Pushing the Envelope: A Case Study of Building the First Manufactured Home Using Structural Insulated Panels

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ABSTRACT

Manufactured housing contributes 20% to 30% of new housing across the United States. In June 2000 Champion Enterprises built the first HUD-code approved manufactured home using structural insulated panels. The demonstration house was built as part of a partnership between Champion, Premier Building Systems, Precision Panel Structures, and the U.S. Department of Energy's Building America Program. The project was undertaken to assess both the performance of the structure in terms of highway durability and energy efficiency, and the flexibility of the manufacturing and HUD-code approval processes to accept a new building material requiring new tools, workstations, and production times. The project extends the concept of building systems beyond the home's structure to include factory production, material flows, and production capacity.

Pressurization tests were completed and long-term monitoring equipment was recently installed in the house, now located in western Washington State. Energy performance information will be presented. Preliminary DOE-2 modeling anticipated energy savings of nearly 50% in comparison with minimum HUD-code building practices. The structure proved durable and resilient during construction and in a 300-mile road test. The test was conducted without typical bracing used during transport. Champion estimates that SIPs use could increase production capacity with minor plant modifications. This translates into flexibility in the manufacturer's ability to adjust to changing market conditions. Increased capacity may also allow a manufacturer to absorb added materials costs.

The project suggests several innovations in SIP materials, manufactured housing factory processes, and housing design. These affect sheathing materials; material optimization; materials handling; and house interior, ductwork, and structural design.

Introduction

Because of its sheer volume and the opportunity for factory replication, energy efficiency improvements in manufactured housing make sense. However, the same factories that represent automated efficiency, also represent fixed costs that do not easily adjust to accommodate varying levels of demand. The incorporation of structural insulated panels into manufactured housing helps with both issues. A more efficient building envelope is achieved. And the change in building materials may allow for the more efficient management of production capacity.

This paper is a case study of the first manufactured home built with an envelope made entirely of structural insulated panels (SIPs). The panels used in this project were made up of expanded polystyrene foam sandwiched between 7/16 inch oriented strand board (OSB). The paper examines the design and approval process leading to the project, the manufacturing process and its adjustment to SIPs, and the transportation and energy performance of the house after it was built.

This project sought an answer to the question: What would happen if a SIP house was built on a HUD-certified production line for manufactured homes? The U.S. Department of Housing and Urban Development (HUD) provides a federal building code for manufactured homes and certifies the factories that build these houses. We were as interested in the production line as in the house itself. Three key production issues presented themselves: 1) could the production line support SIPs without major modifications, 2) could the line work in parallel with SIPs and traditional materials, and 3) would SIPs use result in time savings that would translate into increased capacity. A key motivation for the manufacturer was to determine if SIPs could increase plant capacity at times of high product demand.

The house design was chosen for its simplicity, but not as an optimized SIP home. Although the house turned out quite efficient, more could be done to integrate the building systems and minimize waste. Although cost issues are discussed in this paper, this one-time demonstration house does not provide a basis for economic analysis.

Premier Building Systems, of Fife, Washington, and Precision Panels, of Eagle, Idaho donated SIPs related building materials and expertise. The project team also included Redman Homes, a subsidiary of Champion Enterprises. Redman's factory produced the SIPs house and Champion's commitment to the project and expertise in engineering manufactured houses allowed the project to move forward. The Washington State University Energy Program helped to document the construction process and conducted building diagnostics testing once the house was occupied. Pacific Northwest National Laboratory (PNNL) coordinated this project and conducted long-term monitoring on the house. PNNL's and WSU's project involvement was funded by the U.S. Department of Energy's Building America Program. Our thanks to the Oregon Office of Energy, which conducted blower door and duct blaster tests on the house while it was temporarily set up on the factory lot.

More information on this project can be found at www.pnnl-sips.org.

Project Planning and Preparation

The team for this project formed over several years. It began as a group studying the potential of using SIPs in manufactured housing and eventually narrowed its focus to this case study. Once the focus jelled, five steps were included in preparing for the project, as described in the following sections.

Selecting a Factory to Build the House

Champion selected a factory based on factory features, the willingness of the management to pursue an innovative project, and the availability of capacity. The first choice was a factory in western Washington that, unfortunately, was closed due to the slowing economy. The factory closing delayed the project about 6 months and illustrates both the economic condition of the manufactured housing industry in 1999, and the vagaries that can affect a project of this complexity. In September 1999 Champion chose its Redman plant in Silverton, Oregon for the project.

Planning Factory Materials Flow

This activity involved site visits to the factory to plan how SIPs would flow through the factory. Entry points, clearances, storage areas, cranes, and assembly areas were identified. For the most part, assembly areas matched existing factory workstations, although construction techniques were quite different.

Training the Factory Crew to Handle New Materials

For the first factory, a prototype house was built on the factory site. Workstation foreman were encouraged to attend and get hands-on experience in working with SIPs. The Precision Building Systems General Manager led this session. At the Redman factory, production line foreman were trained in a classroom working with models and instructors. Factory managers were the primary leads for this session.

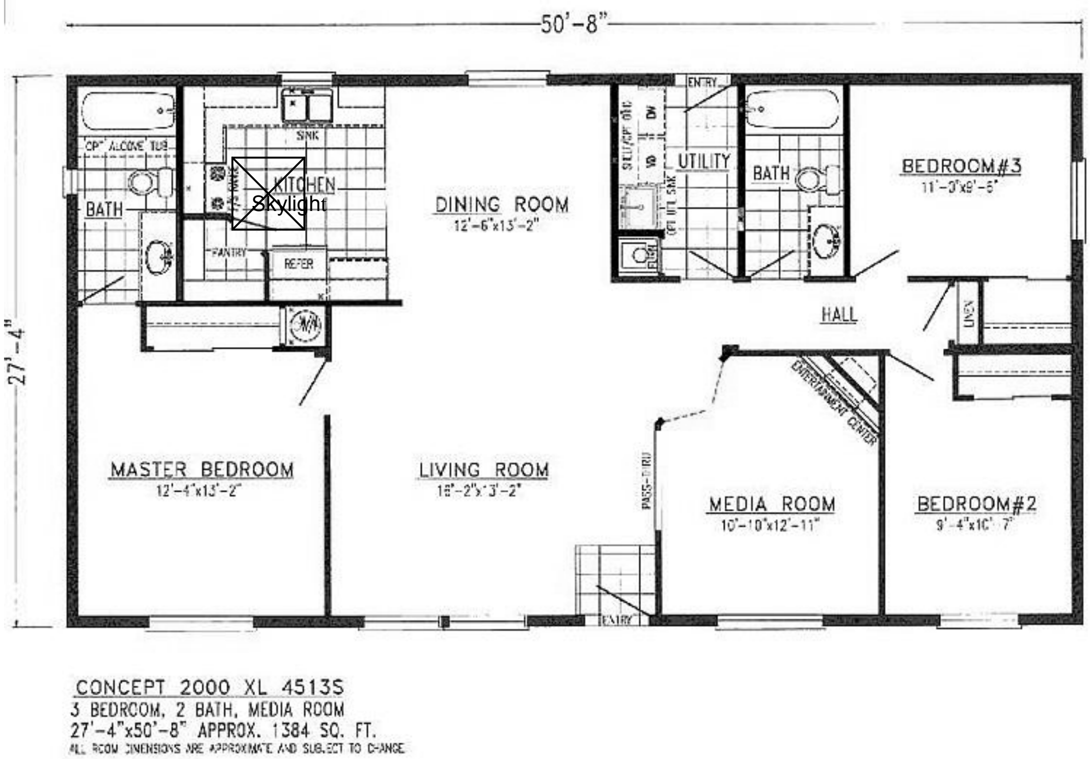
Engineering the House

Champion chose a simple house model as shown in figures 1 and 2. Design decisions and engineering issues were resolved over a three-year period. Key design elements that were unique to this project included the following:

- Floor panel sizes were 6 inches thick and 4 feet wide by nearly 14 feet deep. 2x6 splines were used to connect the floor panels.
- Wall panels were 6 inches thick and 8 feet (vertical) by up to 22 feet (horizontal). Wall panels were connected with studs because most breaks came at major openings for doors and windows. Panels are available in lengths up to 24 feet.
- Roof panel sizes were 8 inches thick and 4 feet by about 14.5 feet. Roof panels were connected using two 7/16 inch OSB splines at each seam.
- The house was designed for a perimeter foundation system.
- Floor cantilever and chassis – design concerns included the ability of the SIPs to provide structural integrity during transport and how SIPs would respond to outriggers angled from the perimeter to the bottom of the chassis. Precision Panel conducted tests to measure deflection of the SIPs over the cantilever. The tests showed modest bowing and engineering tables indicated the panels could function using OSB splines. However, to be conservative, and to allow for attachment of the chassis, which was leg screwed into the splines, 2x6 inch splines were used in the floor. These issues are closely tied to the manufactured home's transportability.
- Preliminary DOE-2 model simulations indicated the Concept 2000 house would use about 50% as much energy as a home built to minimum HUD standards. The Oregon Office of Energy certified the plans as being in compliance with Super Good Cents and Energy Star programs.

Some analysts suggested that using SIPs in manufactured homes would require (or, perhaps, would present an opportunity for) redesigning typical SIP construction and the manufactured home chassis. Several issues were identified and recommendations made to alleviate problem areas. One concern was that SIPs were too rigid to carry the weight of the structure during transport and that the walls would carry much of the load and may fail doing so without structural reinforcement. Another issue was the incompatibility of a cambered chassis with a floor that remains level. A related issue was that the chassis may not be able to flex during transport to keep the floor level. Other issues included the need to install reinforcing beams in sidewalls, the need to reinforce the openings in the marriage wall, the

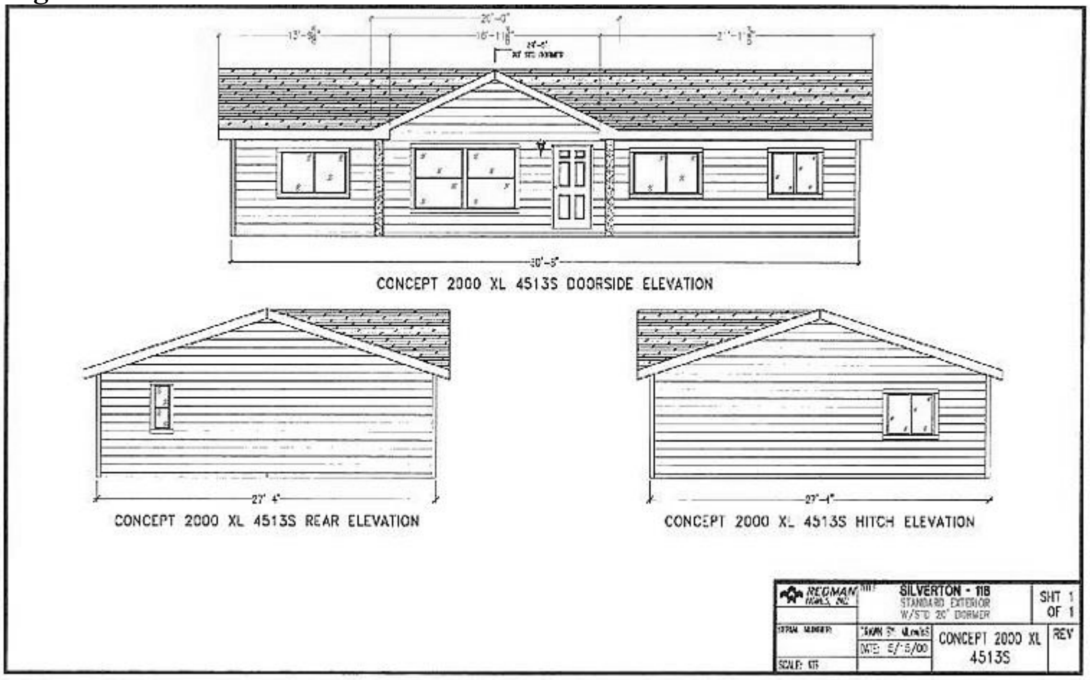
Figure 1. Floor Plan for the SIPs Manufactured Home, which Champion Called the Concept 2000



need for additional shear support to keep sidewalls from twisting, and adding structural brackets under the walls to carry loads to the chassis. It was suggested that with proper reinforcement, the SIPs floor could be made to act as the chassis, eliminating the need for steel I beams under the house. The team did not attempt to design the house to eliminate the traditional chassis, but the idea could be further explored. Although discussed at length during planning, the project proved these structural concerns to be non-issues.

Transportation issues aside, SIPs provided about twice the structural strength required by U.S. Department of Housing and Urban Development (HUD) code.

Figure 2. Elevations for the SIPs Manufactured Home



HUD Approval

HUD is responsible for establishing and enforcing building codes for manufactured housing. HUD regulations require that third-party inspectors and reviewers approve both manufactured home factories and specific designs. Third party testing organizations called Design Approval Primary Inspection Agencies (DAPIA) conduct plan reviews. The Concept 2000 house was the first (and perhaps only) manufactured home with a SIP envelope to receive DAPIA approval, which was granted in February 2000. The overall submittal and response process took nearly 2 years. This time reflects the level of detail and analysis needed to pass the review, as well as the logistical requirements and level of effort that team members could commit to a demonstration project.

The DAPIA raised issues that had not been fully documented in approved International Conference of Building Officials (ICBO) reports and insisted on documented or engineered responses, not anecdotal evidence. Some of the issues included:

- Calculations to use staples instead of nails
- SIP screw specifications
- 24-inch eave overhang substantiation or calculations
- Calculations for fastening partition walls to outside walls
- Calculations for floor to chassis connections
- Calculations to show that panels can resist outrigger loads
- Substantiation to permit filling 6 inch holes in wall panels with foam
- Substantiation to permit panel cutouts of 12 inches or less without blocking

Chassis and outrigger issues were resolved based on the results from the 300-mile transportation test described later.

Production

The Concept 2000 house was built at Champion's Redman factory in Silverton, Oregon. The house was built in two sections, or floors in industry jargon, with each floor making up half of the finished doublewide manufactured home.

Construction began on 16 June 2000. Although this demo was not designed to study labor requirements, many observers of the process noted that the second floor was completed in about half the time of the first floor. Time-savings resulted from the production crew's learning and the reduced interference resulting from fewer observers and expert advisors. The envelope was completed (without windows and doors) along with interior walls and furnishings in about three days. The remaining elements – windows, doors, skylight, exterior siding, interior finish mudding, interior trim, and interior and exterior paint – were completed in 9 days, which included a 300-mile transportation test, described later. The house was set up on the factory lot for tours on 28 June. Time from start of construction to set up was only 12 days, but the house actually took longer than a typical house rolling off the assembly line.

Manufactured homes at the Redman factory begin their lives upside down and are built inside out in comparison to site-built homes. Here are some of the experiences and conclusions from the production process.

The first step inside the factory is floor production. The floor was assembled upside down using standard SIP practices. Ducting, plumbing, and electrical lines were installed. A belly wrap covered the bottom-side of the floor and the chassis was attached.

The floor was then hoisted into the air and flipped right side up. This maneuver was conducted using overhead cranes and was seen as the first structural test of the SIPs. After flipping the floor, a chalk-line was taken and less than 1/8-inch variation was found in the floor from front to back, nearly 51 feet.

The top of the floor now becomes the focus of activity. The 7/16ths OSB skin on the SIP was sanded for the direct application of flooring – no additional subflooring was installed. Work continued on plumbing and electrical, and cabinets and fixtures were set near their destinations.

Interior walls began to be installed. One small hitch in the production run came from the over 11.5-foot-tall interior cathedral peak. The walls were so tall that they needed extra bracing as the assembly line pulled the house along.

Exterior walls were installed using overhead cranes. Both interior and exterior walls come to the main assembly line with sheetrock and initial mud already installed.

The roof assembly was installed using an overhead crane. The center beam on the ceiling was heavier than anticipated and lifting the roof assembly required some experimentation to reach the proper balance point. Sheetrock and initial mud was installed on the ceiling before the roof was placed on the house.

Insulation is typically installed before wall assemblies come to the assembly line. Roof insulation is blown in after, as is floor insulation. None of the blanket or blown-in insulation was needed in the SIPs house except for the wrapping of ducts that were installed under the floor. These ducts were insulated to a minimum of R-5.

The production crew took care to glue and seal the SIP assemblies and to seal all penetrations through the envelope.

Jacks were used to keep the floor level as wall and roof assemblies were dropped into place. Over-extending a jack can cause pressure in wall and roof assemblies that can later lead to cracking in plaster. The production team believed this happened in one instance in the SIPs house.

Overall assembly of the building envelope in the first half of the house (without doors, windows, and the skylight) took about 6 hours longer than would normally be required for a typical house of this size. Time for the second half went much quicker.

Champion production managers concluded that if storage is available in the factory, SIPs construction and standard construction could take place side by side. Dedicated facilities would not be needed. SIPs could be offered as a consumer option without disrupting traditional production lines. Some steps, such as blowing in roof insulation, would be skipped on the SIPs houses; however, these workstations would be needed for typical construction and so could not be eliminated in a side-by-side factory.

Champion engineers believe that ultimately, SIP construction could lead to a 10% increase in capacity at production facilities. Taken together with the last point, SIPs could give manufacturers flexibility in meeting demand in a growing market without requiring investments in new facilities. Champion noted that the Concept 2000 house used 60 panels compared with more than 1,000 parts typical of traditional framing (*Automated Builder* 2000). In making this comparison it should be noted that the engineering and DAPIA approval process in typical manufactured housing has taken value engineering concepts to their zenith. The industry constantly seeks ways to meet structural requirements with less lumber and therefore less expense.

Transportation Test

As is typical of new models, the Concept 2000 house underwent a 300-mile road test over a variety of two-lane and interstate highways. Homes undergoing this test, or being transported for set up, usually are made more roadworthy with corner and vertical bracing. No such bracing was included in the Concept 2000 house. An inspection after the road test found broken tree branches and crushed cherries inside the house. We can't be sure exactly what happened, but clearly the test route came close to cherry orchards. The road test also included one other variable. On one unit, one side of the chassis experienced blown out tires. This is not uncommon. When one tire blows out, weight is shifted to the remaining tires forcing them to blow out. Each unit had four axles. It is safe to say that many of the bumps and stresses envisioned in early structural discussions were present in the test.

The best performance indicator for road testing is the quantity of drywall cracks that develop during the test. This measure is difficult to quantify and may result from other than structural issues, such as the occurrence of blown out tires. Problems with tape and texture finishes are the number one field repair identified by the Oregon Codes Division (OCD), which serves as the In-Plant Primary Inspection Agency (IPIA) in Oregon (BCD 2001). As the IPIA, OCD provides the factory inspections and certifications required by HUD. HUD also funds OCD to respond to consumer complaints.

The SIPs house performed well on the transportation test. First of all it stayed together; it did not experience structural failure. Secondly, in spite of the lack of bracing, there were few tape and texture cracks in comparison to a typical manufactured home. An OCD inspector examined the home during set up on the factory lot and agreed that the Concept 2000 house had far fewer cracks than would be expected in a typical house, especially on the outside walls and in stressed areas, such as above doors and windows.

Energy Performance

The house is now occupied and situated in western Washington, in a climate similar to Portland, Oregon and Olympia, Washington. The homeowners have graciously allowed us to conduct building diagnostic tests and to install long-term energy monitors. Two adults occupy the house, one works during the day and is off weekends and one works swing shift and often works weekends with days off during the week.

De-Pressurization Tests

Fan de-pressurization tests conducted on the SIP's home when it was temporarily set up on the factory lot found 4.0 air changes per hour (ACH) at 50 Pascals (PA) of pressure (OOE 2000). Tests conducted after permanent set up showed the house to be slightly tighter at 3.55 ACH at 50PA. This difference may be explained in that the set-up on the plant lot was temporary, and sections were not taped and textured and as well sealed at the marriage line as during the final on-site home installation. Depending on the climate, shielding, and terrain factors 4.0 ACH at 50PA may result in average seasonal ventilation rates of 0.16 ACH. The tighter measurement found at the permanent site results in 0.142 ACH of infiltration. (Conversion method of dividing the de-pressurization results (ACH at 50PA) by 25 taken from Baylon, Davis & Palmiter 1995). Smoke-stick tests conducted on site found typical leaks at window and skylight rough openings, supply duct registers, and plumbing fixtures.

This SIP home is tighter than the average air tightness found in 49 randomly selected Super Good Cents (SGC) homes built in 1997 and tested in 2000. These homes average was 4.76 ACH at 50PA (Davis, Roberts, and Baylon 2000). The SIP's home was also tighter than the average of a sample of 157 random SGC manufactured homes at 5.5ACH (Baylon, Davis, & Palmiter 95). Finally, the SIP's home was over twice as tight as the average of 29 non-SGC current practice manufactured homes, which averaged 8.75 ACH in tests done in the early 90s (Palmiter et al. 92). Table 1 compares the results of manufactured home house tightness throughout the US.

The home has a 100-cubic feet-per-minute (CFM) kitchen exhaust fan and a 50 CFM bathroom exhaust fan, as well as a SGC-approved whole house 1.0 low-sone exhaust fan in the central hallway. This whole house exhaust fan flow tests indicated 104 CFM, which is twice the 0.035 cfm/ft2 HUD-code and SGC requirement for whole house ventilation capacity for this 1456 square foot home. The whole house fan provides a maximum of 0.46 ACH mechanically. This mechanical ventilation does not include natural leakage, or infiltration induced by supply duct leakage, when the heating system operates.

Long-Term Monitoring

Installation of the metering equipment in the SIPs home was completed in late September 2001. The data logger used was an electrical metering system capable of recording power and energy. The particular logger installed in the SIPs home was configured with four power input channels, four digital input channels and four analog signal input channels. Communication with the logger is via a dedicated phone line installed specifically for this purpose.

The energy end uses metered were the 1) building total, 2) electric furnace, and 3) electric hot water heater. In addition, an "Other" end use category representing all other energy consumption in the home, consisting primarily of the lighting and plug-in appliances, was calculated as the difference between the building total and sum of the furnace and the hot water heater. Room air temperature was recorded in the laundry room near the furnace system's return air register.

Table 1. Comparison of House Tightness Research

Blower Door Tests of U.S. Manufactured Housing					
Sample Description	**Reference**	**Sample Size**	**EE/SP***	**Year Built**	**ACH****
Northwest Survey	Palmiter 92	21	SP	65-80	14.3
Northwest Control Group	Palmiter 92	29	SP	89	8.75
Northwest Model Conservation Standards	Palmiter 92	131	EE	89	6.1
Bonneville Program	Baylon 95	162	EE	95	5.5
Eugene, OR	West 98	1253	SP	59-89	12.1
Eugene, OR	West 98	187	EE	90-97	10.1
SGC, ID	Davis 00	25	EE	97-98	4.6
SGC, WA	Davis 00	11	EE	97-98	4.8
WSU Energy House	Lubliner 00	1	EE	96	2.4
Florida	Chandra 98	6	SP	97	5.5-7.5
Florida	Chandra 98	2	EE	97	5.1-5.5
Florida	Cummings 89	21	SP	74-86	12.6
New York	AEC 96	6	SP	94-95	10.2
North Carolina	AEC 96	8	SP	94-95	12
CONTAM	Persily 00	1	SP	99	6.5
Concept 2000 SIP House	Not Applicable	1	EE	2000	3.5

*SP = Standard Practice EE = Energy Efficient
**ACH = air changes per hour (h^{-1}) at 50 PA

Source: Adapted from Lubliner & Gordon 2000

All power data were collected as 15-minute demand and downloaded nightly to the PNNL data collection workstation in Richland, Washington. The raw 15-minute data were archived daily as part of the project's original data records and working copies of the data files created for subsequent analysis. The data were reviewed for equipment problems weekly. Monitoring data can be viewed at Florida Solar Energy Center's web site dedicated to energy monitoring: http://www.infomonitors.com/sip/.

Data were available for analysis for the period September 27, 2001 through April 30, 2002. During this period, which spanned most of the heating season, the total energy consumption was 11,249 kWh, split among the major end uses as follows: 38% for the electric furnace, 26% for the electric hot water heater, and 36% for the Other end-use category. This amounts to 2.9 kWh/square foot for heating. Monthly energy consumption for each of the three end uses is shown in the bar graph in Figure 3. Data for September 2001 were not included in this analysis because that limited data collected would not be representative of the entire month. As can be seen, the water heater and Other end-uses do not vary significantly between months. However, as expected, the furnace use ramped up during the fall and was relatively constant during the three winter months (December - February).

Although difficult to compare without a full year of monitored data from the Concept 2000 house, Baylon, et al estimated, based on electric bills, that annual heating requirements for a 1337 square foot SGC manufactured home in the same climate zone would use 5652 kWh/year (Baylon, Davis, & Palmiter 1995), or 4.2 kWh/square foot. Total annual energy consumption amounted to 15202 kWh. This same study found in an engineering analysis that a hypothetical HUD-code home would consume 8364 kWh/year for space heating and a SGC manufactured home would consume 4737 kWh/year in the same climate zone as the Concept 2000 house.

A daily profile of energy use is shown in Figure 4 for the same end uses for all days combined. This profile is constructed by averaging the hourly energy consumption for each hour of the day. In this case, the entire data sample was used. Again the pattern is typical of residential energy use with a morning and evening peak in total consumption. The furnace energy use responded to the diurnal pattern of outdoor temperature with a maximum in the early morning (coincident with the minimum temperature) and a minimum in the late afternoon (maximum temperature). The furnace appears to run over a 24-hour period.

The energy use for different day types is summarized in Table 2 for all data September 27, 2001 through February 22, 2002. In this comparison, weekdays are defined as Monday through Friday; weekends are Saturday and Sunday. No distinction was made for holidays. Four consecutive days, Saturday, January 27 through Tuesday, January 30, 2002, were among the coldest of the winter season in southwest Washington. Daily high and low temperatures during this cold spell were 34^{o}F and 30 ^{o}F, 33 ^{o}F and 29 ^{o}F, 39 ^{o}F and 24 ^{o}F, and 33 ^{o}F and 25 ^{o}F, as measured at the WSU Energy House in Olympia, Washington.

Table 2. Average Daily Energy Consumption for Different Types of Days (kWh/day)

Day Type	Furnace	Water Heater	Other	Total
Weekday	20.6	11.6	16.0	48.2
Weekend	17.6	13.0	17.4	48.1
Coldest 4 days	40.9	11.9	13.5	66.3
Winter (Dec – Feb)	28.4	12.1	16.5	57.0
Entire Period	19.8	12.0	16.4	48.2

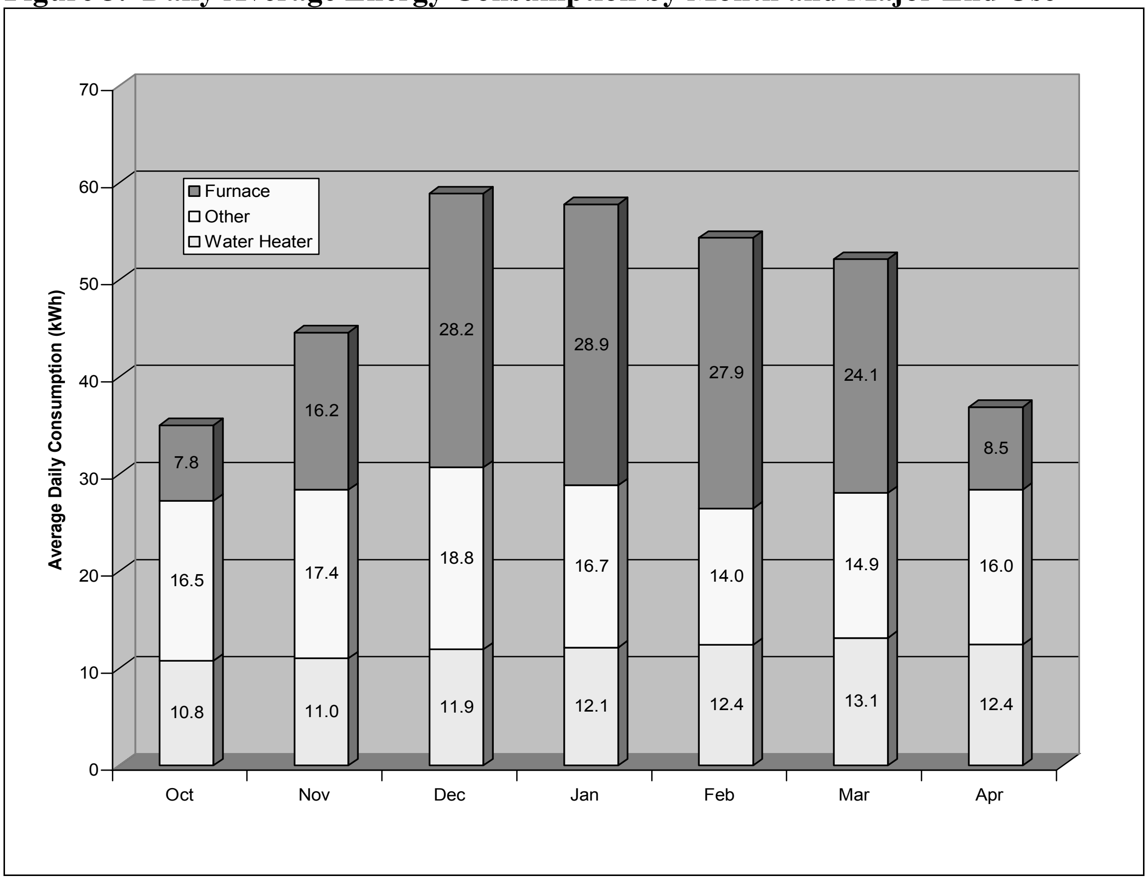
Conclusions

The Concept 2000 house demonstrates that SIP materials and building techniques can be readily adapted for the manufactured housing industry. These materials performed well on the production line and resulted in a structure that stood up well to transportation. SIPs construction could take place in tandem with more traditional framing if adequate storage is available at the manufacturer’s facility. On site de-pressurization tests found a very tight house with air change levels of 3.5 ACH 50PA, near the bottom of levels found in U.S. manufactured homes. Long-term energy monitoring is ongoing, but demonstrates a house performing as predicted at about 50% of energy consumption of manufactured homes meeting minimum HUD-code. Although the Concept 2000 house is compared with traditional manufactured homes for cost purposes, it outperforms typical homes both structurally and in reduced energy consumption.

Economics

Although this demonstration was not designed to measure economic issues, several observations are possible.

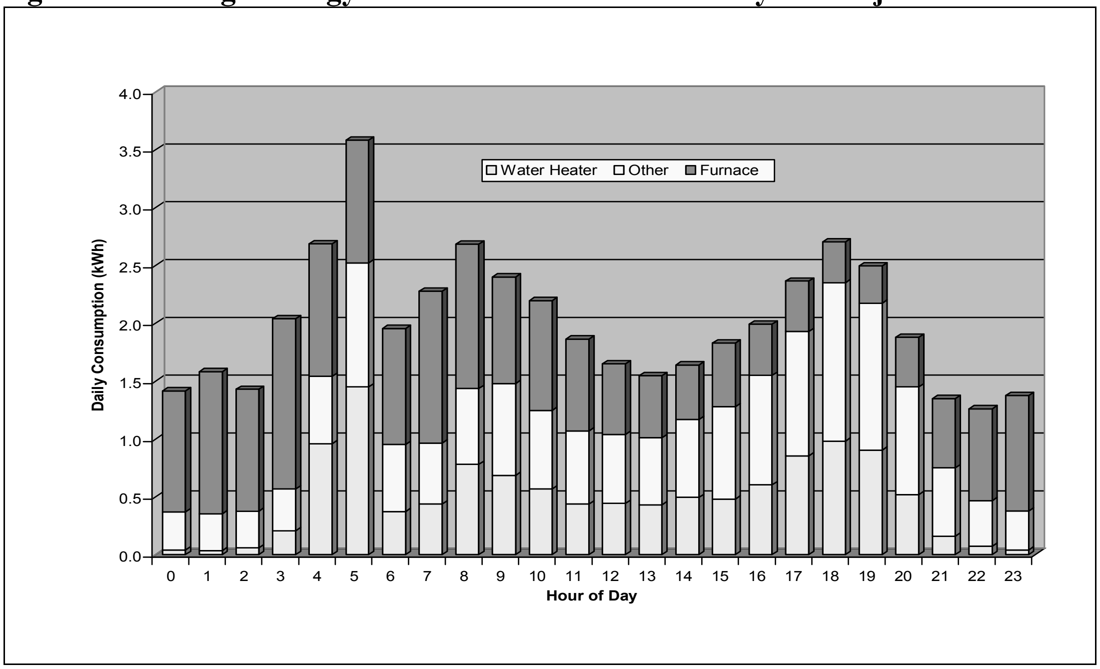
Figure 3. Daily Average Energy Consumption by Month and Major End Use



- A key motivator for the manufactured housing participants was the possibility that SIPs could increase factory capacity without requiring major expenditures. The indications from this study are that SIPs could meet this role.
- SIP materials and construction crews were donated for this project. However all involved agreed that initial costs could be prohibitive. However, several steps could be taken to reduce costs and additional innovations described in the next section could further bring costs down. Cost saving steps could include optimizing house designs and cutouts to match panel sizes and to reduce wastes. With careful planning panel sizes can be stocked to match specific house models.

- Although not yet published, research at Oak Ridge National Laboratory has demonstrated that 4-inch SIP walls outperform whole-wall R-values of 6-inch stud walls. Using thinner panels can reduce cost and weight.

Figure 4. Average Energy Use for Each Hour of the Day for Major End Uses



Further Innovations

- Because of improved energy efficiency, downsized heating and cooling systems are needed for energy-efficient manufactured homes. These could cut costs in existing programs such as SGC, as well as SIPs homes.
- Combined exterior siding and SIP sheathing could cut costs. SIP manufacturers are currently testing a Louisiana Pacific product that holds promise.
- Premier has developed a thinner-skinned SIP that was used for a post office roofing project. Thinner skins reduce weight and costs and could be applied to manufactured housing where HUD-code-required structural loads are typically less than for site built homes.
- Panel manufacturing could be incorporated into manufactured home factories. Panel preparation could run the gamut from onsite modification of existing panels (cutting out windows) to actually producing panels.
- Ducts in the Concept 2000 house were located beneath the floor. Although insulated, these ducts would be much more effective if located in conditioned space. One easy way to accomplish this would be to build a chase in the ample peak of the cathedral roof.

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