUD climate zones are divided along state boundaries. The maximum allowable U_o drops from 0.116 Btu/hr·ft²·°F in Zone 1 (Alabama, Florida, Georgia, Hawaii, Louisiana, Mississippi, South Carolina and Texas) to 0.096 Btu/hr·ft²·°F in Zone 2 (Arizona, Arkansas, California, Kansas, Kentucky, Missouri, New Mexico, North Carolina, Oklahoma, and Tennessee) and 0.079 Btu/hr·ft²·°F in Zone 3 (all remaining states)." (Briggs 88)

A graphic example of the maximum total allowable overall U-values for a manufactured home's thermal envelope is provided below.

Fig: 3 Maximum Allowable Overall U-Values

2.3) The Modern Product: Features and Popularity

Since its legitimate beginnings in 1974, the manufactured housing industry has brought its image, efficiency, and quality a long ways. New construction technologies have allowed the industry to very convincingly replicate the image of the modern suburban home while maintaining a very low cost of ownership. Refined factory processes and economies of scale have allowed the industry to drive prices of manufactured homes below 50% of the cost per square foot of site built homes.

When the HUD code was first enacted manufactured homes were typically only available in single wide options that did not resemble site built homes. These single wide models were designed to be “park” models. Park models were intended to be used in a manufactured housing community or “trailer park.” These early park models did not resemble site built homes and this aesthetic difference created a certain stigma around manufactured housing that the modern industry is now trying to shed. New manufactured homes are sold in single, double, triple, and even quadruple wide models that try very hard to mimic the aesthetic, the plan, and even the size of the American ranch style suburban home. Engineered roof trusses allow for gables and porch eaves giving manufactured homes a similar visual outline to site built home. Usage of modern materials like dual pane low-e windows, hardie-board siding, asphalt roof shingles, modern appliances, and various choices of interior finishes give the industry’s product a similar aesthetic to American site built homes as well. Fig. 4 on the following page depicts the features and options of a manufactured home made by Champion Homes that is intended for use in HUD thermal zone 3. (Champion Homes)

While manufacturers strive to generate an image with modern American vernacular, many other features of manufactured homes help to create popularity for the product. After having worked for a manufactured home installation company, I can personally attest to the speed and efficiency of setting up a new manufactured home on site. With a properly trained and experienced crew, a new double wide mobile home can be installed on site in less than two days. This installation includes foundation installation, electrical connections, plumbing connections, gas

Fig 4: Champion Homes Zone 3 Model

connections, module joining, and a small amount of exterior finish work (i.e. painting). After the installation crew has finished, another day or two of labor is needed in interior finish work such as drywall finishing, paint finishing, and flooring finishing. After these quick installation processes, all that is required is an inspection from a local code official before the owner can move in and enjoy the full benefits of their new home.

When compared to the modular home industry, manufactured housing installation is faster by a factor of weeks or even months. The House of the Immediate Future, which was prototyped this year in Seattle, WA is an affordable modular home product that took 5,300 hours of volunteer work just to install (Broom). That's equivalent to one person working full time for almost 3 years. Another modular home product produced by Living Homes, which boasts its speedy installation still takes at least 4 weeks of finish work after installation before it is move-in ready (FAQ, Living Homes)

The other major factor that generates popularity in the manufactured housing industry is the cost of the finished product. From factory efficiency, bulk material ordering, cheap labor, and cheap installation costs, the manufactured housing industry finds ways to drive the final cost of their product down while still making healthy profits. A tour of one of Champion Home's (one of the top ten manufactured housing producers in the U.S.) factories provided some insight into the costing figures that the industry is able to achieve. During the housing boom of the early 2000's the Champion Home factory in Lindsay, CA was producing on average 7 double wide homes a day from start to finish for a cost to the factory of only \$22 a square foot. With such a low cost of production, the factory is able to sell their homes to retailers for almost twice as much as it costs to build them. Even after such a mark-up the manufactured housing product is still drastically cheaper to buy than a site built home. Table 1 below illustrates the cost differences between manufactured homes and site built homes in the years of 2007-2011 (Manufactured Homes Survey).

Table 1: Manufactured to Site Built Home Cost Comparison

All Manufactured Homes	2007	2008	2009	2010	2011
Average Sales Price	\$65,400	\$64,700	\$63,100	\$62,800	\$60,600
Average Square Footage	1,600	1,565	1,530	1,520	1,470
Cost Per Square Foot	\$40.88	\$41.34	\$41.24	\$41.32	\$41.22
Site Built Homes					
Average Sales Price	\$313,600	\$292,600	\$270,900	\$272,900	\$267,900
Less Land Price	- 84,268	- 74,209	- 67,718	- 66,340	- 59,950
Price of Structure	\$229,332	\$218,391	\$203,182	\$206,560	\$207,950
Average Square Footage	2,479	2,473	2,422	2,457	2,494
Cost Per Square Foot	\$92.51	\$88.31	\$83.89	\$84.07	\$83.38

Since the cost of manufactured housing is not associated with land costs, table 1 subtracts average land prices from the cost of site built homes to create an appropriate number for comparison. Even after the price of land has been factored out, new manufactured homes are still less than 50% of the price per square foot to buy than a new site built home.

Between the manufactured housing industry's push for a modern competitive aesthetic

and affordability, manufactured homes make up around 10% of all new homes produced in this nation. Table 2 below shows a comparison from 2007 to 2011 of site built housing starts to manufactured homes shipped in the U.S (Manufactured Homes Survey).

Table 2: Site Built vs. Manufactured Home Construction

Site Built Homes	2007	2008	2009	2010	2011
Site-Built Housing Starts	1,046	622	445	471	431
Percent of Total	92%	88%	90%	90%	89%
Manufacture Homes					
Shipped	96	82	50	50	52
Percent of Total	8%	12%	10%	10%	11%

With such low market prices the manufactured housing industry has been unintentionally filling a small affordable housing role for the nation. Figure 5 below illustrates the employment and income demographics associated with Americans who own manufactured homes (Manufactured Housing Survey). Over 75% of manufactured homes have an annual household income of less than \$50k.

Employment Status of Household Head

Annual Household Income

Fig 5: Manufactured Housing Demographics

2.4) Efficiencies of Factory Production:

As this thesis investigates the implications of the use of an alternative building envelope system in the manufactured housing industry, it is important to understand the entire factory process that such a change would affect. The manufactured housing industry is able to achieve such a low market price with their products due to labor, material, and cost efficiencies associated with the factory construction process. Just like most other mass produced consumer items, manufactured homes are produced on an assembly line that minimizes labor, waste, and mistakes.

To gain an understanding of the factory process of manufactured home construction a tour of Champions Home's factory in Lindsay, CA was arranged. Upon starting the tour, it was immediately obvious that most components of the home (trailer chassis, ducts, floors, walls, roofs, cabinets, etc.) were fabricated completely in the factory from large pre-bought material supplies. Components not made in the factory from raw material stock (toilets, showers, sinks, etc.) were bought in surplus. The method of doing as much in house fabrication as possible, and ordering all materials or pre-fabricated components in massive economies of scale is what allows the manufactured housing industry to make homes so cheaply.

"The inherent advantages of the manufactured housing industry are the economies of mass production along with a single-minded focus on the low-cost segment of the housing market (Briggs, 116)."

There is a certain portion of the affordable housing market that desires a cheap detached home and the manufactured housing industry is especially good at creating a mass produced product to satisfy that market.

Fig 6: Champion Homes Factory Floor

Fig 7: Champion Homes Trailer Chassis Fab.

Fig 8: Champion Homes Ducting Fabrication

2.5) Champion Homes Factory Tour:

In the factory the first process on the assembly line is the in house fabrication of the trailer chassis. The trailer chassis starts with two pre-stressed I-beams that run the full length of the home that will be built on top of it. The I-beams are placed in a large jig where additional steel structure and the trailer tongue are welded on. Then axles and wheels are added and the chassis is sent down the line. An almost finished trailer chassis still in the welding jig is shown in Figure 7 to the left. Near the chassis fabrication area is the square duct making machine (fig 8) where all of the sub-floor ducting is rolled into shape. This area is also where bulk materials like showers, toilets, pipe for plumbing, conduit, rolls of laminate flooring, and lumber is stored before installation in a new model. (Fig. 9)

Fig 9: Champion Homes Bulk Material Storage

Fig 10: Champion Homes Floor Fabrication

Fig 11: Champion Homes Flipping a Floor

Fig 12: Champion Homes Laminate Flooring

Once the chassis is assembled, it moves down the line where a floor is added. The floor of the home is laid out and pre-constructed on the flat slab of the factory floor. The floor joists are typically either 2x6 or 2x8 lumber members at 24" O.C. depending on what HUD climate zone the home is intended to be placed in. The joists get laid out on the slab, then plywood sheeting is nailed over the joists. At this point the floor assembly is flipped so that wiring can be laid, plumbing can be installed, ducting can be routed, and insulation can be rolled out over the joists. Figure 10 shows an upside down floor component that is having wiring added to it. Once a floor is a complete assembly upside down on the factory floor, the trailer chassis is flipped on top of it and anchored to the floor joists. Then the chassis/floor assembly is flipped back over to right side up for laminate flooring to be rolled out. Figure 11 shows the process of flipping the whole floor and trailer chassis assembly. Figure 12 shows the finished floor plate with laminate flooring rolled out. This laminate product allows single tiles to be replaced later in the construction process if one happens to be damaged in the factory.

Fig 13: Champion Homes Wall Framing

Fig 14: Champion Homes Electrical/Plumbing

Fig 15: Champion Homes Cabinet Shop

After the floor component has been secured to the trailer chassis and the laminate flooring has been applied the assembly is moved to its next position down the factory line. At this point in the process interior walls, plumbing fixtures, cabinets, and appliances are installed on the floor component. Plumbing and electrical lines have already been stubbed up through the floor and are awaiting connection. Interior walls are framed and fully or partially drywalled before being lifted onto the floor. Figure 13 shows an interior wall being lifted onto the floor. This wall is only drywalled on one side so that electrical and plumbing will be easy to route through it once it is placed. Figure 14 shows some finished electrical and plumbing in a partially drywalled interior wall.

All cabinets are made in house and installed at this point on the assembly line. Without exterior walls on the home it is much easier to move and install cabinets, fixtures, and appliances. Figure 15 shows the cabinet shop inside the factory. The cabinet shop is an excellent example of how the construction of an entire home is divided up into different factory processes all under one roof.

Fig 16: Champion Homes Exterior Wall

Once the interior walls are all placed with plumbing routed, electrical routed, fixtures installed, and appliances installed the assembly moves to its next position down the line. At this part of the line, exterior walls and insulation are added. Figure 16 shows an exterior wall laid out on the floor that has already been framed and is waiting to be craned onto the floor. The empty space to the right of the wall is where the assembly will move to after it has been fitted with interior walls and fixtures.

Fig 17: Champion Homes Anchor Strapping

After exterior walls are placed the assembly moves down the line again. Now strapping/tie-downs are added, plumbing and electrical are run in the exterior walls, remaining drywall is added to the interior, and a roof is placed on the assembly. Figure 17 shows the assembly after anchor straps have been applied to the wall and floor framing. Like the floor and walls, the roof is pre-made on the factory floor then lifted into place. To save on finishing time the drywall of the ceiling is glued to the small roof trusses. In the left side of Figure 18 a roof sits on the floor awaiting more OSB sheathing and placement on the home.

Fig 18: Champion Homes Roof

Fig 19: Champion Homes Exterior Paneling

Fig 20: Champion Homes Excess Blocking

Fig 21: Champion Homes Roof

When all of the framed and insulated envelope is in place with all additions to the interior installed, the assembly moves down the line where exterior sheathing and roofing are added. Rather than sheathing the exterior of manufactured homes in OSB or plywood then applying a finish material, the manufactured housing industry is able to use a Hardie-board product that provides shear strength and an exterior finish. The Hardie-board is all painted before it is nailed to the exterior framing. Figure 19 shows the painting station where the hardie-board is painted before installation. Any blemish to the paint job of these panels during installation is touched up quickly later in the process. To mount certain sections of the Hardie-board extra blocking is placed between the exterior wall studs. (Fig. 20)

While the Harie panels are being installed roofers add felt and shingles to the roof. Figure 21 shows a roof partially finished with material waiting to be added.

Fig 22: Champion Homes Installed Window

Fig 23: Champion Homes Drywall Finishing

Fig 24: Champion Homes Finish Painting

After the exterior sheeting has been nailed on and the roof is complete, the assembly moves down for final finish work. At this point windows are added, drywall is taped and spackled, interior paint is applied, and trim is added. Figure 22 is an interior shot of windows that were just installed and before trim is added. Figure 23 depicts a custom arch option in the drywall of a threshold between the living and dining room of a double wide unit. A large header above this opening will be joined to another in the other module after installation on site. During transportation, openings like this are braced with temporary lumber columns.

After the drywall is completely finished and trim has been added, touch-up painting is done on the interior. (Fig. 24) After painting has been finished the home is moved aside where it waits for inspection and finally carpet. Once the home has passed inspection and has been cleared from the factory floor, it is stored in the factory lot until shipment to a retailer.

2.6) Economies of Scale:

While the efficiencies of a well refined factory process minimize costs associated with labor, wasted material, and job/task transition the manufactured housing industry creates efficiency in cost through bulk material ordering. When building a custom site built home, materials are ordered after the design process and are bought on the scale of a single custom project. The manufactured housing industry, however, uses a set of material stock over and over again that is bought in large quantities.

Champion Homes, for instance, has 26 factories across the nation that share the same ordering account with product suppliers. While one factory would be able to get a premium price due to bulk material ordering, Champion as a company can get an even better price because they do bulk material ordering for 26 factories at once. Large suburban home developments work around the same concept of economy of scale but even a 200 home development will be finished and material ordering will stop. The factory environment means construction will always take place in the same location so material ordering can continue taking advantage of economies of scale indefinitely. With material always available and already paid for, the factory process of home construction never has to worry about last minute trips to the hardware store or lumber yard. A manufactured home factory is like a suburban development contractor, a cabinet shop, a welding shop, a hardware store, and a lumber yard all under one roof.

2.7) Energy Consumption and Health Issues

The manufactured housing industry has found ways to streamline construction processes and acquire very low prices for materials. Because of this they are able to create a product with similar feel and aesthetic style as an American site built home but for a fraction of the price to own. However, this process of creating affordability has left out much consideration for the amount of energy such a product requires to maintain and the comfort qualities associated with manufactured homes.

On the following page, table 3 illustrates the annual energy consumption of a typical manufactured home and the annual energy consumption of a typical detached site built home (2030 Challenge). These values are broken into four different regions of the United States with the energy use of detached site built homes highlighted in yellow and the energy use of manufactured homes highlighted in red. This table shows that through the course of a year, manufactured homes typically use twice as much energy per square foot of occupiable floor space when compared to a detached site built home. This difference is not quite as large in the southern states of the U.S. due to less harsh climate types. The energy consumption of manufactured homes is higher due to typically lower insulation values and higher air infiltration values in the building's envelope.

While this thesis focuses on energy consumption related to the thermal envelope, manufactured homes also use many materials that are known to have very high emissions of volatile organic compounds (VOC's). "Major identified sources (of VOC's in new homes) include plywood flooring, latex paint, and sheet vinyl flooring (Rudd, Abstract)." These materials are all staples of the manufactured housing industry that can be bought very cheaply in large quantities. Some manufactured home producers give options for increased energy efficiency by sealing the building envelope better for lower values of air infiltration. This reduces losses through the building's envelope, but at the same time it creates a very sealed atmosphere where VOC's can accumulate and become harmful.

Table 3: 2030 Challenge Average Residential Site EUI's

2030 CHALLENGE Targets: U.S. Residential Regional Averages

U.S. Regional Averages for Site Energy Use and 2030 Challenge Energy Reduction Targets by Residential Space/Building Type (RECS 2001) ¹							
From the Environmental Protection Agency (EPA): Use this chart to find the site fossil-fuel energy targets.							
Residential Space/Building Type ²	Average Source EUI ^{3,4} (kBtu/Sq.Ft./Yr)	Average Site EUI ^{3,5} (kBtu/Sq.Ft./Yr)	2030 Challenge Site EUI Targets (kBtu/Sq.Ft./Yr)				
			50% Target	60% Target	70% Target	80% Target	90% Target
Northeast							
Single-Family Detached	67.5	45.7	22.9	18.3	13.7	9.1	4.6
Single-Family Attached	68.6	50.3	25.1	20.1	15.1	10.1	5.0
Multi-Family, 2 to 4 units	78.8	57.8	28.9	23.1	17.3	11.6	5.8
Multi-Family, 5 or more units	98.2	60.7	30.4	24.3	18.2	12.1	6.1
Mobile Homes	145.5	89.3	44.6	35.7	26.8	17.9	8.9
Midwest							
Single-Family Detached	76.2	49.5	24.7	19.8	14.8	9.9	4.9
Single-Family Attached	66.6	44.8	22.4	17.9	13.4	9.0	4.5
Multi-Family, 2 to 4 units	104.8	74.0	37.0	29.6	22.2	14.8	7.4
Multi-Family, 5 or more units	93.3	50.9	25.4	20.4	15.3	10.2	5.1
Mobile Homes	168.9	103.3	51.6	41.3	31.0	20.7	10.3
South							
Single-Family Detached	86.0	41.5	20.8	16.6	12.5	8.3	4.2
Single-Family Attached	82.5	38.8	19.4	15.5	11.6	7.8	3.9
Multi-Family, 2 to 4 units	113.6	46.9	23.5	18.8	14.1	9.4	4.7
Multi-Family, 5 or more units	122.4	47.9	24.0	19.2	14.4	9.6	4.8
Mobile Homes	162.0	63.3	31.6	25.3	19.0	12.7	6.3
West							
Single-Family Detached	67.2	38.4	19.2	15.4	11.5	7.7	3.8
Single-Family Attached	63.2	38.8	19.4	15.5	11.6	7.8	3.9
Multi-Family, 2 to 4 units	87.3	47.6	23.8	19.1	14.3	9.5	4.8
Multi-Family, 5 or more units	81.7	40.0	20.0	16.0	12.0	8.0	4.0
Mobile Homes	128.2	65.8	32.9	26.3	19.7	13.2	6.6

2.8) The Stick Framed Envelope

The Manufactured Housing Industry uses traditional wood stud framing to create the thermal envelope for its buildings. Wood stud framing allows factory workers to create floor, wall, and roof components quickly and the materials can be bought cheaply by the manufacturer. While wood stud framing is easy to build and can be done with cheap materials, its thermal performance is hindered by many thermal bridges and lack of airtightness.

Thermal bridges in a building's thermal envelope occur when a structural member creates an un-insulated bridge between the building's exterior and the controlled interior environment. In wood stud framed walls, for instance, a thermal bridge occurs vertically every 16 inches where a stud is placed. These bridges allow energy to transfer through the thermal envelope faster. This means that during winter months, heat is lost through the thermal envelope due to thermal bridging and in the summer months, heat is gained through the thermal envelope due to thermal bridging. If figure 25 below, a 2x4 framed wall section was modeled in the thermal bridge analysis program THERM. THERM calculates heat transfer through building elements to generate a visual display of thermal bridging. The top section in Fig. 25 shows a stud framed wall in plan view. The bottom section in Fig. 25 shows how heat transfer is affected through the wall due to thermal bridging at each stud. Figure 26 is thermal imaging of a 2x4 wall of a home during a winter night. The image clearly displays a more heat loss through the wall at each stud.

Fig 25: THERM Model of 2x4 Framing

Fig 26: 2x4 Wall Thermal Imaging

CHAPTER 3: ALTERNATIVE THERMAL ENVELOPE SYSTEM

3.1) Product Comparison

To generate an energy and cost comparison between the traditional wood stud framing used by the manufactured housing industry and an alternative envelope system, an alternative system must first be chosen. Many new envelope systems in the residential building industry are being used in place of traditional wood stud framing. Alternative envelope systems to be considered are designed to eliminate much of the thermal bridging effect found in stud framing. These systems will be compared to each other while considering their appropriateness for the manufactured housing industry. Insulated concrete forms, the Vitruvian Building System, and structural insulated panels will all be considered, but one will be deemed most appropriate for use in the manufactured housing industry and will be used to generate energy use and cost comparisons.

Insulated concrete forms (ICF's) offer a prefabricated building envelope solution which creates a mostly thermal bridge free structural/thermal envelope while giving thermal mass to the building. ICF's are usually foam forms stacked in place. Rebar is placed inside these foam forms and then concrete is poured into them. The concrete and rebar create a very sustainable structure while the prefabricated forms speed up the construction process and create a continuous layer of insulation on the interior and the exterior of the thermal envelopes. Figure 27 shows a wall section of ICF's, with rebar placed inside, ready for concrete to be poured inside. While ICF's

are a widely accepted structural/thermal envelope system with speedy construction times, they will not be considered as an appropriate thermal envelope substitution for the manufactured housing industry. The weight and permanence of concrete would not be conducive to the transportation that manufactured homes must undergo.

Fig 27: Insulated Concrete Forms

The Vitruvian building system is a new prefabricated building product manufactured in California's central coast. This system uses EPS foam panels and off-set metal stud framing to create sections of building envelope. The steel studs are inset into the foam panels which provides a vertical and shear loading solution. Figure 28 shows the Vitruvian building system mid-way through construction. The Vitruvian building system offers speedy construction, a lightweight envelope, and continuous insulation in the thermal envelope. While these three characteristics make it a very technically appropriate envelope solution for the manufactured housing industry, the Vitruvian building system is a proprietary construction technique that is not yet widely accepted by building code. It is also not available at a national scale which is necessary for the material resources of manufactured housing. For these reasons the Vitruvian building system will not be considered for comparison the wood stud framing of the manufactured housing industry.

Fig 28: The Vitruvian Building System

Structural Insulate Panels (SIP's) are a prefabricated building envelope system that sandwiches EPS foam between two sheets of OSB plywood (Fig. 29). This sandwich creates a structural panel that can be used for floor, wall, and roof components. The panel creates a structural section that is widely accepted by American building codes to provide similar to better structural performance when compared to traditional wood stud framing. SIP's are a lightweight prefabricated system that speeds up on site construction time while providing structure and continuous insulation through much of the building envelope. Figure 30 shows how SIPs can be

Fig 29: A Structural Insulated Panel

Fig 30: A SIP Home in Construction

used to frame the entire envelope of a home. SIPs are a widely used and accepted building envelope system nation-wide. SIPs incorporate a fast and easy construction system with a lightweight product. As a product they are available anywhere in the nation with a large network of distributors. Design and construction information regarding SIPs is also available to the public. Because of their physical characteristics, construction/installation process, and national availability SIPs will be used as the alternative building envelope system being scrutinized by this thesis.

3.2) Structural Insulated Panels

“Structural insulated panels (SIPs) should be more frequently used by architects as an alternative to conventional ‘stick built’ systems. All SIPs consist of two sheets of plywood, gypsum board or sheet metal adhered to a plastic foam core. The foam contains no CFCs, and maintains an R-value equal to other types of insulating materials. The panels are lightweight, and can be installed by hand or with the help of cranes. SIPs provide superb structural performance, local loading capability and are easily cut to order. SIPs also make for an air-tight house, so a good ventilation system is required (Winter, 88).”

The abstract from Stephen Winter’s article sums up the advantages of the SIP product well. It is a very versatile product with the ability to provide a tight thermal envelope for floor, wall, and roof components of low rise structures. While still a relatively new technology when compared to wood stud framing, it generates the same level of acceptance from the perspective of code officials because of its widespread use. When considering material costs, SIP panels are a more expensive alternative to wood stud framing. But when “labor savings resulting from shorter construction time and less job site waste” are factored into the cost equation, the cost of building with SIPs begins to resemble that of wood stud framing (SIPs FAQ). SIPs can also “outperform the conduction resistance of conventional (stick framed) walls even if they are statistically the same in R-values (Winter, 88).” Due to the continuous insulation that is inherent in the construction of SIP panels, a SIP thermal envelope will have far less thermal bridging than a stick framed envelope and therefore less energy loss.

To gain a deeper understanding of the SIP industry, a tour of Premier SIPs manufacturing facility in Dixon, Ca was arranged. Premier SIPs is the leading producer of SIPs in the nation and is a subsidiary company of Insulfoam, an EPS foam manufacturing company. Premier manufactures SIPs in panel sizes that range from 4’ x 8’ to 8’ x 24’ with EPS foam cores that range from 3.5” to 11.25” in thickness (R-14 to R-50 insulation values depending on climate). 90% of SIP orders to Premier ask for pre-cut products based on specific building plans produced by a SIP designer, architect, or builder. This means that Premier will manufacture the panels then cut window openings, door openings, and bevels into the panels in their factory. This custom pre-fabrication process speeds up installation time of the SIPs on site drastically.

Fig 31: Insulfoam EPS block storage

Fig 32: SIP Pneumatic Press

Fig 33: SIP Custom Panel Fabrication

When Premier receives an order for pre-cut panels, the first step in their process is to cut foam that will be needed to cut the panels. Insulfoam compresses extruded polystyrene foam into large blocks that can range from 4' x 4' x 8' to 4' x 4' x 24'. Unfortunately, much of the machinery Insulfoam uses to produce and handle its EPS foam is proprietary technology so pictures of this process are limited. Figure 31 shows the Insulfoam EPS block storage area to give a sense of production scale.

Once the necessary foam is cut for the panels, it is adhered to two OSB panels with polyurethane glue, pressure, and heat. Figure 32 shows the 8' x 24' pneumatic press used to create the panel sandwich. Three 8' x 24' panels can be seen behind the press. Lamination time of a 8' x 24' panel can take anywhere from 40 minutes to 2 hours depending on air temperature. After the panels have been pressed, they move to a different section of the factory where openings are cut and the foam edge are routed for installation (Fig 33). Depending on the level of prefabrication desired by the builder or designer, this process can take anywhere from 10 minutes to an hour per panel.

3.3) SIPs for Manufactured Housing:

If SIPs are to be considered as a replacement for a building envelope, it is important to understand what they would be replacing. If SIPs were used in the manufactured housing industry they would be replacing the floor component, the wall components, and the roof component. When using conventional SIPs with two OSB skins, a SIP thermal envelope in the manufactured housing industry would replace:

- Floor Component: Floor Joists, Fiberglass Insulation, and Floor Decking
- Wall Components: Wall framing, and Fiberglass Insulation
- Roof Component: Roof Joists, Cellulose or Fiberglass Insulation, and Roof Decking

Using SIPs for the roof component of a manufactured home would also create a higher ceiling and it would require the under-floor air distribution system to be moved inside the thermal envelope or insulated separately. Typical manufactured home construction places air distribution ducts under the floor joists but within the insulating layer.

SIPs can be made with finish materials as the panel skin. Drywall can be used for the interior skin of a SIP with an OSB outside skin. In the same respect, Hardie-board fiber cement panels can be used for the exterior skin of a SIP with an OSB interior skin. However, these solutions present some problems in the longevity of the product. If your finish material is also an integral part of the structure, then it is very difficult to repair or replace. Having just a drywall skin on the interior requires embedding lumber in the EPS core behind the drywall to create a structural strip to hang cabinets or other items to the walls.

These options for SIP manufacturing, and what they actually replace in the manufactured housing thermal envelope, will be heavily considered when comparing envelope costs.

CHAPTER 4: HUD CODE COMPARISON

4.1) Energy Use Modeling

To generate a thermal performance comparison between the typical thermal envelope of the manufactured housing industry and a SIP envelope two building types will be digitally modeled. These digital models will mimic HUD code compliant manufactured homes built with stick framing and will be compared to a similar model of a manufactured home built with SIPs. Each model will be undergo an annual energy use simulation. Energy data from these simulations will be scrutinized and translated into a more relatable consumer perspective with current energy rates.

Digital control models of the HUD code compliant manufactured homes will simulate different envelope constructions for each HUD climate zone. The manufactured housing industry responds to the three different climate zones and their required overall U-values by changing insulation thickness. The manufactured housing industry typically uses 2 x 3 stud framing in the walls for climate zone 1, 2 x 4 stud framing in climate zone 2, and 2 x 6 stud framing in climate zone 3. This response by the industry creates three different control models for energy simulation, one for each climate zone. These three models will be tested in two different climates found in each of their respective climatic zones.

Energy data created by simulating the HUD compliant homes will be compared to simulation data generated by the SIP model manufactured home. This model's overall U-value is lower than that required by HUD climate zone 3, so it will be compared to all of the HUD code compliant control models. This means that it will be simulated in all of the same climates.

4.2) Thermal Performance Model:

To compare the thermal performance of stick framing and structural insulated panels a building model must be created and consistently used for analysis. This building model will always maintain original exterior geometry whether stick framing or SIPs are being analyzed. One wall of the building model will be used as the “south” wall in each simulation comparing stick framing to SIPs. The building model will take form from the standard geometry of a double wide manufactured home. The schematic plans for the double-wide base model are provided below and on the following pages. These plans have been slightly adapted from the “Price Fighter 3483B”, a manufactured home produced and sold by Champion Homes, one of the nation’s largest and widespread manufactured housing corporations.

Control Model: Floor Plan

Discounted Floor Area (excludes walls): 1013.5 sq. ft.

Fig 34: Energy Model Floor Plan

Control Model: East Elevation

Control Model: West Elevation

Control Model: South Elevation

Control Model: North Elevation

Fig 35: Energy Model Elevations

4.3) U-Value Component Calculations and Overall U-Value Calculations:

“The calculation of the manufactured home’s transmission heat loss coefficient (Uo) must be in accordance with the fundamental principles of the 1997 ASHRAE Handbook of Fundamentals, Inch-Pound Edition, and, at a minimum, must address all the heat loss or heat gain considerations in a manner consistent with the calculation procedures provided in the document, Overall U-values and Heating/Cooling Loads—Manufactured Homes—February 1992—PNL 8006, HUD User No. 0005945.” (Manufactured Home Construction and Safety Standards)

To comply with the u-value calculation procedures presented in the document, “Overall U-Values and Heating/Cooling Loads,” a building assembly u-value calculator found in the Passive House Planning Package will be used along with an “overall u-values worksheet” provided in the document. U-values for floor, wall, and ceiling/roof assemblies will be calculated with the Passive House tool. U-values for glazing and doors are assigned values that are consistent with what the manufactured housing industry typically uses. The Passive House assembly u-value calculator is described below.

Material R-Value

Material Call out

Interior/Exterior Surface Films

Material Thickness

Assembly	Building Assembly Description	Surface Film Resistance, R	Interior	Exterior	Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness (in)	Percentage of Mat'l 2	Percentage of Mat'l 3	Total Width	R-Value	U-Value
3	Control Model 1.0 Ceiling	0.57	0.45		5/8" Gypsum Board	0.910					0.625	7.0%		4.1	12.2	0.0823
					Fiberglass Insulation	3.330	Roof Trusses	1.280								

Secondary Material

Secondary Material Framing Factor

Assembly U-Value

Assembly Width

Fig 36: Passive House U-value Calculator

4.4) Control Model 1:

Control model 1 is designed to replicate the thermal envelope and construction typology of a double wide manufactured home unit intended for distribution and use in HUD defined climate zone 1. Of the three, this zone has the least stringent requirements for the performance of the thermal envelope. The maximum allowable overall u-value in climate zone 1 is 0.116 w/(m²K). This model uses 2x6 joists with fiberglass insulation for the floor component, 2x3 stud framing with fiberglass insulation for the wall components, and engineered roof trusses with fiberglass insulation for the ceiling/roof component. The u-value calculations for these components are shown below and on the following page. This model will be digitally tested for its thermal envelope performance in New Orleans, LA and El Paso, TX. New Orleans will simulate a sub-tropical climate type within HUD climate zone 1 while El Paso will simulate a hot and dry climate.

Control Model 1: Component U-Values

Table 4: Control Model 1 Floor Component U-Value

Assembly	Building Assembly Description					
1	Control Model 1.0 Floor					
Surface Film Resistance, R		Interior:	0.97	(hr.ft².F/BTU)		
		Exterior:	0.23			
Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1. 1/2" Laminate Flooring	2.040					0.500
2. 3/4" OSB Sheeting	1.390					0.750
3. Air Cavity	1.000	2x6 Floor Joists	1.280			2.000
4. Fiberglass Insulation	3.330			2x6 Floor Joists	1.280	3.500
5.						
6.						
7.						
8.						
Percentage of Mat'l 2			Percentage of Mat'l 3			Total Width
7.0%			7.0%			6.8 in
R-Value:			16.0			(hr.ft².F/BTU)
U-Value:			0.0627			(BTU/hr.ft².F)

Control Model 1: Component U-Values (cont.)

Table 5: Control Model 1 Wall Components U-Value

Assembly	Building Assembly Description
2	Control Model 1.0 Walls

Surface Film Resistance, R

Interior: 0.74 (hr.ft².F/BTU)

Exterior: 0.23

	Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1.	5/8" Gypsum Board	0.910					0.625
2.	Fiberglass Insulation	3.330	2x3 Wall Studs	1.280			2.500
3.	3/4" OSB Sheeting	1.390					0.750
4.	1/2" Hardiboard	0.685					0.500
5.							
6.							
7.							
8.							

Percentage of Mat'l 2: 15.0%

Percentage of Mat'l 3:

Total Width: 4.4 in

R-Value: 9.8 (hr.ft².F/BTU)

U-Value: 0.1019 (BTU/hr.ft².F)

Table 6: Control Model 1 Roof Component U-Value

Assembly	Building Assembly Description
3	Control Model 1.0 Ceiling

Surface Film Resistance, R

Interior: 0.57 (hr.ft².F/BTU)

Exterior: 0.45

	Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1.	5/8" Gypsum Board	0.910					0.625
2.	Fiberglass Insulation	3.330	Roof Trusses	1.280			3.500
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Mat'l 2: 7.0%

Percentage of Mat'l 3:

Total Width: 4.1 in

R-Value: 12.2 (hr.ft².F/BTU)

U-Value: 0.0823 (BTU/hr.ft².F)

Table 7: Control Model 1 Overall U-Value Calculation

Component	U-Value	Envelope Area	Envelope %	U-Value %
Floor	0.0627	1119 sq. ft.	31.8	0.0200
Ceiling	0.0823	1121 sq. ft.	32.0	0.0262
Walls	0.1019	1110.2 sq. ft.	31.6	0.0322
Doors	0.32	39.6 sq. ft.	1.1	0.0036
Windows	0.34	125.2 sq. ft.	3.6	0.0321
Total Envelope		3515 sq. ft.	100%	0.0941 w/(m²K)

Fig 37: Control Model 1 Schematic Section

4.5) Control Model 2: Component U-Values

Control model 2 is designed to replicate the thermal envelope and construction typology of a double wide manufactured home unit intended for distribution and use in HUD defined climate zone 2. Of the three, this zone has the highest variability of climate types as it includes California, the south-west, the great plains, and the appalachians in one strip across the nation. The maximum allowable overall u-value in climate zone 2 is 0.096 w/(m²K). This model uses 2x6 joists with fiberglass insulation for the floor component, 2x4 stud framing with fiberglass insulation for the wall components, and engineered roof trusses with fiberglass insulation for the ceiling/roof component. The U-value calculations for these components are shown below and on the following page. This model will be digitally tested for its thermal envelope performance in Phoenix, AZ, San Luis Obispo, CA, and St. Louis, MO. Phoenix will simulate a hot and dry climate type within HUD climate zone 2, San Luis Obispo will simulate a very moderate climate type, and St. Louis will simulate both a hot-humid and a cold-humid climate depending on the season.

Control Model 2: Component U-Values

Table 8: Control Model 2 Floor Component U-Value

Assembly	Building Assembly Description						
4	Control Model 1.1 Floor						
		Surface Film Resistance, R		Interior:	0.97	(hr.ft².F/BTU)	
				Exterior:	0.23		
	Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1.	1/2" Laminate Flooring	2.040					0.500
2.	3/4" OSB Sheeting	1.390					0.750
3.	Fiberglass Insulation	3.330	2x6 Floor Joists	1.280			5.500
4.							
5.							
6.							
7.							
8.							
				Percentage of Mat'l 2	Percentage of Mat'l 3	Total Width	
				7.0%	7.0%	6.8 in	
		R-Value:		19.9	(hr.ft².F/BTU)		
		U-Value:		0.0503	(BTU/hr.ft².F)		

Control Model 2: Component U-Values (cont.)

Table 9: Control Model 2 Wall Components U-Value

Assembly	Building Assembly Description				
5	Control Model 1.1 Walls				
Surface Film Resistance, R					Interior: 0.74 (hr.ft ² .F/BTU)
					Exterior: 0.23
Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	
1. 5/8" Gypsum Board	0.910				
2. Fiberglass Insulation	3.330	2x4 Wall Studs	1.280		
3. 3/4" OSB Sheeting	1.390				
4. 1/2" Hardiboard	0.685				
5.					
6.					

Table 10: Control Model 2 Roof Component U-Value

Assembly	Building Assembly Description						
6	Control Model 1.1 Ceiling						
Surface Film Resistance, R							Interior: 0.57 (hr.ft ² .F/BTU)
							Exterior: 0.45
Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]	
1. 5/8" Gypsum Board	0.910					0.625	
2. Fiberglass Insulation	3.330	Roof Trusses	1.280			6.250	
3.							
4.							
5.							
6.							
7.							
8.							
Percentage of Mat'l 2			Percentage of Mat'l 3			Total Width	
7.0%						6.9	in
R-Value: 20.4 (hr.ft ² .F/BTU)							
U-Value: 0.0490 (BTU/hr.ft ² .F)							

Table 11: Control Model 2 Overall U-Value Calculation

Component	U-Value	Envelope Area	Envelope %	U-Value %
Floor	0.0503	1119 sq. ft.	31.5	0.0159
Ceiling	0.0490	1121 sq. ft.	31.6	0.0155
Walls	0.0798	1146.2 sq. ft.	32.3	0.0258
Doors	0.32	39.6 sq. ft.	1.1	0.0036
Windows	0.34	125.2 sq. ft.	3.5	0.0317
Total Envelope		3551 sq. ft.	100%	0.0726 w/(m²K)

Fig 38: Control Model 2 Schematic Section

4.6) Control Model 3: Component U-Values

Control model 3 is designed to replicate the thermal envelope and construction typology of a double wide manufactured home unit intended for distribution and use in HUD defined climate zone 3. Of the three, this zone presents the harshest winters as it includes all of the northern states. The maximum allowable overall u-value in climate zone 3 is 0.079 w/(m²K). This model uses 2x6 joists with fiberglass insulation for the floor component, 2x6 stud framing with fiberglass insulation for the wall components, and engineered roof trusses with blown in cellulose insulation for the ceiling/roof component. The U-value calculations for these components are shown below and on the following page. This model will be digitally tested for its thermal envelope performance in Boise, ID and Minneapolis, MN. Boise will simulate a cold and relatively dry climate type within HUD climate zone 3 while Minneapolis will simulate cold and wet climate.

Control Model 3: Component U-Values

Table 12: Control Model 3 Floor Component U-Value

Assembly	Building Assembly Description					
7	Control Model 1.2 Floor					
Surface Film Resistance, R				Interior:	0.97	(hr.ft².F/BTU)
				Exterior:	0.23	
Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1. 1/2" Laminate Flooring	2.040					0.500
2. 3/4" OSB Sheeting	1.390					0.750
3. Fiberglass Insulation	3.330	2x6 Floor Joists	1.280			5.500
4.						
5.						
6.						
7.						
8.						
			Percentage of Mat'l 2	Percentage of Mat'l 3	Total Width	
			7.0%		6.8 in	
				R-Value:	19.9	(hr.ft².F/BTU)
				U-Value:	0.0503	(BTU/hr.ft².F)

Control Model 3: Component U-Values (cont.)

Table 13: Control Model 3 Wall Components U-Value

Assembly	Building Assembly Description
8	Control Model 1.2 Walls

Surface Film Resistance, R	Interior:	0.74	(hr.ft ² .F/BTU)
	Exterior:	0.23	

	Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1.	5/8" Gypsum Board	0.910					0.625
2.	Fiberglass Insulation	3.330	2x6 Wall Studs	1.280			5.500
3.	3/4" OSB Sheeting	1.390					0.750
4.	1/2" Hardiboard	0.685					0.500
5.							
6.							
7.							
8.							

Percentage of Mat'l 2	Percentage of Mat'l 3	Total Width
15.0%		7.4 in

R-Value:	17.9	(hr.ft ² .F/BTU)
U-Value:	0.0558	(BTU/hr.ft ² .F)

Table 14: Control Model 3 Roof Component U-Value

Assembly	Building Assembly Description
9	Control Model 1.2 Ceiling

Surface Film Resistance, R	Interior:	0.57	(hr.ft ² .F/BTU)
	Exterior:	0.45	

	Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1.	5/8" Gypsum Board	0.910					0.625
2.	Blown Cellulose Insula	3.465	Roof Trusses	1.280			3.500
3.	Blown Cellulose Insula	3.465					6.500
4.							
5.							
6.							
7.							
8.							

Percentage of Mat'l 2	Percentage of Mat'l 3	Total Width
7.0%		10.6 in

R-Value:	35.3	(hr.ft ² .F/BTU)
U-Value:	0.0284	(BTU/hr.ft ² .F)

Table 15: Control Model 3 Overall U-Value Calculation

Component	U-Value	Envelope Area	Envelope %	U-Value %
Floor	0.0503	1119 sq. ft.	31.5	0.0159
Ceiling	0.0284	1121 sq. ft.	31.6	0.0090
Walls	0.0558	1146.2 sq. ft.	32.3	0.0180
Doors	0.32	39.6 sq. ft.	1.1	0.0036
Windows	0.34	125.2 sq. ft.	3.5	0.0317
Total Envelope		3551 sq. ft.	100%	0.0584 w/(m²K)

Fig 39: Control Model 3 Schematic Section

4.7) SIP Model 1: Component U-Values

SIP model 1 is designed to replicate the exterior and interior geometry of the control models while presenting an alternative envelope construction type for the manufactured housing industry. The U-value calculations done for this model imply that it could serve as a manufactured housing model in all three of the HUD climate zones. This model uses 4.75" thick SIPs (5/8" OSB, 3.5" EPS Foam, 5/8" OSB) for the floor component, 5" thick SIPs (3/4" OSB, 3.5" EPS Foam, 3/4" OSB) for the wall components, and 6.75" thick SIPs (5/8" OSB, 5.5" EPS Foam, 5/8" OSB) for the ceiling/roof component. The floor and wall SIPs have the thinnest available EPS cores while the roof SIPs have the thinnest core that would span the width of half the double wide section (SIP product availability and spanning ability from Premeir SIPs Design Manual). The U-value calculations for these components are shown below and on the following page. This model will be digitally tested for its thermal envelope performance in all of the climates the control models were tested in.

SIP Model 1: Component U-Values

Table 16: SIP Model 1 Floor Component U-Value

Assembly	Building Assembly Description					
10	SIP Model 1.0 Floor					
Surface Film Resistance, R			Interior:	0.97	(hr.ft².F/BTU)	
			Exterior:	0.23		
Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1. 1/2" Laminate Flooring	2.040					0.500
2. 5/8" OSB	1.390	Skirting Lumber	1.280			0.625
3. EPS Foam	4.125					3.500
4. 5/8" OSB	1.390					0.625
5.						
6.						
7.						
8.						
Percentage of Mat'l 2			2.1%	Percentage of Mat'l 3		Total Width
						5.3 in
R-Value:			18.4	(hr.ft².F/BTU)		
U-Value:			0.0544	(BTU/hr.ft².F)		

SIP Model 1: Component U-Values (cont.)

Table 17: SIP Model 1 Wall Components U-Value

Assembly	Building Assembly Description					
11	SIP Model 1.0 Walls					
Surface Film Resistance, R						
Interior:				0.74	(hr.ft².F/BTU)	
Exterior:				0.23		
Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1. 5/8" Gypsum Board	0.910					0.625
2. 3/4" OSB Sheeting	1.390					0.750
3. EPS Foam	4.125	Skirting Lumber	1.280			3.500
4. 3/4" OSB Sheeting	1.390					0.750
5. 1/2" Hardiboard	0.685					0.500
6.						
7.						
8.						
Percentage of Mat'l 2			5.0%	Percentage of Mat'l 3		Total Width
						6.1 in
R-Value:				17.2	(hr.ft².F/BTU)	
U-Value:				0.0582	(BTU/hr.ft².F)	

Table 18: SIP Model 1 Roof Component U-Value

Assembly	Building Assembly Description					
12	SIP Model 1.0 Ceiling					
Surface Film Resistance, R						
Interior:				0.57	(hr.ft².F/BTU)	
Exterior:				0.23		
Primary Material (Enter from interior to exterior)	Resistivity R per inch	Secondary Material (optional)	Resistivity R per inch	Tertiary Material (optional)	Resistivity R per inch	Thickness [in]
1. 5/8" Gypsum Board	0.910					0.625
2. 5/8" OSB	1.390					0.625
3. EPS Foam	4.125	Skirting Lumber	1.280			5.500
4. 5/8" OSB	1.390					0.625
5. Asphalt Shingles	0.230					0.250
6.						
7.						
8.						
Percentage of Mat'l 2			Percentage of Mat'l 3			Total Width
6.3%						7.6 in
R-Value:				23.3		(hr.ft².F/BTU)
U-Value:				0.0428		(BTU/hr.ft².F)

Table 19: SIP Model 1 Overall U-Value Calculation

Component	U-Value	Envelope Area	Envelope %	U-Value %
Floor	0.0544	1119 sq. ft.	30.5	0.0166
Ceiling	0.0428	1176 sq. ft.	32.1	0.0137
Walls	0.0582	1206.2 sq. ft.	32.9	0.0191
Doors	0.32	39.6 sq. ft.	1.1	0.0035
Windows	0.34	125.2 sq. ft.	3.4	0.0307
Total Envelope		3666 sq. ft.	100%	0.0646 w/(m²K)

4.8) Design Builder Energy Model

To analyze the different control models and the SIP model the software of Design Builder will be used. Design builder is based off of the DOE-2 software platform and runs in conjunction with Energy Plus. This software is given its credibility after vigorous testing by the U.S. Department of Energy.

The base form of the energy model is defined with geometry and openings input parameters and replicates the manufactured home models being examined. The model is divided up into ten different zones that each have unique internal load, lighting requirements, heating/ventilation requirements, and schedules. The roof simulates an attic ceiling for the Control Models and a vaulted ceiling for the SIP Model. Due to this construction difference, the SIP model has more interior volume.

Fig 41: Design Builder Axonometric

Fig 42: Design Builder Model Energy Zones

To maintain consistency throughout the energy use comparisons the only differences between the models will be location and thermal envelope construction. All energy use from lighting, electrical plug loads, and hot water generation are the same in every energy model. This way, any energy use differences can be attributed to climatic changes and thermal envelope performance.

Each building model is scheduled to have the heating system turn on if the interior temperature falls below 68 degrees Fahrenheit and the cooling system to turn on if the interior temperature rises above 78 degrees Fahrenheit. This scheduling is constant throughout the year and does not reflect any user influenced circumstances that at times might use these systems in excess or not at all. The constant scheduling is yet another energy parameter that remains constant so that only the climate and thermal envelope can be scrutinized.

The SIP building model will have three advantages to its typical HUD code manufactured home counterparts. In climate zones 1 and 2 the SIP model has higher insulation values due to the performance of EPS foam insulation compared to fiberglass batt insulation. The construction of SIPs will minimize thermal bridging and will create an envelope with mostly continuous insulation. Also, higher values of air tightness are inherent in SIP construction so this is reflected in the energy model as well. The SIP energy model is set to have air tightness level of .3 ach (air changes per hour) while the manufactured home energy models all have air tightness levels of .6 ach. To understand how much the continuous insulation and air tightness effect the energy model a sensitivity study will be done after the comparison.

4.9) Energy Use Comparison 1: El Paso, Texas

The first energy use comparison will be made between control model 1 and SIP model 1 in El Paso, TX.

Fig 43: Control 1-El Paso Fuel Totals

Fig 44: SIP 1-El Paso Fuel Totals

A comparison of the total gas and electric usage by each of these models shows a total consumption of 68,500 kBtu per year by control model 1 and 39,500 kBtu per year by SIP model 1.

Fig 45: Control 1-El Paso Fuel Breakdown

Fig 46: SIP 1-El Paso Fuel Breakdown

These fuel graphs portray an accurate energy usage pattern of a cooling dominated climate with more energy spent cooling the building rather than heating it. The annual fuel breakdowns of each energy model have equal values for plug loads, lighting, and DHW. The SIP model shows a drastic decrease in the amount of fuel used for heating and cooling.

Fig 47: Control 1-El Paso Heating Design:
Energy Loss through Thermal Envelope Fig 48: SIP 1-El Paso Heating Design:
Energy Loss through Thermal Envelope

The heating design loss graphs show energy lost through the thermal envelop of each model during a winter heating design period. The amount of energy lost by each model through its glazing and external ventilation are the same because each model has the same windows and the same fresh air ventilation requirements. The SIP model's thermal envelope, however, out performs the thermal envelope of the control model with its wall, roof, and external infiltration components. The wall and the roof components of the SIP model show better performance because of their higher insulation values and more continuous insulation. As heat rises, the roof components of each model have the highest losses of any envelope component of the model. The SIP roof only loses half the heat energy through its roof as the control model does during the same heating time period with similar interior temperatures. The SIP model loses less energy through external infiltration because of its lower levels of air leakage through the thermal envelope. The SIP energy model has an airtightness of .3 ach while the control model has and airtightness of .6 ach. As expected, the energy lost through the SIP model's thermal envelope due to external infiltration is half that lost by the control model.

Fig 49: Control 1-El Paso Cooling Design Day

Fig 50: SIP 1-El Paso Cooling Design Day

During a summer cooling design day identical cooling systems in each energy model are keeping interior temperatures of the models at or below 78 degrees. Even though the same temperature is maintained in each model, the cooling system in the SIP model does not have to work as hard to maintain it. The continuous insulation of the SIPs creates so little thermal bridging that the interior surfaces of the SIP model's envelope only reach 85 degrees in the middle of the day while the interior surfaces of the control model's envelope reach 95 degrees. Interior radiant temperatures like those displayed by control model 1 in El Paso would typically cause an occupant to feel discomfort and turn the thermostat down even further.

The operative temperature (the green line in each graph) represents the apparent temperature to an occupant when in the interior of the space. The operative temperature of the control model goes above 85 degrees, which would probably cause discomfort, and the operative temperature of the SIP model stays below 85 degrees.

4.10) Energy Use Comparison 1.1: New Orleans, LA

This data compares control model 1 to SIP model 1 in the hot humid climate of New Orleans.

Fig 51: Control 1-New Orleans Fuel Totals

Fig 52: SIP 1-New Orleans Fuel Totals

A comparison of the total gas and electric usage by each of these models shows a total consumption of 65,000 kBtu per year by control model 1 and 42,500 kBtu per year by SIP model 1.

Fig 53: Control 1-New Orleans Fuel Breakdown

Fig 54: SIP 1-New Orleans Fuel Breakdown

These fuel graphs portray an accurate energy usage pattern of a cooling dominated climate with more energy spent cooling the building rather than heating it. The annual fuel breakdowns of each energy model have equal values for plug loads, lighting, and DHW. The SIP model shows a drastic decrease in the amount of fuel used for heating and cooling.

Fig 55: Control 1-New Orleans Heating Design:
Energy Loss through Thermal Envelope Fig 56: SIP 1-New Orleans Heating Design:
Energy Loss through Thermal Envelope

The heating design loss graphs show energy lost through the thermal envelop of each model during a winter heating design period. The amount of energy lost by each model through its glazing and external ventilation are the same because each model has the same windows and the same fresh air ventilation requirements. Like Energy Use Comparison 1 the SIP model's thermal envelope out performs the thermal envelope of the control model with its wall, roof, and external infiltration components. The wall and the roof components of the SIP model show better performance because of their higher insulation values and more continuous insulation. As heat rises, the roof components of each model have the highest losses of any envelope component of the model. The SIP roof only loses half the heat energy through its roof as the control model does during the same heating time period with similar interior temperatures. The SIP model loses less energy through external infiltration because of its lower levels of air leakage through the thermal envelope. The SIP energy model has an airtightness of .3 ach while the control model has and airtightness of .6 ach. As expected, the energy lost through the SIP model's thermal envelope due to external infiltration is half that lost by the control model.

Fig 57: Control 1-New Orleans Cooling Design Day

Fig 58: SIP 1-New Orleans Cooling Design Day

During a summer cooling design day identical cooling systems in each energy model are keeping interior temperatures of the models at or below 78 degrees. Even though the same temperature is maintained in each model, the cooling system in the SIP model does not have to work as hard to maintain it. The continuous insulation of the SIPs creates so little thermal bridging that the interior surfaces of the SIP model's envelope only reach 84 degrees in the middle of the day while the interior surfaces of the control model's envelope reach temperatures as high as the outside air. Interior radiant temperatures like those displayed by control model 1 in New Orleans would typically cause an occupant to feel discomfort and turn the thermostat down even further.

The operative temperature (the green line in each graph) represents the apparent temperature to an occupant when in the interior of the space. The operative temperature of the control model goes above 85 degrees, which would probably cause discomfort, and the operative temperature of the SIP model stays below 82 degrees.

4.11) Energy Use Comparison 2: Phoenix, AZ

This data compares control model 2 to SIP model 1 in the hot and dry climate of Phoenix, Arizona.

Fig 59: Control 2-Phoenix Fuel Totals

Fig 60: SIP 1-Phoenix Fuel Totals

A comparison of the total gas and electric usage by each of these models shows a total consumption of 75,500 kBtu per year by control model 2 and 48,000 kBtu per year by SIP model 1.

Fig 61: Control 2-Phoenix Fuel Breakdown

Fig 62: SIP 1-Phoenix Fuel Breakdown

These fuel graphs portray an accurate energy usage pattern of a cooling dominated climate with more energy spent cooling the building rather than heating it. The annual fuel breakdowns of each energy model have equal values for plug loads, lighting, and DHW. The SIP model shows a drastic decrease in the amount of fuel used for heating and cooling.

Fig 63: Control 2-Phoenix Heating Design:
Energy Loss through Thermal Envelope Fig 64: SIP 1-Phoenix Heating Design:
Energy Loss through Thermal Envelope

The heating design loss graphs show energy lost through the thermal envelop of each model during a winter heating design period. The amount of energy lost by each model through its glazing and external ventilation are the same because each model has the same windows and the same fresh air ventilation requirements. Like the previous Energy Use Comparisons the SIP model's thermal envelope out performs the thermal envelope of the control model with its wall, roof, and external infiltration components. The wall and the roof components of the SIP model show better performance because of their higher insulation values and more continuous insulation. As heat rises, the roof components of each model have the highest losses of any envelope component of the model. The SIP roof only loses half the heat energy through its roof as the control model does during the same heating time period with similar interior temperatures. The SIP model loses less energy through external infiltration because of its lower levels of air leakage through the thermal envelope. The SIP energy model has an airtightness of .3 ach while the control model has an airtightness of .6 ach. As expected, the energy lost through the SIP model's thermal envelope due to external infiltration is half that lost by the control model.

Fig 65: Control 2-Phoenix Cooling Design Day

Fig 66: SIP 1-Phoenix Cooling Design Day

During a summer cooling design day identical cooling systems in each energy model are keeping interior temperatures of the models at or below 78 degrees. Even though the same temperature is maintained in each model, the cooling system in the SIP model does not have to work as hard to maintain it. The continuous insulation of the SIPs creates so little thermal bridging that the interior surfaces of the SIP model's envelope only reach 85 degrees in the middle of the day while the interior surfaces of the control model's envelope exceed 95 degrees. Interior radiant temperatures like those displayed by control model 2 in Phoenix would typically cause an occupant to feel discomfort and turn the thermostat down even further.

The operative temperature (the green line in each graph) represents the apparent temperature to an occupant when in the interior of the space. The operative temperature of the control model goes above 86 degrees, which would probably cause discomfort, and the operative temperature of the SIP model stays below 83 degrees.

4.12) Energy Use Comparison 2.1: San Luis Obispo, CA

This data compares control model 2 to SIP model 1 in the very moderate climate of San Luis Obispo, CA (SLO).

Fig 67: Control 2-SLO Fuel Totals

Fig 68: SIP 1-SLO Fuel Totals

A comparison of the total gas and electric usage by each of these models shows a total consumption of 57,000 kBTU per year by control model 2 and 30,500 kBTU per year by SIP model 1.

Fig 69: Control 2-SLO Fuel Breakdown

Fig 70: SIP 1-SLO Fuel Breakdown

These fuel graphs portray an accurate energy usage pattern of a heating dominated climate with more energy spent heating the building rather than cooling it. The annual fuel breakdowns of each energy model have equal values for plug loads, lighting, and DHW. The SIP model shows a drastic decrease in the amount of fuel used for heating and cooling.

Fig 71: Control 2-SLO Heating Design:
Energy Loss through Thermal Envelope Fig 72: SIP 1-SLO Heating Design:
Energy Loss through Thermal Envelope

The heating design loss graphs show energy lost through the thermal envelop of each model during a winter heating design period. The amount of energy lost by each model through its glazing and external ventilation are the same because each model has the same windows and the same fresh air ventilation requirements. Like the previous Energy Use Comparisons the SIP model's thermal envelope out performs the thermal envelope of the control model with its wall, roof, and external infiltration components. The wall and the roof components of the SIP model show better performance because of their higher insulation values and more continuous insulation. As heat rises, the roof components of each model have the highest losses of any envelope component of the model. The SIP roof only loses half the heat energy through its roof as the control model does during the same heating time period with similar interior temperatures. The SIP model loses less energy through external infiltration because of its lower levels of air leakage through the thermal envelope. The SIP energy model has an airtightness of .3 ach while the control model has an airtightness of .6 ach. As expected, the energy lost through the SIP model's thermal envelope due to external infiltration is half that lost by the control model.

Fig 73: Control 2-SLO Cooling Design Day

Fig 74: SIP 1-SLO Cooling Design Day

During a summer cooling design day identical cooling systems in each energy model are keeping interior temperatures of the models at or below 78 degrees. Even though the same temperature is maintained in each model, the cooling system in the SIP model does not have to work as hard to maintain it. The continuous insulation of the SIPs creates so little thermal bridging that the interior surfaces of the SIP model's envelope only reach 83 degrees in the middle of the day while the interior surfaces of the control model's envelope actually exceed the temperature of the outside air. Interior radiant temperatures like those displayed by control model 2 in San Luis Obispo would typically cause an occupant to feel discomfort and turn the thermostat down even further.

The operative temperature (the green line in each graph) represents the apparent temperature to an occupant when in the interior of the space. The operative temperature of the control model goes above 85 degrees, and the operative temperature of the SIP model stays below 82 degrees.

4.13) Energy Use Comparison 2.2: St. Louis, MO

This data compares control model 2 to SIP model 1 in the very mixed cold and hot climate of St. Louis, MO.

Fig 75: Control 2-St. Louis Fuel Totals

Fig 76: SIP 1-St. Louis Fuel Totals

A comparison of the total gas and electric usage by each of these models shows a total consumption of 80,000 kBtu per year by control model 2 and 51,000 kBtu per year by SIP model 1.

Fig 77: Control 2-St. Louis Fuel Breakdown

Fig 78: SIP 1-St. Louis Fuel Breakdown

These fuel graphs portray an accurate energy usage pattern of a heating dominated climate with more energy spent heating the building rather than cooling it. The annual fuel breakdowns of each energy model have equal values for plug loads, lighting, and DHW. The SIP model shows a drastic decrease in the amount of fuel used for heating and cooling.

Fig 79: Control 2-St. Louis Heating Design:
Energy Loss through Thermal Envelope Fig 80: SIP 1-St. Louis Heating Design:
Energy Loss through Thermal Envelope

The heating design loss graphs show energy lost through the thermal envelop of each model during a winter heating design period. The amount of energy lost by each model through its glazing and external ventilation are the same because each model has the same windows and the same fresh air ventilation requirements. Like the previous Energy Use Comparisons the SIP model's thermal envelope out performs the thermal envelope of the control model with its wall, roof, and external infiltration components. The wall and the roof components of the SIP model show better performance because of their higher insulation values and more continuous insulation. As heat rises, the roof components of each model have the highest losses of any envelope component of the model. The SIP roof only loses half the heat energy through its roof as the control model does during the same heating time period with similar interior temperatures. The SIP model loses less energy through external infiltration because of its lower levels of air leakage through the thermal envelope. The SIP energy model has an airtightness of .3 ach while the control model has an airtightness of .6 ach. As expected, the energy lost through the SIP model's thermal envelope due to external infiltration is half that lost by the control model.

Fig 81: Control 2-St. Louis Cooling Design Day

Fig 82: SIP 1-St. Louis Cooling Design Day

During a summer cooling design day identical cooling systems in each energy model are keeping interior temperatures of the models at or below 78 degrees. Even though the same temperature is maintained in each model, the cooling system in the SIP model does not have to work as hard to maintain it. The continuous insulation of the SIPs creates so little thermal bridging that the interior surfaces of the SIP model's envelope only reach 84 degrees in the middle of the day while the interior surfaces of the control model's envelope reach almost 95 degrees. Interior radiant temperatures like those displayed by control model 2 in St. Louis would typically cause an occupant to feel discomfort and turn the thermostat down even further.

The operative temperature (the green line in each graph) represents the apparent temperature to an occupant when in the interior of the space. The operative temperature of the control model goes above 85 degrees, and the operative temperature of the SIP model stays below 82 degrees.

4.14) Energy Use Comparison 3: Boise, ID

This data compares control model 3 to SIP model 1 in the northern but moderate climate of Boise, ID.

Fig 83: Control 3-Boise Fuel Totals

Fig 84: SIP 1-Boise Fuel Totals

A comparison of the total gas and electric usage by each of these models shows a total consumption of 79,000 kBtu per year by control model 3 and 51,000 kBtu per year by SIP model 1.

Fig 85: Control 3-Boise Fuel Breakdown

Fig 86: SIP 1-Boise Fuel Breakdown

These fuel graphs portray an accurate energy usage pattern of a heating dominated climate with more energy spent heating the building rather than cooling it. The annual fuel breakdowns of each energy model have equal values for plug loads, lighting, and DHW. The SIP model shows a drastic decrease in the amount of fuel used for heating and cooling.

Fig 87: Control 3-Boise Heating Design:
Energy Loss through Thermal Envelope

Fig 88: SIP 1-Boise Heating Design:
Energy Loss through Thermal Envelope

The heating design loss graphs show energy lost through the thermal envelop of each model during a winter heating design period. The amount of energy lost by each model through its glazing and external ventilation are the same because each model has the same windows and the same fresh air ventilation requirements. Like the previous Energy Use Comparisons the SIP model's thermal envelope out performs the thermal envelope of the control model with its wall, roof, and external infiltration components. The wall and the roof components of the SIP model show better performance because of their higher insulation values and more continuous insulation. As heat rises, the roof components of each model have the highest losses of any envelope component of the model. The SIP roof only loses half the heat energy through its roof as the control model does during the same heating time period with similar interior temperatures. The SIP model loses less energy through external infiltration because of its lower levels of air leakage through the thermal envelope. The SIP energy model has an airtightness of .3 ach while the control model has an airtightness of .6 ach. As expected, the energy lost through the SIP model's thermal envelope due to external infiltration is half that lost by the control model.

Fig 89: Control 3-Boise Cooling Design Day

Fig 90: SIP 1-Boise Cooling Design Day

During a summer cooling design day identical cooling systems in each energy model are keeping interior temperatures of the models at or below 78 degrees. Even though the same temperature is maintained in each model, the cooling system in the SIP model does not have to work as hard to maintain it. The continuous insulation of the SIPs creates so little thermal bridging that the interior surfaces of the SIP model's envelope only reach 85 degrees in the middle of the day while the interior surfaces of the control model's envelope reach almost 95 degrees. Interior radiant temperatures like those displayed by control model 3 in Boise would typically cause an occupant to feel discomfort and turn the thermostat down even further.

The operative temperature (the green line in each graph) represents the apparent temperature to an occupant when in the interior of the space. The operative temperature of the control model goes above 85 degrees, and the operative temperature of the SIP model stays below 82 degrees.

4.15) Energy Use Comparison 3: Minneapolis, MN

This data compares control model 3 to SIP model 1 in the northern cold-wet and hot-humid climate of Minneapolis, MN.

Fig 91: Control 3-Minneapolis Fuel Totals

Fig 92: SIP 1-Minneapolis Fuel Totals

A comparison of the total gas and electric usage by each of these models shows a total consumption of 103,500 kBtu per year by control model 3 and 69,500 kBtu per year by SIP model 1.

Fig 93: Control 3-Minneapolis Fuel Breakdown

Fig 94: SIP 1-Minneapolis Fuel Breakdown

These fuel graphs portray an accurate energy usage pattern of a heating dominated climate with more energy spent heating the building rather than cooling it. The annual fuel breakdowns of each energy model have equal values for plug loads, lighting, and DHW. The SIP model shows a drastic decrease in the amount of fuel used for heating and cooling.

Fig 95: Control 3-Minneapolis Heating Design:
Energy Loss through Thermal Envelope Fig 96: SIP 1-Minneapolis Heating Design:
Energy Loss through Thermal Envelope

The heating design loss graphs show energy lost through the thermal envelop of each model during a winter heating design period. The amount of energy lost by each model through its glazing and external ventilation are the same because each model has the same windows and the same fresh air ventilation requirements. Like the previous Energy Use Comparisons the SIP model's thermal envelope out performs the thermal envelope of the control model with its wall, roof, and external infiltration components. The wall and the roof components of the SIP model show better performance because of their higher insulation values and more continuous insulation. As heat rises, the roof components of each model have the highest losses of any envelope component of the model. The SIP roof only loses half the heat energy through its roof as the control model does during the same heating time period with similar interior temperatures. The SIP model loses less energy through external infiltration because of its lower levels of air leakage through the thermal envelope. The SIP energy model has an airtightness of .3 ach while the control model has an airtightness of .6 ach. As expected, the energy lost through the SIP model's thermal envelope due to external infiltration is half that lost by the control model.

Fig 97: Control 3-Minneapolis Cooling Design Day

Fig 98: SIP 1-Minneapolis Cooling Design Day

During a summer cooling design day identical cooling systems in each energy model are keeping interior temperatures of the models at or below 78 degrees. Even though the same temperature is maintained in each model, the cooling system in the SIP model does not have to work as hard to maintain it. The continuous insulation of the SIPs creates so little thermal bridging that the interior surfaces of the SIP model's envelope only reach 84 degrees in the middle of the day while the interior surfaces of the control model's envelope reach almost 95 degrees. Interior radiant temperatures like those displayed by control model 3 in Minneapolis would typically cause an occupant to feel discomfort and turn the thermostat down even further.

The operative temperature (the green line in each graph) represents the apparent temperature to an occupant when in the interior of the space. The operative temperature of the control model goes above 85 degrees, and the operative temperature of the SIP model stays below 82 degrees.

4.16) Design Builder Energy Modeling Cost and Efficiency Comparison:

To better understand the practical implications of this energy modeling, energy prices were gathered for each city and an annual operating cost estimate was made for each model and location. Electric and gas rates quoted were found in the 2009 National Energy Rate Survey and from residential rates published by energy providers in these locations.

Table 20: Gas and Electric Energy Rate Costs

City	Electric Rate per kWhr	Gas Rate per ccf
New Orleans	\$0.106	\$0.29
El Paso	\$0.11	\$0.64
Phoenix	\$0.113	\$0.70
San Luis Obispo	\$0.132	\$0.45
St. Louis	\$0.10	\$0.45
Boise	\$0.078	\$0.70
Minneapolis	\$0.102	\$0.69

On the following page these energy rates are applied to the results of the energy models. The equations for converting the data from the energy models to the units of energy used by gas and electric companies are shown below.

Energy Conversion Calculations:

Electricity	Natural Gas
$\frac{\text{kBtu}}{(3.412)} = \text{kWhr}$	$\frac{\text{kBtu}}{(102.9)} = \text{ccf}$

Table 21: HUD Code vs. SIPs Cost and Efficiency Comparison

HUD Climate Zone	City	Control Model EUI kBtu/sq.ft.	Control Annual Operation \$	SIP Model 1 EUI kBtu/sq.ft.	SIP 1 Annual Operation \$	EUI Reduction %	Annual Savings \$
1	El Paso	67.4	\$1518	38.8	\$935	42.3%	\$583
1	New Orleans	63.9	\$1510	41.8	\$1009	34.6%	\$501
2	Phoenix	74.2	\$2092	47.2	\$1366	36.4%	\$726
2	SLO	56	\$1210	30	\$733	46.5%	\$476
2	St. Louis	78.7	\$1197	50.1	\$809	36.3%	\$388
3	Boise	77.7	\$1011	50.1	\$676	35.4%	\$335
3	Minneapolis	101.8	\$1378	68.3	\$929	32.9%	\$448

The table above compares the energy use of all of the control models to the SIP model and converts the energy use into a more relatable unit of dollars. In table 21 the energy use of the models is given in EUI. EUI refers to Energy Use Intensity. This unit is a measurement of annual energy used per square foot of a building's occupiable space.

Table 21 very clearly shows the superior performance of SIP panels when compared to the same stick framed thermal envelope. With an average energy use reduction of 37% in this comparison SIP panels reduced the building's load while saving the occupants money. As most owners of manufactured homes are fall into a lower income status, the money saved by such an increase in their home's efficiency would certainly be desirable.

4.17) Energy Sensitivity Comparison:

To gain a better understanding of what factors are contributing the most to the higher performance of the SIP model when compared to the HUD code models, sensitivity analysis of the control model's airtightness is conducted. To do this, control model 3 in the Minneapolis climate is given an airtightness of .3 ach. With the airtightness of the control model being the same as the SIP model the only difference will be insulation amount and insulation configuration. Control model 3 has a lower overall U-value than SIP model 1 but SIP model 1 has much more continuous insulation. Any superior performance displayed by the SIP model in this comparison can be attributed to its continuous insulation.

Fig 99: Control 3-Minneapolis Fuel Totals
.6 ACH model

Fig 100: Control 3-Minneapolis Fuel Totals
.3 ACH Model

When compared to the original control model of .6 ach airtightness in Minneapolis, the control model 3 with .3 ach airtightness uses about 10% less energy annually. This energy use reduction comes mostly from lower heating demand during the winter time. As Minneapolis is a heating dominated climate, large reductions in the models electrical energy are not expected.

Fig 101: Control 3-Minneapolis Fuel Totals
.3 ACH model

Fig 102: SIP 1-Minneapolis Fuel Totals

When the more airtight control model in Minneapolis is compared to the original SIP model in the same location, it is clear to see that just improving the airtightness of a manufactured home will not bring nearly the energy savings of a continuously insulated envelope. The Control Model 3 with .3 ach airtightness uses 93,000 kBtu annually, while the original SIP model 1 uses only 69,500 kBtu.

Fig 103: Control 3-Minneapolis Heating Design:
Energy Loss through Thermal Envelope
.3 ach model Fig 104: SIP 1-Minneapolis Heating Design:
Energy Loss through Thermal Envelope

The energy loss graphs articulate the higher performing envelope of the SIP model further. Now the external infiltration losses are the same in both models, but the SIP model's roof only loses about half the energy the control model does.

CHAPTER 5: ENERGY STAR COMPARISON

5.1) Energy Star Manufactured Housing:

In this section, the Energy Star certification method for manufactured housing is examined. The Energy Star certification, like the HUD code, associates thermal envelope effectiveness with different climate zones in the U.S. However, while HUD only mandates a certain overall U-value be met per climate zone, the Energy Star certification considers airtightness, duct losses, duct insulation, heating unit efficiency, glazing performance, water heater performance, and programmable thermostats. The Energy Star method attributes more factors to a manufactured home's energy use than HUD code, but it creates incentives for higher efficiency mechanical systems rather than better building construction to meet energy use goals.

Fig 105: Energy Star Manufactured Housing Climate Zone Map

Energy Star breaks the U.S. into one more climate zone than HUD code does. Unlike HUD code, Energy Star uses county boundaries rather than state boundaries to define its climate zones. When considering the energy models/climates already analyzed, El Paso, New Orleans, and Phoenix all fall into region 4. San Luis Obispo falls into region 4. St Louis and Boise fall into region 2 and Minneapolis is in region 1. Each Energy Star climate zone comes with its own pre-

scriptive design package options and requirements. These design packages and requirements can be viewed in full in the appendix.

While the Energy Star design packages seem to require much lower overall U-values, the incentives provided by using higher efficiency equipment in mechanical systems allows regular HUD homes to comply with Energy Star. With an overall U-value of 0.0941, control model 1 is able to achieve Energy Star certification in the Energy Star climate zone 4 so long as it has a maximum of 7% duct losses, a minimum .80 AFUE gas furnace, and a programmable thermostat. With an overall U-value of 0.0726, control model 2 is able to achieve Energy Star certification in the Energy Star climate zone 3 so long as it has a maximum of 7% duct losses, a minimum .80 AFUE gas furnace, and a programmable thermostat. With an overall U-value of 0.0584, control model 3 is able to achieve Energy Star certification in Energy Star climate zone 2 so long as it has a maximum of 7% duct losses, a minimum .80 AFUE gas furnace, and a programmable thermostat. Control model 3 is also able to achieve Energy Star certification in Energy Star climate zone 1 so long as it has a maximum of 5% duct losses, a minimum .90 AFUE gas furnace, a high efficiency water heater, and a programmable thermostat. Control 3 can also be certified in zone 1 with a maximum of 3% duct losses, a minimum .90 AFUE gas furnace, and a programmable thermostat.

To meet Energy Star certification criteria manufactured homes built to HUD code compliance standards only need to add certain high efficiency equipment while controlling energy loss through ducts and external air infiltration. Because of this, the Energy Star certified manufactured housing does not necessarily have drastically reduced energy use when compared to its HUD compliant counterpart.

CHAPTER 6: COST COMPARISON

6.1) SIP Cost V. Stick Cost: Retail Price Comparison

SIPs greatly out perform the stick framed envelope used in the manufactured housing industry to provide much lower annual energy usage. This savings in energy would create cost annual cost savings to the owner of a manufactured home built with SIPs. However, if SIPs are to be used in the manufactured housing industry, they must be a viable economic alternative to stick framing from the manufacturer's point of view. To begin a cost comparison between the two products, a simple 4' long by 8' tall wall section is considered. (Fig. 106) As manufactured housing producers have the advantage of ordering materials in economies of scale, and as SIPs are primarily used in custom one-off projects, this cost comparison will scrutinize the retail pricing associated with each product.

Fig 106: 4'x8' Wall Section: SIPs v. Stick Framed

The retail price comparison, depicted in figure 106 on the previous page, shows a very obvious price gap between the affordability of SIPs and stick framing. When only considering material costs at retail pricing, stick framing is only a quarter of the cost of SIPs. The Structural Insulated Panel Association claims that in site built projects SIPs are able to recover this price gap through efficiency of installation and waste control on site. However, the factory process of manufactured housing is able to negate the waste and labor inefficiencies associated with typical wood stud framing.

The retail price comparison does not directly relate to the material prices that the manufactured housing industry is able to achieve. With manufactured home factories ordering materials and supplies on massive economies of scale they are able to buy material for prices far below retail value. Unfortunately, Champion Homes and other producers of manufactured homes are very tight lipped about their pricing information and very little was divulged about their material costs. The SIP industry on the other hand has no relatable precedent of projects large enough to take advantage of the economies of scale seen by the manufactured housing industry. Because of the lack of available information regarding the material costs the manufactured housing industry is able to achieve and the lack of large scale precedent in the SIP industry, the only direct cost comparison that can be made is a retail cost comparison.

CHAPTER 7: CONCLUSIONS

7.1) Energy Use Comparison

The energy use of three manufactured home models in 7 different climates was modeled and compared to a similar home using SIPs in the same climates. The SIP home demonstrated drastically better energy performance (32%-46% energy use reductions) in all climates tested. The SIP home's thermal envelope out performed the manufactured home models built with wood stud framing because of the inherent airtight properties and continuous insulation of structural insulated panels. The energy use reduction contributed by SIP's airtightness is most apparent when comparing winter design days of manufactured homes to the SIP home. The inherent airtightness of SIPs allows the SIP home to lose far less energy through air leakage in the thermal envelope. The effects of continuous insulation in a building's envelope is demonstrated best by the cooling design day analysis. During summer days, radiant temperatures of interior surfaces of a home built with SIPs will remain much cooler than the interior surfaces of a home built with wood stud framing. Wood studs in a conventionally built manufactured home create thermal bridges in the building envelope and allow thermal energy to transfer through the envelope more easily.

When the energy savings of SIP panels from this thesis's comparison are converted into monetary units, the use of SIP panels in the manufactured housing industry could save manufactured home owners between \$300 and \$700 annually. This number is dependent on climate type and local energy prices but creates possible monetary gain for manufactured home owners through the reduced energy use of a more efficient thermal envelope.

7.2) Price Comparison & Appropriateness of SIPs for Manufactured Homes

While using a SIP panel envelope in the manufactured housing industry creates annual energy savings through thermal envelope efficiency, the cost of structural insulated panels is simply too high to be viewed by the manufactured housing industry as a viable material option. As the retail price comparison of this thesis shows, the price of raw materials required to frame a wall with conventional stick framing is much lower than the cost of a standard SIP panel envelope.

The price comparison used in this thesis only compares costs at a retail pricing level. The production scale of manufactured housing allows factories to order materials in extreme surplus for greatly reduced cost. This gives them the ability to buy on economies of scale for further reduced material prices. The SIP industry is too small at this point in time to provide the product volume needed by the manufactured housing industry and . It is very hard to directly compare the cost implications of using SIPs in the manufactured housing industry because manufactured home companies consider their cost reduction strategies and construction budgets proprietary information. Both of these being very necessary when scrutinizing the construction and material costs of stick framing used for manufactured homes. Also, the SIP industry has never seen production at a large enough scale to be able to create cost savings for customers through bulk purchasing.

At this point in time the SIP panel industry has no desire to try to compete directly with the cost of stick framing. The industry has “no desire to be the least expensive on the market” as it is trying to target customers interested in the longer term payback of reduced energy use rather than a lower initial price point. Currently, most SIP projects produced require lots of custom cuts and panel sizes in the factory. If the SIP industry were to achieve “more continuous volume, particularly with the manufacture of generic or ‘stock’ panels, prices can come down (James Hodgson, Premier SIPs).” The manufactured housing industry could create potential for continuous volume of such panels. A partnership between the manufactured housing industry and the SIP industry could help to lower the price point of SIP products while providing a much more energy efficient affordable housing solution.

Even if SIP panels are not able to quite able to match the low material price of stick framing, it creates annual energy savings over conventional framing. This annual energy savings can be translated into a short term payback that can be considered as an offset to the higher material prices of a SIP envelope. After 5 years a SIP manufactured home can save \$1,500 to \$3,500 in energy savings. This savings created by energy reduction can be used to market more efficient manufactured housing directly, or it can be imbedded into the financing system of manufactured

home sales.

7.3) Further Research and Investigation:

This thesis compares one modern thermal envelope technology to the conventional wood framing used by the manufactured housing industry to demonstrate the energy use reductions a thermal envelope change is capable of. In doing so, the shortcomings of the HUD code's thermal requirements are revealed. The appropriateness of the HUD code's thermal requirements should be reexamined and compared to more modern code requirements mandated by state and local codes, such as California's Title-24 building code. The HUD code should also be compared to proposed national agendas to reduce the energy consumption by our built environment, such as the goals of Architecture 2030.

SIPs do not create a financially viable solution for energy reduction in the manufactured housing industry at this time. More research can be done to understand how the manufactured housing industry can keep the same financial price point to its customers while reducing the energy consumption of their products. More studies investigating airtightness and the mitigation of thermal bridging in the thermal envelope of a manufactured home should be conducted. Research of how stick framing can be improved, enhanced, or perfected to reduce thermal bridging and increase airtightness will give insight into how the manufactured housing industry can provide more efficient homes while still producing affordable homes.

More information about the material price of SIP panels and the conventional framed envelope of manufactured housing is also needed. The manufactured housing industry is too focused on shaving costs at every corner to consider a higher initial cost of green building. On the other hand, the SIP industry has not had enough precedent of high volume production to speculate on possible price reductions of large scale ordering. For these industries to compare costing and feasibility, the manufactured housing industry will have to see profit in providing a more energy efficient product. Hopefully this will be created by consumer demand or code requirements in the near future.

REFERENCES

- "2030 Challenge Targets: U.S. Residential Regional Averages." Architecture 2030. Architecture 2030, n.d. Web. 29 Sep 2013. <http://www.architecture2030.org/files/2030_Challenge_Targets_Res_Regional.pdf>.
- Briggs, Xavier de Souza. United States of America. U.S. Department of Housing and Urban Development. Factory and Site Built Housing: A comparison for the 21st Century. Upper Marlboro: NAHB Research Center, Inc., 1998. Web. <<http://www.huduser.org/Publications/pdf/factory.pdf>>.
- Broom, Jack. "A House with a Future Goes Up at Seattle Center." Local News, The Seattle Times. The Seattle Times, 27 Aug 2012. Web. 29 Sep 2013. <http://seattletimes.com/html/localnews/2019005101_futurehouse28m.html>.
- "FAQ." Living Homes. Living Homes, 2012. Web. 29 Sep 2013. <<http://www.livinghomes.net/faq.html>>.
- "History of Manufactured Housing." Manufactured Housing Association of Oklahoma. Manufactured Housing Association of Oklahoma. Web. 29 Sep 2013. <<http://www.mhao.org/history.asp>>.
- Rudd, , Hodgson, Beal, and Chandra. "Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site Built Houses." Building Science.com. Building Science Press, n.d. Web. 29 Sep 2013. <<http://www.buildingscience.com/documents/reports/rr-0803-volatile-organic-compound-concentrations-and-emission-rates-in-new-manufactured-and-site-built-houses>>.
- "SIPs FAQ." Structural Insulated Panel Association. Structural Insulated Panel Association, 2011. Web. 29 Sep 2013. <<http://www.sips.org/about/what-are-sips>>.
- Sutter, Paul. "Driven Wild: The Origins of Wilderness Advocacy During Interwar Periods." People and Place: The Human Experience in Greater Yellowstone.. Ed. Paul Schullery and Sarah Stevenson. Yellowstone National Park: National Park Service, 1997. 217-227. Web. 29 Sep. 2013. <<http://www.nps.gov/yell/naturescience/upload/part4.pdf>>.
- United States of America. U.S. Department of Census. Manufactured Homes Survey. Washington, D.C.: U.S. Department of Housing and Urban Development, 2012. Print. <<http://www.census.gov/construction/mhs/mhsindex.html>>.
- United States of America. U.S. Department of Housing and Urban Development. National Manufactured Housing Construction and Safety Standards Act of 1974. Washington, D.C.: U.S. Department of Housing and Urban Development, 1974. Print.
- United States of America. U.S. Environmental Protection Agency. Residential Energy Consumption Survey. Washington, D.C.: U.S. Energy Information Administration, 2001. Web. <<http://www.eia.gov/data/consumption>>.

REFERENCES (CONTINUED)

Winter , Stephen. "Building with Panels." Progressive Architecture. 74. November (1993): 88. Print.

BIBLIOGRAPHY

- "From Massive Construction to Decomposition of Housing." *International Journal for Housing Science & Its Applications*, 25.4 (2001): 279-291.
- "High-performance Building Envelopes: New Prefab Systems for Facades and Roofing Deliver Multiple Benefits, with Some Providing Thermal Insulation While Harvesting Solar Energy." *Azure*, 25.193 (2009): 77-78.
- "Home Delivery,' Museum of Modern Art (Spring 2008)." *Design Issues*, 25.3 (2009): 102-107.
- Ivy, Robery. "Simply Fab." *Architectural Record*, 196.8 (2008): 23.
- "Kit House by Design: The Huf Haus." *Architecture Ireland*, 251 (2010): 49.
- Rawson, John. "A New Kind of Kit House." *Architect's Journal*. 203.21 (1996): 40-41. Print.
- Rose, William. "Moisture Control in the Modern Building Envelope: History of the Vapor Barrier in the U.S., 1923-52." *APT Bulletin*, 28.4 (1997): 13-19.
- Stannard, Sandra. "EcoFab: A Climatic Responsive Alternative to Manufactured Housing." San Luis Obispo: Cal Poly San Luis Obispo, 2012. Print.
- Winter, Stephen. "Building with Panels." *Progressive Architecture*. 74. November (1993): 88. Print.

Appendices

Designing ENERGY STAR Qualified Homes

Table A-1 State-by-State Climate Region Index

State	Primary Region	Exception	Counties
Alabama	3	Region 4:	Baldwin Barbour Bullock Butler Choctaw Clarke Coffee Conecuh Covington Crenshaw Dale Dallas Escambia Geneva Greene Hale Henry Houston Lowndes Macon Marengo Mobile Monroe Montgomery Perry Pike Russell Sumter Washington Wilcox
Alaska	1	None	
Arizona	4	Region 2:	Apache Cochise Coconino Gila Graham Greenlee Navajo Pima Santa Cruz Yavapai
Arkansas	3	Region 4:	Ashley Bradley Calhoun Chicot Clark Cleveland Columbia Dallas Desha Drew Hempstead Howard Jefferson Lafayette Lincoln Little River Miller Montgomery Nevada Ouachita Pike Sevier Union
California	3	Region 2: Region 4:	Alpine Butte Colusa Glenn Imperial Lake Lassen Modoc Mono Inyo Nevada Placer Plumas Shasta Riverside Sierra Solano Sutter Tehama San Bernardino Yolo Yuba
Colorado	1	Region 2:	Baca Bent Chaffee Cheyenne Crowley Custer El Paso Fremont Huerfano Kiowa Kit Carson Lake Las Animas Lincoln Otero Phillips Prowers Pueblo Sedgwick Teller Washington Yuma
Connecticut	2	None	
Delaware	2	None	
Florida	4	None	
Georgia	4	Region 3:	Banks Barrow Bartow Carroll Catoosa Chattahoochee Chattooga Cherokee Clarke Clayton Cobb Coweta Dade Dawson DeKalb Douglas Elbert Fannin Fayette Floyd Forsyth Franklin Fulton Gilmer Gordon Gwinnett Habersham Hall Haralson Harris Hart Heard Henry Jackson Lamar Lincoln Lumpkin Macon Madison Marion Meriwether Murray Muscogee Oconee Oglethorpe Paulding Pickens Pike Polk Rabun Schley Spalding Stephens Talbot Taylor Towns Troup Union Upson Walker Walton White Whitfield Wilkes
Hawaii	4	None	
Idaho	1	Region 2:	Ada Canyon Gem Gooding Jerome Lemhi Lincoln Minidoka Nez Perce Payette Washington
Illinois	2	None	

State	Primary Region	Exception Counties				
Indiana	2	None				
Iowa	2	Region 1:	Allamakee Black Hawk Bremer Buchanan Buena Vista Butler Cerro Gordo	Cherokee Chickasaw Clay Clayton Delaware Dickinson Dubuque	Emmet Fayette Floyd Franklin Hancock Howard Humboldt	Kossuth Lyon Mitchell O'Brien Osceola Palo Alto Plymouth
Kansas	2	None				
Kentucky	2	None				
Louisiana	4	None				
Maine	1	None				
Maryland	2	None				
Massachusetts	2	Region 1:	Berkshire	Franklin	Hampden	Hampshire
Michigan	2	Region 1:	Alcona Alger Alpena Antrim Arenac Baraga Bay Benzie Charlevoix Cheboygan Chippewa	Clare Crawford Delta Dickinson Emmet Gladwin Gogebic Grand Taverse Gratiot Houghton Huron	Iosco Iron Isabella Kalkaska Keweenaw Lake Leelanau Luce Mackinac Manistee Marquette	Mason Mecosta Menominee Midland Missaukee Montcalm Montmorency Muskegon Newaygo Oceana Ogemaw
Minnesota	1	None				
Mississippi	4	Region 3:	Alcorn Benton Calhoun DeSoto	Grenada Itawamba Lafayette Lee	Marshall Panola Pontotoc	Prentiss Tate Tippah
Missouri	2	Region 3:	Butler Duncan	Mississippi New Madrid	Pemiscot	Scott Stoddard
Montana	1	None				
Nebraska	2	None				
Nevada	4	Region 1: Region 2:	Elko Carson City Churchill Douglas	Eureka Esmeralda Humboldt Lincoln	Lander Lyon Mineral	White Pine Nye Pershing Storey Washoe
New Hampshire	1	None				
New Jersey	2	None				
New Mexico	2	Region 3:	Chaves DeBaca	Dona Ana Eddy	Guadalupe Hidalgo	Lea Luna Otero

Designing ENERGY STAR Qualified Homes

State	Primary Region	Exception Counties						
New York	2	Region 1:	Allegany Broome Cattaraugus Cayuga Chemung Chenango Clinton	Cortland Delaware Essex Franklin Fulton Hamilton Herkimer	Lewis Livingston Madison Montgomery Oneida Onondaga Ontario	Otsego Schoharie Schuyler Seneca St. Lawrence Steuben Sullivan	Tioga Tompkins Warren Wyoming Yates	
North Carolina	3	Region 2:	Alleghany Ashe Avery Buncombe Burke	Caldwell Cherokee Clay Graham Haywood	Henderson Jackson McDowell Macon Madison	Mitchell Polk Rutherford Surry Swain	Transylvania Watauga Wilkes Yadkin Yancey	
North Dakota	1	None						
Ohio	2	None						
Oklahoma	4	Region 2: Region 3:	Beaver Craig Delaware Mayes	Cimarron Nowata Osage	Ellis Ottawa Pawnee	Harper Rogers Tulsa	Texas Wagoner Washington	
Oregon	2	Region 1:	Baker	Klamath	Union	Wallowa		
Pennsylvania	2	Region 1:	Bradford	Sullivan	Susquehanna	Tioga	Wyoming	
Rhode Island	2	None						
South Carolina	3	Region 4:	Allendale Bamberg Barnwell Beaufort	Berkeley Calhoun Charleston Clarendon	Colleton Dorchester Hampton	Jasper Lee Lexington	Orangeburg Richland Sumter	
South Dakota	1	Region 2:	Gregory	Mellette	Todd	Tripp		
Tennessee	3	Region 2:	Bledsoe Coffee Cumberland Fentress	Franklin Grundy Marion	Morgan Overton Pickett	Putnum Scott Sequatchie	Van Buren Warren White	
Texas	4	Region 3:	Andrews Armstrong Bailey Briscoe Carson Castro Cochran Crosby	Dallam Dawson Deaf Smith Floyd Gaines Glasscock Gray Hale	Hansford Hartley Hemphill Hockley Howard Hutchinson Lamb Lipscomb	Lubbock Lynn Martin Midland Moore Ochiltree Oldham Parmer	Potter Randall Roberts Sherman Swisher Terry Yoakum	
Utah	2	Region 1: Region 4:	Cache Carbon Washington	Daggett Duchesne	Morgan Rich	Summit Uintah	Wasatch	
Vermont	1	None						
Virginia	2	Region 3:	Accomack Charles City Essex Gloucester Greensville	Isle of Wight James City King and Queen King George King William	Lancaster Mathews Middlesex New Kent Northampton	Northumberland Prince George Richmond Southampton Stafford	Surry Sussex Westmoreland York	

State	Primary Region	Exception Counties
Washington	2	Region 1: Chelan Ferry Kittitas Okanogan Pend Orielle Skamania Spokane Stevens Yakima
West Virginia	2	None
Wisconsin	1	None
Wyoming	1	None

Table A-2 ENERGY STAR Design Packages

CLIMATE REGION 1

Basic Requirements:

- Maximum shell leakage: 7.0 ACH₅₀
- Window SHGC: any
- Minimum duct insulation: R-8

Packages for homes with maximum 3% duct losses

Heating Type	Minimum Heating Efficiency	Maximum Envelope Heat Resistance U _e -value	High Efficiency WH ¹¹	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.054			1-1
		0.056		✓	1-2
		0.058	✓	✓	1-3
	0.90 AFUE	0.060		✓	1-4
		0.063	✓	✓	1-5
Heat Pump	7.7 HSPF	0.052	✓	✓	1-6
		0.053	✓	✓	1-7
Electric Resistance (Forced Air) ¹²	1.0 EF	0.048		✓ ¹³	1-8
		0.050	✓	✓ ¹³	1-9

Packages for homes with maximum 5% duct losses

Heating Type	Minimum Heating Efficiency	Maximum U _e -value	High Efficiency WH ¹¹	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.052			1-10
		0.054		✓	1-11
		0.056	✓	✓	1-12
	0.90 AFUE	0.058		✓	1-13
		0.061	✓	✓	1-14
Heat Pump	7.7 HSPF	0.050		✓	1-15
		0.051	✓	✓	1-16
	8.0 HSPF	0.052		✓	1-17
		0.053	✓	✓	1-18

¹¹ The high efficiency WH requirement may be met by using a 0.59 EF gas WH or a 0.91 EF electric WH or by wrapping a lower-rated WH with a minimum of R-5 insulation.

¹² Electric resistance packages in Climate Region 1 require a maximum shell leakage rate of 4.0 ACH₅₀ and a 70% efficient heat recovery ventilator to ensure that total ventilation rate is maintained at 0.35 ACH at all times.

¹³ A programmable thermostat is required for a forced air all-electric heating system. Zone controls are required for baseboard electric resistance heating systems.

Designing ENERGY STAR Qualified Homes

CLIMATE REGION 2

Basic Requirements:

- Maximum shell leakage: 7.0 ACH₅₀
- Maximum window SHGC: 0.55
- Minimum duct insulation: R-8

Packages for homes with maximum 3% duct losses

Heating Type	Minimum Heating Efficiency	Maximum U _o -value	High Efficiency WH ¹⁴	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.061			2-1
		0.065		✓	2-2
		0.067	✓	✓	2-3
Heat Pump	7.7 HSPF	0.061		✓	2-6
		0.063	✓	✓	2-7

Packages for homes with maximum 5% duct losses

Heating Type	Minimum Heating Efficiency	Maximum U _o -value	High Efficiency WH ¹⁴	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.057			2-8
		0.061		✓	2-9
		0.063	✓	✓	2-10
	0.90 AFUE	0.063		✓	2-11
		0.065	✓	✓	2-12
Heat Pump	7.7 HSPF	0.058			2-13
		0.059		✓	2-16
		0.062	✓	✓	2-17
	8.0 HSPF	0.062		✓	2-18
		0.064	✓	✓	2-19

Packages for homes with maximum 7% duct losses

Heating Type	Minimum Heating Efficiency	Maximum U _o -value	High Efficiency WH ¹⁴	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.056			2-20
		0.060		✓	2-21
		0.062	✓	✓	2-22
	0.90 AFUE	0.062		✓	2-23
		0.064	✓	✓	2-24
Heat Pump	7.7 HSPF	0.054			2-25
		0.055		✓	2-26
		0.059	✓	✓	2-27

¹⁴ The high efficiency WH requirement may be met by using a 0.59 EF gas WH or a 0.91 EF electric WH or by wrapping a lower-rated WH with a minimum of R-5 insulation.

CLIMATE REGION 3

Basic Requirements:

- Maximum shell leakage: 7.0 ACH₅₀
- Minimum duct insulation: R-6

Packages for homes with maximum 3% duct losses

Heating Type	Minimum Heating Efficiency	Maximum U _o -value	Maximum Window SHGC	High Efficiency WH ¹⁵	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.075	0.50			3-1
		0.082	0.50		✓	3-2
		0.084	0.50	✓	✓	3-3
		0.084	0.40		✓	3-4
		0.086	0.40	✓	✓	3-5
Heat Pump	7.7 HSPF	0.074	0.50			3-6
		0.075	0.50		✓	3-7
		0.076	0.50	✓	✓	3-8
		0.076	0.40		✓	3-9
		0.077	0.40	✓	✓	3-10

Packages for homes with maximum 5% duct losses

Heating Type	Minimum Heating Efficiency	Maximum U _o -value	Maximum Window SHGC	High Efficiency WH ¹⁵	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.073	0.50			3-11
		0.080	0.50		✓	3-12
		0.082	0.50	✓	✓	3-13
		0.082	0.40		✓	3-14
		0.084	0.40	✓	✓	3-15
Heat Pump	7.7 HSPF	0.073	0.50			3-16
		0.074	0.50		✓	3-21
		0.075	0.50	✓	✓	3-22
		0.076	0.40	✓	✓	3-23
	8.0 HSPF	0.077	0.50		✓	3-24
		0.078	0.50	✓	✓	3-25
		0.079	0.40	✓	✓	3-26

Packages for homes with maximum 7% duct losses

Heating Type	Minimum Heating Efficiency	Maximum U _o -value	Maximum Window SHGC	High Efficiency WH ¹⁵	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.068	0.50			3-27
		0.075	0.50		✓	3-28
		0.077	0.50	✓	✓	3-29
		0.078	0.40		✓	3-30
		0.080	0.40	✓	✓	3-31
Heat Pump	7.7 HSPF	0.066	0.50			3-32
		0.067	0.50		✓	3-33
		0.068	0.50	✓	✓	3-34
		0.070	0.40		✓	3-35
		0.071	0.40	✓	✓	3-36

¹⁵ The high efficiency WH requirement may be met by using a 0.59 EF gas WH or a 0.91 EF electric WH or by wrapping a lower-rated WH with a minimum of R-5 insulation.

Designing ENERGY STAR Qualified Homes

CLIMATE REGION 4

Basic Requirements:

- Maximum shell leakage: 7.0 ACH₅₀
- Minimum duct insulation: R-6

Packages for homes with maximum 3% duct losses

Heating Type	Minimum Heating Efficiency	Maximum Uo-value	Maximum Window SHGC	High Efficiency WH ¹⁷	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.111	0.50			4-1
Heat Pump	7.7 HSPF	0.097	0.50			4-2
		0.104	0.50		✓	4-3
		0.108	0.50	✓	✓	4-4
Electric Resistance ¹⁶	1.0 EF	0.074	0.40		✓ ¹⁸	4-5
		0.075	0.40	✓	✓ ¹⁸	4-6
Electric Resistance (Florida Only)	1.0 EF	0.111	0.40		✓ ¹⁸	4-7
		0.114	0.40	✓	✓ ¹⁸	4-8

Packages for homes with maximum 5% duct losses

Heating Type	Minimum Heating Efficiency	Maximum Uo-value	Maximum Window SHGC	High Efficiency WH ¹⁷	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.102	0.50			4-9
		0.116	0.50		✓	4-10
Heat Pump	7.7 HSPF	0.095	0.50			4-11
		0.102	0.50		✓	4-14
		0.106	0.50	✓	✓	4-15
	8.0 HSPF	0.104	0.50		✓	4-16
		0.108	0.50	✓	✓	4-17
Electric Resistance ¹⁶	1.0 EF	0.070	0.40		✓ ¹⁸	4-18
		0.071	0.40	✓	✓ ¹⁸	4-19
Electric Resistance (Florida Only)	1.0 EF	0.116	0.40		✓ ¹⁸	4-20

Packages for homes with maximum 7% duct losses

Heating Type	Minimum Heating Efficiency	Maximum Uo-value	Maximum Window SHGC	High Efficiency WH ¹⁷	Programmable Thermostat	Package Number
Gas/Oil Furnace	0.80 AFUE	0.092	0.50			4-21
		0.106	0.50		✓	4-22
		0.109	0.40		✓	4-23
		0.111	0.50	✓	✓	4-24
		0.115	0.40	✓	✓	4-25
Heat Pump	7.7 HSPF	0.086	0.50			4-26
		0.093	0.50		✓	4-27
		0.095	0.40		✓	4-28
		0.099	0.50	✓	✓	4-29
		0.101	0.40	✓	✓	4-30

¹⁶ Electric resistance packages are not available for homes placed in HUD Thermal Zone 3.

¹⁷ The high efficiency WH requirement may be met by using a 0.59 EF gas WH, a 0.91 EF electric WH or by wrapping a lower-rated WH with a minimum of R-5 insulation.

¹⁸ A programmable thermostat is required for a forced air all-electric heating system. Zone controls are required for baseboard electric resistance heating systems.