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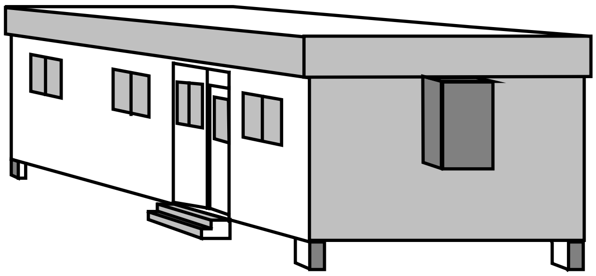
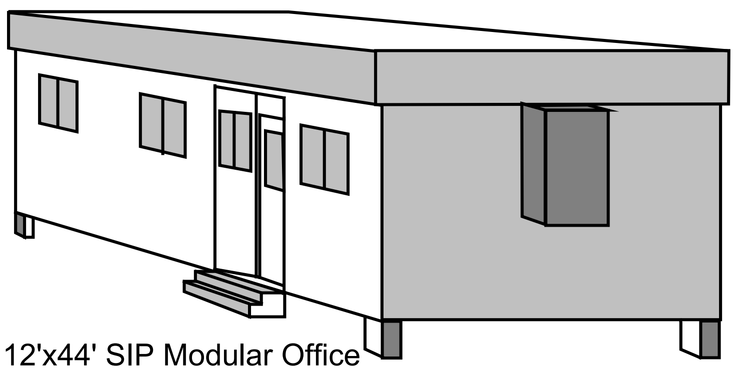


12'x44' Frame Modular Office



12'x44' SIP Modular Office

## Acknowledgements

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# Contents

## Introduction

Two modular office units were tested at the National Renewable Energy Laboratory (NREL) to establish each unit's thermal performance. The two units were nearly identical in appearance, but one was built with structural insulating panels (SIP), and the other was built using standard frame construction. The primary objective of these tests was to compare the thermal performance of buildings using SIP and standard frame construction. Both units were tested under carefully controlled steady-state conditions in the NREL large-scale environmental enclosure. They were then moved outdoors where Short-Term Energy Monitoring (STEM) tests were performed, and long-term heating and cooling energy use was measured. A secondary objective was to evaluate the accuracy of the NREL STEM method by comparing the results of outdoor STEM tests to steady-state indoor test results. STEM is a method developed by NREL to determine key thermal parameters of a building in-situ, based on a 3-day test sequence. The indoor test facility also provided the opportunity to investigate the phenomenon of infiltration heat recovery in a real building, under carefully controlled conditions, to evaluate the stability of the "concentration decay" method of tracer gas-based infiltration monitoring, and to compare the blower-door method with the tracer-gas technique in determining infiltration.

This project was a cooperative effort with the Structural Insulated Panel Association, the Modular Building Institute, All-American Modular (AAM, the manufacturer of the units), and GE Capitol (the owner of the units). Richard Harmon, the president of AAM, requested NREL's assistance in exploring the feasibility of converting his manufacturing process to SIP construction. His engineering staff needed to assess which comfort and energy benefits might be associated with this new technology. AAM manufactured the two units. NREL tested the modules for 8 months.

## Background

The National Renewable Energy Laboratory (NREL) Building Energy Technology Program has had extensive experience with manufactured buildings, including:

- A program sponsored by the Department of Energy (DOE) National Low Income Weatherization Program that resulted in a 600% increase in the cost-effectiveness and energy savings of retrofits (Judkoff et al. 1988; Judkoff et al. 1990a; Judkoff et al. 1990b; Judkoff et al. 1991; Burch et al. 1993).

- A project that resulted in improvements to the 1993 HUD Energy Code for new manufactured buildings (Judkoff et al. 1992; Judkoff 1993).

NREL has also had extensive experience with residential and commercial site-constructed buildings. NREL's mission, under DOE's High Performance and Building America Programs, is to develop, test, and monitor technologies and design and analysis methods that reduce energy use in buildings. We are also tasked to develop quicker, less expensive, and more accurate, techniques for measuring and evaluating building energy performance in the field.

As an example of this program, NREL collaborated with the National Park Service to design, build, and monitor a SIP house on the south rim of the Grand Canyon. Super-insulation and airtightness provided by the SIPs, combined with direct passive solar gains and a small Trombe wall, are predicted to reduce the annual heating load of the building by 91%, compared with typical construction in the area (Balcomb 1993). Monitoring the SIP components on manufactured buildings under controlled conditions allowed us to test our assumptions about the thermal performance of SIPs.

### *Test Methods*

During our work with manufactured and site-constructed buildings, we have developed special facilities and experimental techniques that allow short-term thermal testing of:

- Mobile buildings within an environmental enclosure under controlled, repeatable conditions (Judkoff et al. 1990b), and
- Buildings in the outside world (a necessity for site-constructed buildings) using the STEM method (Subarao et al. 1990; Subbarao 1988a; Subbarao et al. 1988b; Balcomb et al. 1993).

These techniques were suitable for the types of modular office buildings produced by AAM. They are briefly described below.

***Blower door test:*** Determines the size of construction cracks and holes in the building's envelope by depressurizing and/or pressurizing the building with a large fan (Sherman et al. 1980; Sherman et al. 1986; Judkoff 1986). The change in this measurement over time, or after transport, can be used as a rough indicator of construction integrity and durability.

***Tracer-gas test:*** Determines the air exchange rate (infiltration rate) between the exterior and interior of a building by measuring the decrease in concentration over time of a gas (usually sulfur hexafluoride) injected into the building. Other tracer-gas techniques include the constant concentration and constant injection methods (ASHRAE 1993).

***Infrared imaging test:*** Uses an infrared camera to visualize heat-loss paths in the building.

***Co-heating (calorimeter) test in the NREL Environmental Enclosure:*** Determines the overall building heat transmission coefficient ($U_o$), often referred to as the building loss or load coefficient (BLC), by measuring the heating power required to maintain a constant temperature difference between the interior and exterior of the building under steady-state and repeatable conditions. Variants of this test can be performed in combination to determine in-situ delivered heating and cooling efficiencies and reductions to the BLC due to various retrofit measures (Judkoff et al. 1990b).

***Short Term Energy Monitoring (STEM) test:*** A STEM test usually consists of a 3-day protocol in which the key thermal performance parameters of a building are determined by measuring the building's response to certain external and internal excitations (Subarao et al. 1990; Subbarao 1988a; Subbarao et al. 1988b; Balcomb et al. 1993). These include:

- A co-heating test to determine the building's overall heat loss coefficient
- A cool-down test to determine the building's heat capacitance properties
- A floating temperature test to determine the building's response to solar energy absorbed through transparent and opaque surfaces
- A blower-door test or tracer-gas test, or both, to determine infiltration rate
- Measurement of solar energy and other meteorological variables.

A STEM test can be conducted outside because the method includes mathematical correction and parameter estimation techniques to account for the effects of solar energy and varying weather conditions on the building (Subarao 1988a; Subbarao 1988b; Balcomb et al. 1993).

A unique benefit of this project was the ability to test the homes using both our indoor and outdoor techniques. Comparing the results enabled us to further refine our outdoor STEM methods. The inside tests give greater precision and can be used to validate techniques for interpreting tests done outside under varying weather conditions. The outside tests produce results that are more representative of actual operating conditions and provide insight into other effects, such as the units' response to solar gains. Outside tests are, of course, the only option for site-constructed buildings.

Tests were also done to understand the performance of the heating, ventilating, and air-conditioning (HVAC) units in combination with, and in isolation from, the performance of the building envelope. The data gathered with the inside and outside tests provided us the opportunity to improve our knowledge of the thermal performance of the buildings, their HVAC equipment, and the integrated performance of the buildings and their mechanical systems.

## *Building Description: The Modular Office Units*

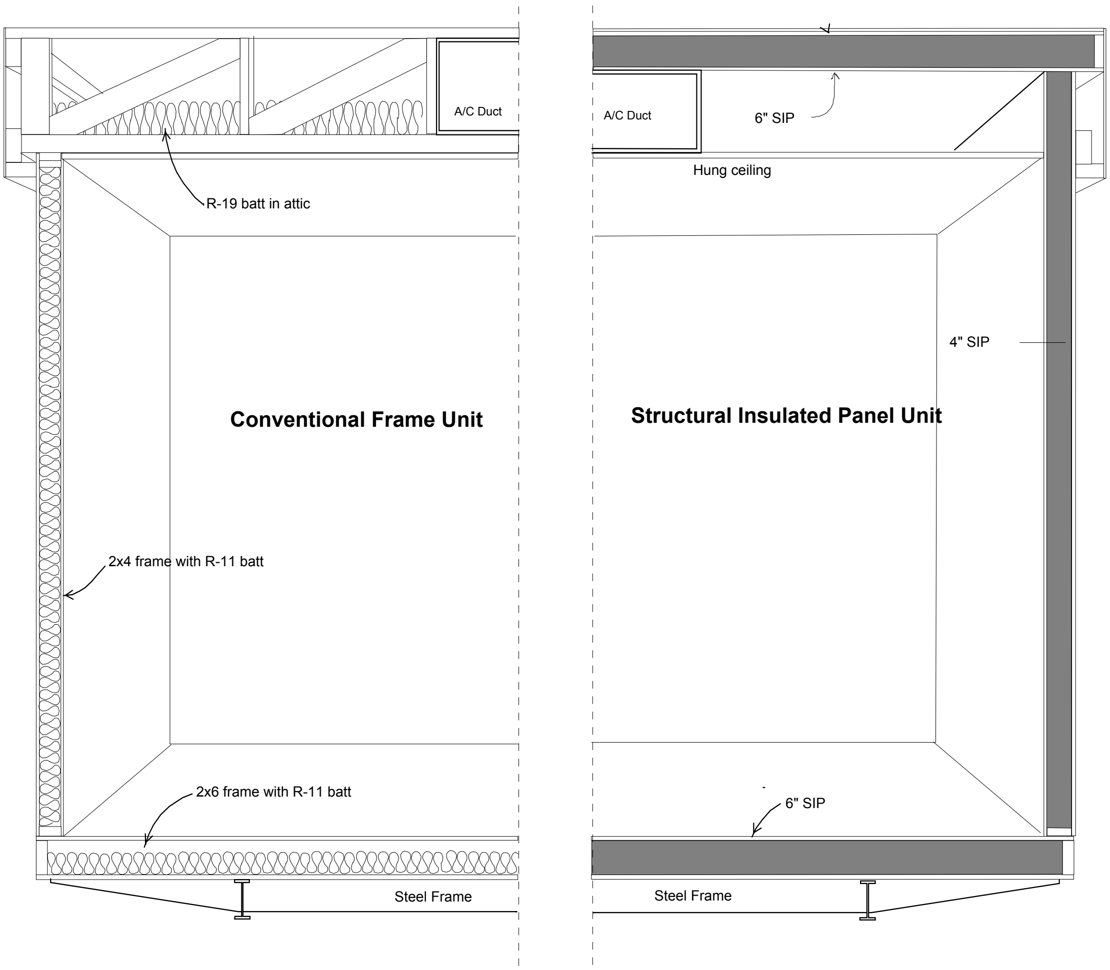
Two 12-ft x 44-ft modular offices were constructed for these tests. The first is a conventional office unit typical of thousands of such units built every year. It is of frame construction. The second is as identical as possible to the first, except it is made of SIP, using 4-inch panels for the walls and 6-inch panels for the floor and roof. Windows and doors are identical. Both units are heated and cooled using a 2.5-ton heat-pump system mounted on the "tongue" end. Air distribution is through a duct running the length of the unit in the ceiling.

These units were built by AAM, a manufacturer of modular offices located in Arlington, Texas. AAM proposed to manufacture and market modular offices very similar to the unit being tested. Richard Harmon, the president of AAM, stated that such a SIP unit might be constructed at little or no increased cost because of various manufacturing advantages. These included reducing the steel frame under the unit because of the SIP's added strength, laminating interior and exterior finishes directly to the insulation, and down-sizing the HVAC equipment. The prototype we tested was not yet cost optimized. The steel frame, finishes, and HVAC equipment were conventional. These characteristics would be modified in a production unit. Nevertheless, the thermal characteristics of an optimized unit would be practically identical to the SIP building we tested.

Figure 1 shows the two units. The frame building has a shallow attic with 6-inch fiberglass batt insulation laid on top of the ceiling. The SIP unit has a hung ceiling to provide space for the lighting fixtures and the air-distribution duct. Several advantages of the SIP construction are apparent from the sections. First, virtually all air and heat leakage from the duct remains in the thermal and pressure envelope of the SIP unit; on the contrary, most of the air and heat leaking from the duct in the AAM frame unit will enter the ventilated attic and be lost to the outside. (Some other manufacturers of mobile frame buildings avoid this problem by placing ducts under the floor, but above the insulation.) Second, attic ventilation is not necessary in the SIP unit because the inside of the roof surface is on the warm side of the roof insulation, thereby preventing condensation on that surface.

Table 1 shows the thermal and physical characteristics of each unit. The conditioned volume and heat transfer surface area are somewhat larger on the SIP unit because the insulation is integral with the roof plane. In the frame module, the insulation sits on top of the ceiling plane. The biggest thermal difference between the two modules was in the floor insulation. The SIP unit had R-25 in the floor, while the frame unit had R-11, even though the 2" x 6" floor joists provided plenty of cavity depth for a higher R-value batt. We accepted this difference because the manufacturer wanted to compare its current typical frame product to its proposed SIP product. The SIP floor had to contain 5.5 inches of expanded polystyrene for structural rigidity. The 2" x 6" floor joists with R-11 batts were a typical component of the frame product the manufacturer had been producing all along. Other minor differences existed in the electric lighting and ventilation systems. The SIP unit had approximately twice the electric lighting density as the frame unit. Also, the frame unit had a bathroom vent fan, whereas the SIP unit did not. We corrected for these differences in our experimental design by sealing the bathroom vent, and using the same amount of electric lighting in both units throughout the tests.

**Figure 1: Cross-section of office modules**




Schematic cross-section through the modular offices, frame unit on the left, SIP unit on the right

**Table 1: Physical Characteristics of AAM Office Modules**

| Component | SIP Module | Frame Module |
|---|---|---|
| Floor Area | 495 $ft^2$ | 495 $ft^2$ |
| Heat Transfer Surface Area | 1980 $ft^2$ | 1870 $ft^2$ |
| Volume (conditioned) | 4455 $ft^3$ | 3710 $ft^3$ |
| Wall | 3.5" EPS (R-16) | 2" x 4" with R-11 batts |
| Roof | 5.5" EPS (R-25) | Truss with R-22 batts |
| Floor | 5.5" EPS (R-25) | 2" x 6" with R-11 batts |
| Window Area | 75 $ft^2$(double glazed) | 75 $ft^2$ (double glazed) |

### *Test Sequence*

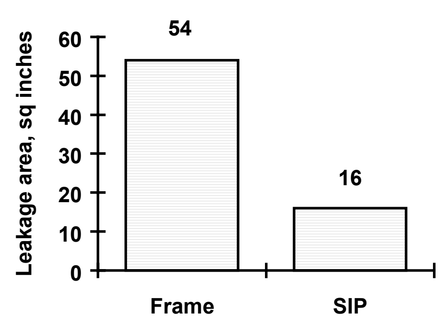
Both units were initially inspected in December 1993 soon after construction at the manufacturing facility in Arlington, Texas. Blower-door tests were performed at this time to determine the effective leakage area (ELA) for the entire building and for the duct system only. The units were then moved to the NREL test facility in Golden, Colorado, where blower-door tests were repeated to determine if the airtightness of the modules changed during the 1,500-mile trip. Indoor testing began on December 20, 1993, and continued through February 5, 1994. In the indoor tests, the building load coefficient was determined under steady-state heating conditions. The steady-state heating performance of both heat pump units also was determined. An infrared imaging system was used to identify any thermal anomalies in the units. The infiltration heat recovery characteristics of the frame unit also were investigated as part of the indoor test sequence. Both units were moved outdoors on February 15, 1994. The electrical energy required for heating the units under normal operating conditions was measured for extended periods. The outdoor test sequence included repeated STEM tests under a wide range of weather conditions. On April 14, 1994, 1,000 bricks were added to the SIP unit to evaluate any change in thermal performance and to assess the ability of STEM tests to identify the change in interior mass of the building. Both units were operated in the cooling mode during June and July 1994.

## Results

### *Blower-Door Test Results*

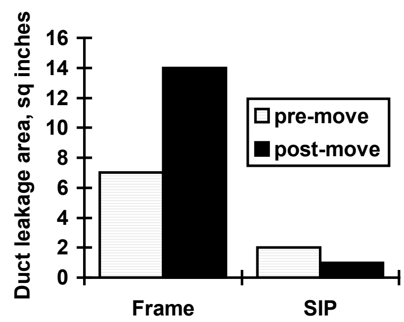
Both units were tested using the blower-door de-pressurization/pressurization technique. Tests were done in Texas, before transport, and in Colorado after the trip. Figure 2 shows the SIP unit to be extremely airtight with an ELA of only 16 $in^2$. The 2” x 4” frame unit shows a considerably larger leakage area of 54 $in^2$, still reasonably airtight. Neither unit showed any significant change in total leakage area due to transport. However, the *duct* leakage area for the frame module doubled as a result of the road trip (Figure 3).

**Figure 2: Blower- door tests**



Three blower-door tests were completed on each unit during the test sequence. On December 9, 1993, both units were tested in Arlington, Texas, before they were moved from the AAM manufacturing facility. They were tested again on December 20, 1993, after they had been moved approximately 1,500 miles to the NREL test facility in Golden, Colorado. Finally, after nearly 6 months of outdoor thermal tests in Golden, blower-door tests were repeated to determine whether there was any degradation in infiltration characteristics due to weathering. Each blower-door test sequence included a measurement of the total ELA of the building (at an effective pressure difference of 4 Pa), and an estimate of the leakage area in the heating and cooling ducts. The duct leakage area was estimated by taping over the supply and return diffusers, and subtracting the leakage area of the building in this condition from the leakage area in the "untaped" condition. This provides an estimate of the duct leakage to the outdoors. Tests for each condition were repeated at least four times to ensure high-quality results. Results from all repeated tests were found to be within 5% of each other.

**Figure 3: Duct leakage**



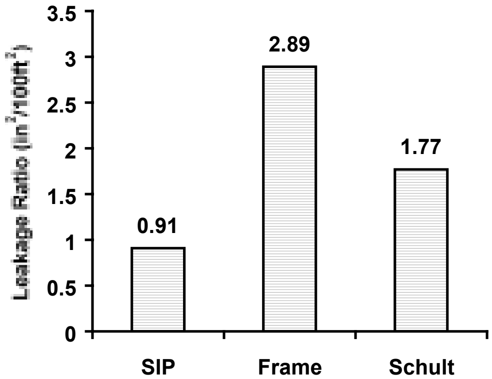

The results of all the blower-door tests are presented in Table 2. Also presented, for comparative purposes, are the average results from blower-door tests conducted on five manufactured frame homes produced by Schult in the fall of 1991 (Judkoff et al. 1992). The SIP unit had an initial ELA of 18 in$^2$ (remarkably tight), which did not change significantly during the test period. The tests consistently indicated that air leakage to the outside in the ducts was very small for the SIP unit. The initial ELA for the frame unit was 51 in$^2$. A slight increase was observed after transport to Colorado and a further increase of about 20% was measured after 6 months of testing. Duct leakage in the frame unit was approximately 25% of the total leakage area at the end of the test, and it increased substantially after transport. Although the ELA of the frame unit is more than three times greater than that of the SIP unit, its ELA is typical of many new frame-constructed buildings of the same size. The Schult homes, tested shortly after they were produced, had an average ELA of 47 in$^2$. However, the Schult homes were considerably larger than the AAM Office Modules (836 ft$^2$ versus 495 ft$^2$). A more meaningful comparison can be made by normalizing the ELAs by the surface areas of the homes. This is known as the "leakage ratio" and is defined as the ELA per 100 ft$^2$ of envelope area.

**Table 2: Blower-Door Test Results:**

| | Frame Unit | | SIP Unit | | Schult Average of 5 Homes | |
|---|---|---|---|---|---|---|
| | Leakage Area (in$^2$) | | Leakage Area (in$^2$) | | Leakage Area (in$^2$) | |
| | Total | Duct | | | Total | Duct |
| Test Date: | | | | | | |
| Dec. 9, 1993 | 51 | 7 | 18 | 2 | | |
| Dec. 20, 1993 | 54 | 14 | 16 | 1 | | |
| June 11, 1994 | 63 | 16 | 19 | 1 | | |
| Dec. 1991 | | | | | 47 | 3 |

Figure 4 compares the leakage ratios of the two AAM modules to the average leakage ratio of five frame-constructed mobile homes manufactured by Schult in 1991. The Schult homes, although of frame construction, are quite a bit tighter than the frame-constructed office module, but still not as tight as the SIP unit. We should note, however, that office units lack kitchen and dryer vents; residential units have an increased ELA due to these added penetrations. Therefore, it appears that with good detailing it is possible to construct frame buildings to be about as airtight as SIP buildings. The frame building in this study showed more tendency to loosen up over time than the SIP building. However, we saw no such trend in the frame homes constructed by Schult (Judkoff et al. 1992).

**Figure 4: Leakage ratio**




## *Thermal Tests in the Environmental Enclosure*

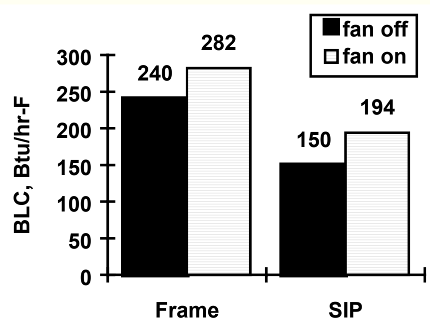
### *Co-heating Tests*

The SIP and frame units were both heated using portable electric heaters deployed inside, controlled by the data-acquisition computer to maintain constant and uniform temperatures in the rooms. Steady-state conditions could be attained because the temperature outside the unit was held constant. This test provides a direct, highly accurate measurement of the BLC.

BLC is defined as the amount of heat, in Btu/hr, required to maintain a 1°F temperature difference between the inside and outside. In these tests, it was measured by maintaining a constant temperature difference of about 30°F.[1] Under steady-state conditions, BLC = (Btu supplied)/$\Delta T$, where $\Delta T = T_{inside} - T_{outside}$.

Figure 5 shows that, with the fan off, the frame unit's BLC was 240 Btu/hr-°F and that of the SIP unit was 150 Btu/hr-°F, 38% lower. The BLC increased by about 44 Btu/hr-°F for both units when the heat-pump fan was turned on (with the outside air damper shut). One reason is that warm air was being circulated through the metal cases of the HVAC units mounted on the end of each modular office. These metal surfaces are less insulated and leakier than the building envelopes. A second reason is that the fan's operation increased pressure imbalances and pressure differences across the building shells, thereby increasing envelope infiltration losses. These findings are consistent with the results from tracer-gas tests and infrared scans documented later in this report.

**Figure 5: Co-heating tests**

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[1] In reality, BLC depends slightly on the temperature difference because the rate of infiltration increases as the temperature difference increases. A BLC measured at $\Delta T$ = 30°F is a good average value. For some tests, we disaggregate infiltration from other modes of heat transfer by conducting a tracer-gas test during the co-heating test.

Figure 6 shows the conduction portion of the overall heat transmission coefficient for the two office modules normalized by total exposed surface area. The figure also shows this coefficient for:

- Two homes manufactured by Schult to meet the 1993 Department of Housing and Urban Development (HUD) Code in zones 2 and 4 (warm and cold),
- The average of eight older mobile homes tested for the National Low Income Weatherization Program, before and after weatherization with an NREL-developed group of measures, and
- The 1993 HUD Code standard ($U_o$) for zones 2 and 4 (warm and cold).

The SIP unit meets 1993 HUD code requirements for mobile homes in all temperature zones in the United States, including Alaska. It shows performance similar to the Schult zone 4 home (cold zone). The Schult home, with frame construction, used a 2" x 6" (R-19) wall, an R-22 floor, and an R-19 ceiling to achieve this performance. The SIP unit attains equivalent performance with a 4-in SIP wall and 6-in SIP floor and ceiling. The main difference is that the SIP unit achieves this performance with thinner envelope components. The AAM frame unit would not have met the HUD code for either zone. Modular offices are not required to meet the HUD code for mobile homes. Its $U_o$ is about 12% less than an average pre-1976 mobile home qualifying for retrofit under the National Low Income Weatherization Program. It is a credit to this program that the typical post-weatherized mobile home exceeds the HUD code for zone 2 by about 15% and has a lower $U_o$ than the AAM frame office module. Such retrofits are done in part by blowing chopped fiberglass or cellulose into envelope cavities. A fiberglass-batt stuffing method developed at NREL also works well for walls.

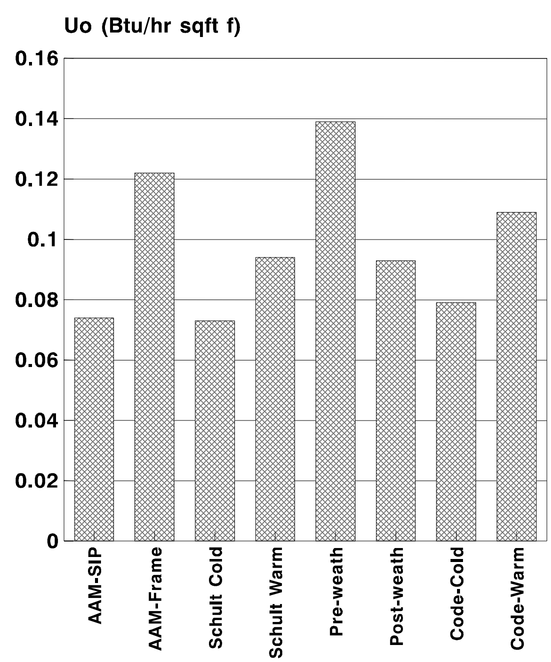
### *HVAC System Tests*

The units were operated with heating from the installed HVAC system. These systems are heat pumps mounted on the hitch end of the units, supplying hot air to the space through the overhead ducts. Return air from the offices is mixed with air drawn in through the inlet damper, which was set to the minimum-opening position. Electricity to the system required to maintain a 30°F ΔT was 1,221 watts for the frame unit and 861 watts for the SIP unit (Figure 7). From these numbers and the BLC given previously, it is possible to calculate the HVAC system's overall efficiency. This overall efficiency represents a combination of several effects, all acting simultaneously: (1) the coefficient of performance (COP) of the heat pump itself, claimed to be about 2.7 in these units under steady operation at an outside temperature of 47°F[2]; (2) the performance degradation due to cycling of the system, observed to be more frequent in the SIP unit because of the reduced load, and (3) the leakage of air from the duct to

**Figure 6**

**Conduction Heat Loss Coefficient**

**Normalized by Exposed Surface Area**

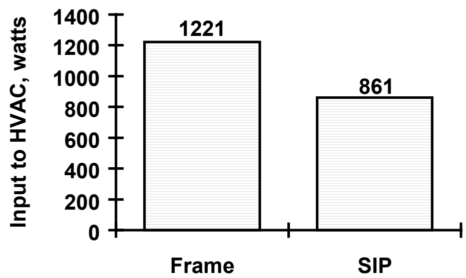



| | AAM-SIP | AAM-Frame | Schult Cold | Schult Warm | Pre-weath | Post-weath | Code-Cold | Code-Warm |
|---|---|---|---|---|---|---|---|---|
| Uo cond | 0.074 | 0.122 | 0.073 | 0.094 | 0.139 | 0.093 | 0.079 | 0.109 |

2 Temperatures in the environmental enclosure were close to 45°F throughout the heat pump tests.

the outdoors, thought to be greater in the frame unit because of the location of the duct in the attic. The *overall system* COP of the two units, determined by dividing the measured load by the electric input (in consistent units), is 2.00 for the frame unit and 1.85 for the SIP unit.

**Figure 7: HVAC Power**

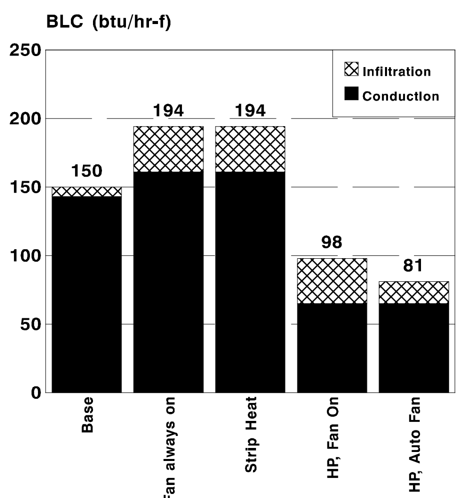



Figures 8 and 9 display data that allow us to understand in more detail the performance of the packaged mechanical system on the SIP and frame modules. In these figures, the electrical consumption measured for each case has been divided by the temperature difference between the environmental enclosure and the inside of the units during the test. These values are then converted from watts/°F to Btu/hr/°F to yield an "effective" BLC.

The bar on the far left of each figure shows the building loss coefficient when the building is heated with internal electric-resistance heaters (equivalent to an internal electric-baseboard heating system). Infiltration in the SIP module measured with tracer gas is very small—about 0.1 air-changes per hour (ACH)—as shown by the upper portion of the bar. The next bar shows the increase in heat loss that occurs when the packaged system supply air blower is activated while the outside air damper remains shut. This increase is caused by the circulation of air through the packaged unit itself, which is fairly leaky, and by the poorly insulated metal box hanging on the exterior of the module.

**Figure 8**

**SIP Packaged Heat Pump**

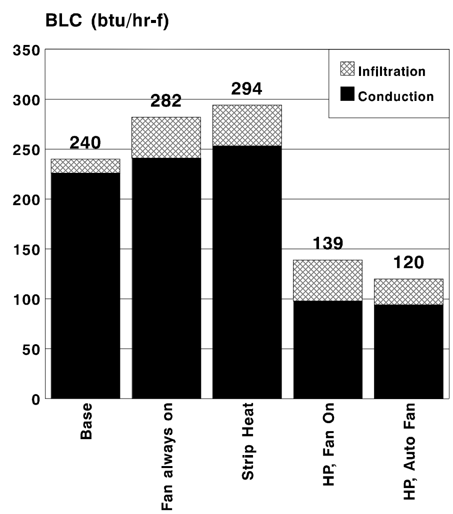



| | | | | | |
|---|---|---|---|---|---|
| ACH | 0.1 | 0.5 | 0.5 | 0.5 | 0.24 |
| Total | 150 | 194 | 194 | 98 | 81 |
| Infiltration | 7 | 33 | 33 | 33 | 16 |
| Conduction | 143 | 161 | 161 | 65 | 65 |

1ACH=66 btu/hr-f

**Figure 9**

**Frame Packaged Heat Pump**




| | | | | | |
|---|---|---|---|---|---|
| ACH | 0.27 | 0.8 | 0.8 | 0.8 | 0.5 |
| Total | 240 | 282 | 294 | 139 | 120 |
| Infiltration | 14 | 41 | 41 | 41 | 26 |
| Conduction | 226 | 241 | 253 | 98 | 94 |

1ACH=53btu/hr-f

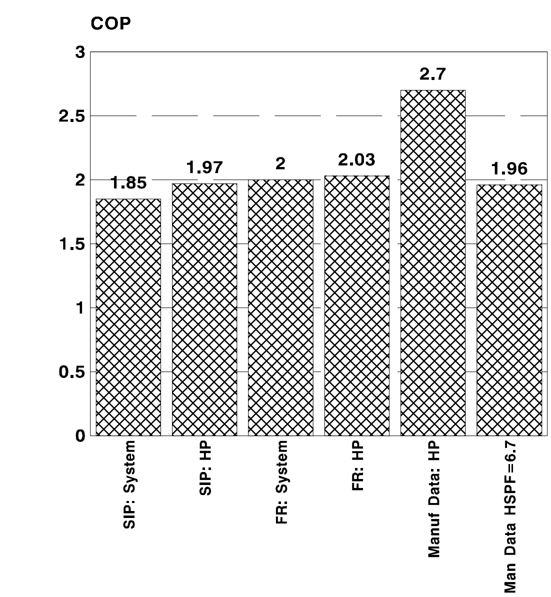
The third bar shows what happens when the strip heater in the heat pump—rather than the co-heaters—is used to maintain temperature. This tests duct losses by introducing the heat at the intake plenum of the supply duct. In the SIP module, heat losses do not increase when the packaged unit back-up resistance heater is turned on with the supply-air blower on. This is because the SIP design allows the ducts to be retained completely within the insulated envelope and the pressure envelope of the building. This is not the case with the frame module, in which heat losses increase because the R-4 supply duct runs through a ventilated attic. The fourth bar results from allowing the heat pump to heat the unit instead of the co-heaters or strip heater. We observed an apparent large decrease in the effective heat loss when the heat pump operates because of the higher COP of the heat pump as compared to electric-resistance heat, which has a COP of 1.0. In this case, we force the heat pump to operate with the supply blower always on. This is so we can determine the in-situ COP of the heat pump itself. We do this by taking the ratio of the second bar to the fourth bar. The fifth bar shows the heat pump performing in its normal operating mode. The in-situ COP of the entire heating system, including ducts and blowers, can be determined by taking the ratio of the first bar to the fifth bar.

Figure 10 shows the in-situ measured COPs for the heat pumps on the SIP and frame modules. The COP is slightly higher in the frame building, indicating that the equipment may be oversized for the SIP module, causing extra cycling inefficiency under the test conditions. The bar labeled "SIP: System" shows the whole system COP for the SIP module, including equipment, distribution, and cycling efficiencies. The bar labeled "SIP: HP" shows the COP for the heat pump alone. The manufacturer's data gives a COP of 2.7 at an outside temperature of 47°F. However, this value is based on fairly unrealistic test conditions. A somewhat more realistic value provided by the manufacturer is the Heat Pump Seasonal Performance Factor (HSPF), which attempts to account for realistic conditions in a "typical" climate. This typical climate is similar to that of Indianapolis. The manufacturer's data gives an HSPF of 6.7, which is equivalent to a COP of 1.96 (6.7/3.41). The results of all our tests were close to this value.

It should be possible to increase the overall COP of both units by changing the system design. Duct leakage could be reduced in the frame unit by sealing the duct better and by improving the duct insulation, or by moving the duct inside the thermal and pressure envelopes of the building. Cycling in the heating mode could be reduced in the SIP unit by reducing the compressor size. However, performance in the cooling mode would also have to be checked. The downsizing issue is further explored in the section on equipment sizing.

**Figure 10**

**Heat Pump & Whole System COP's**



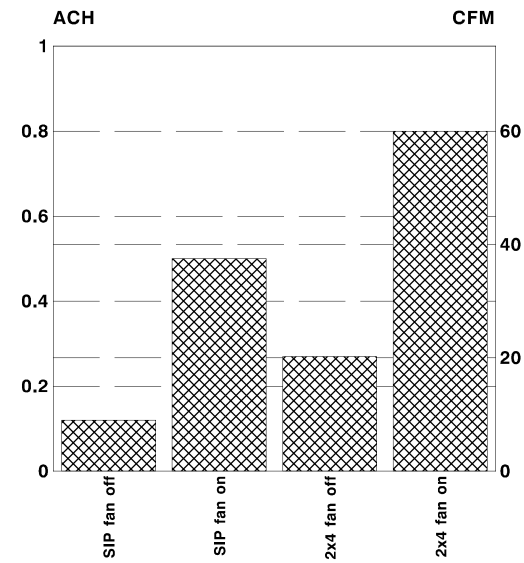

| | | | | | | |
|---|---|---|---|---|---|---|
| COP | 1.85 | 1.97 | 2 | 2.03 | 2.7 | 1.96 |

*Tracer-Gas Tests*

The units were tested inside a temperature-controlled environmental enclosure. Infiltration was measured by observing the rate of decrease in the concentration of a tracer gas previously injected into the space. Figure 11 shows that the infiltration rate of the frame unit with the heat-pump fan off was 0.27 ACH and the infiltration rate of the SIP unit (fan off) was 0.12 ACH, both measured with a temperature difference between inside and outside of 30°F. Note that this amount of infiltration would be insufficient to satisfy ventilation required for an office, which is 20 cubic feet per minute (CFM) per person (ASHRAE 1989). Thus, if nominal occupancy is five people, 100 CFM would be required. This corresponds to 1.3 ACH in the SIP unit and 1.6 ACH in the frame unit (using the volumes for each unit listed in Table 1). This ventilation would normally be supplied by the HVAC units. The principal advantage of tight construction is in reducing uncontrolled infiltration during unoccupied periods and minimizing uncomfortable drafts.

**Figure 11**

**Tracer Gas Test**
**Infiltration Rate**




| ACH | 0.12 | 0.5 | 0.27 | 0.8 |
|---|---|---|---|---|

Outside air damper closed

Ventilation rates with the fan on—also measured using the tracer-gas technique—are shown on the graph. Ventilation in the frame unit with the fan on would be adequate for about three people. Ventilation in the SIP unit with the fan on would be adequate for about two people. These tests were done with the inlet-air damper in the minimum-opening position. Increased ventilation could be achieved by adjusting the damper to a more open position. Meeting the ASHRAE standard for five occupants increases the instantaneous heat loss in the SIP and frame units by about 46% and 29%, respectively. Therefore, using heat recovery for ventilation air should be investigated.

With the heat-pump fan off, infiltration was entirely due to the "stack effect." The data shown in Figure 12 are based on tests done with different values of inside-outside temperature difference. These data are consistent with the accepted theory that buoyancy-driven infiltration increases as a function of the $\sqrt{\Delta T}$.

$$Q = L\sqrt{H\Delta T}$$

where:

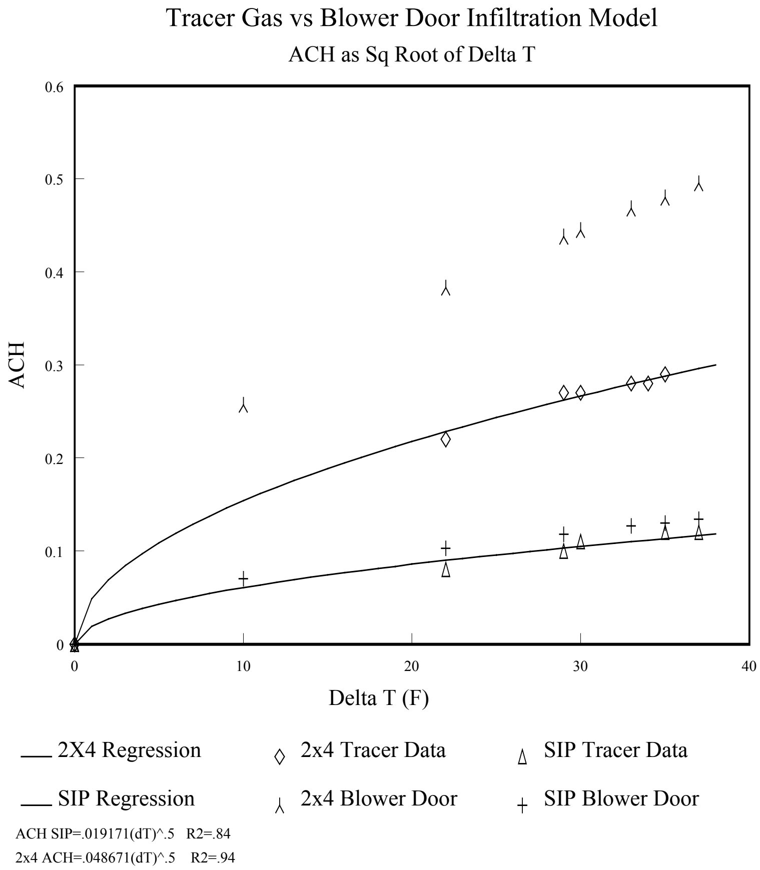
$Q$ =Infiltration rate

$L$ = Leak area

$H$ = Stack coefficient

$\Delta T$ =Temperature difference between inlet and outlet air.

**Figure 12**

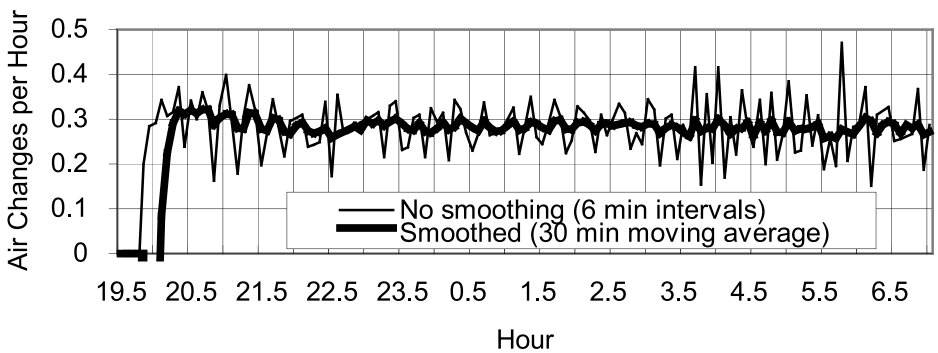



The "+" and "inverted Y" symbols in Figure 12 represent values produced using the stack portion of the Lawrence Berkeley National Laboratory blower door–based infiltration model (Sherman et al. 1986). The data show a strong trend toward overprediction by the blower-door method as compared to tracer-gas measurements. Others have observed a similar trend in previous studies (Judkoff et al. 1990b; Palmiter et al. 1991 and 1994) Effective leakage areas were determined for each module using the American Society for Testing and Materials (ASTM) E-779 blower-door test protocol, and a blower door calibrated at the Colorado State Blower Door Certification Chamber. Inputs to the infiltration model were done to reflect the same set of conditions that existed during the tracer-gas tests.

Figure 13 shows data from the tracer-gas tests using the B&K SF6 Specific Vapor Analyzer. The steady-state conditions in the environmental enclosure allow the gas-decay method to be scrutinized in a way that would not be possible in the outside world. Under steady-state conditions, we know that the infiltration rate should remain constant. The figure shows the air changes per hour determined over a 12-hour period beginning with a fresh injection of gas and terminating as the gas concentration becomes too low for accurate measurement. The thin line shows the ACH calculated based on the beginning and ending concentration of each 6-minute interval during the test. The thick line shows the ACH calculated based on a moving window of 30-minute intervals, a smoothing technique. For the first 1.5 hours after injection of the gas, the ACH is relatively high. We surmise that this is caused by the gas not having fully dispersed and mixed through the building (including closed cavities). After about 3 hours, results are very steady, and they remain steady for the next 5 hours. Then the un-smoothed data shows increased random noise as the gas concentration nears the bottom of the instrument's sensitivity range. The smoothing function is successful during this period because of the random nature of the noise. However, it is clear that the most robust data may be taken from the middle 5-hour period. This information is useful for developing improved data-collection protocols for outdoor tests, where varying conditions prevent observations of this kind. The initialization period may be longer than many users of the tracer decay method expect.

**Figure 13**

**Frame Unit: SF6 Measured Infiltration**
Environmental Enclosure 12/31/93 - 1/1/94




## *Infiltration Heat Recovery Tests*

The environmental enclosure provides a unique opportunity to measure the effect of infiltration heat recovery in a real building. Infiltration heat recovery is the heat transfer between the air passing through the shell of the building and the solid parts of the building shell. Air that starts at the average inside temperature of the building transfers some of its energy to the cooler (in winter) walls as it exfiltrates when the interior is pressurized relative to the outside. When the interior of the building is depressurized, the shell transfers some of its heat to infiltrating air. The heat loss rate due to infiltration may be less than that indicated by the heat associated with the total air exchange rate. This phenomenon has been studied and described by Anderlind (1985), Kohonen et al. (1987), Claridge et al. (1990), Bhattacharyya et al. (1992), Liu (1992), Claridge et al. (1995), Krarti (1994), and others. These researchers have reported heat recovery factors of approximately 20% using test boxes. The exact magnitude of the heat recovery depends on crack geometry, path length, and air velocity. Also, heat recovery factors much higher than 20% have been reported for buildings exposed to solar energy (Claridge et al. 1995). However, this is a different phenomenon in which the transfer of solar energy into the building is increased by air infiltrating through the solar-exposed wall.

The general phenomenon of infiltration heat recovery is of interest because it is the net *heat loss* due to air exchange that must be quantified in building energy analysis problems, not just the net air exchange rate, which is the quantity that can be most easily measured with tracer-gas techniques. In our case, where we were able to test a real building within a controlled environment, we had the capability to directly measure simultaneously both the net air exchange rate using tracer-gas techniques *and* the heat loss associated with that air exchange rate using calorimetry.

Our infiltration heat recovery tests were performed on the frame unit after its baseline steady-state BLC had been characterized in repeated tests. A pressure difference was imposed on the building's shell by operating a small fan temporarily installed in a small hole in the floor. By adjusting the speed and direction of this blower, the infiltration rate could be controlled, and positive and negative pressures of different magnitudes could be imposed. We accounted for the extra fan heat when the blower was operated in pressurization mode. The net air exchange rate between the inside and outside air while the fan was running was measured using tracer gas as in the previous tests. The BLC, including the effect of the increased infiltration, was measured in a steady-state co-heating test, as in the previous tests. If there is no infiltration heat recovery, the change in the BLC from its baseline value is expected to be the change in enthalpy of the additional air exchange, or:

$BLC_{new} = BLC_{base\ line} + (ACH_{new} - ACH_{base\ line})$x(volume of building)x(density of air)x(specific heat of air).

If the BLC measured in the infiltration heat recovery test is less than this expected value, then the infiltration heat recovery effect can be quantified by simply subtracting the measured BLC from the expected BLC. A measured BLC greater than expected would, of course, violate the first law of thermodynamics, and indicate an experimental error.

Table 3 presents the results of the infiltration heat recovery tests. Repeated measurements of BLC and ACH are presented for both positive and negative pressures. These measurements are compared to the base case, and the infiltration heat recovery fraction is calculated for both conditions. Essentially, no heat recovery is observed for negative pressurization at 1 ACH. For positive pressurization at 1.5 ACH, an infiltration heat recovery fraction of about 38% is observed, indicating appreciable heat recovery.

**Table 3: Infiltration Heat Recovery Test Results**

| | ACH | BLC Btu/hr/F | ΔACH | $\Delta BLC_{tracer}$ | $\Delta BLC_{coheat}$ | IHR fraction | |
|---|---|---|---|---|---|---|---|
| Base Case | | | | | | | |
| test #1 | 0.25 | 228 | | | | | |
| test #2 | 0.28 | 230 | | | | | |
| test #3 | 0.25 | 228 | | | | | |
| Pressurized | | | | | | | |
| test #1 | 1.45 | 267 | 1.19 | 61 | 38 | 0.37 | |
| test #2 | 1.50 | 267 | 1.24 | 63 | 38 | 0.39 | |
| Depressurized | | | | | | | |
| test #1 | 1.0 | 266 | 0.74 | 38 | 37 | 0.01 | |
| test #2 | 1.0 | 265 | 0.74 | 38 | 36 | 0.04 | |

ACH = net air exchange rate measured with tracer gas
BLC = building load coefficient measured in co-heating test
$\Delta ACH = ACH_{measured} - ACH_{Base\ Case}$
$\Delta BLC_{tracer} = BLC_{Base\ Case} + \Delta ACH$ x (density of air) x (specific heat of air)
$\Delta BLC_{co\text{-}heat} = BLC_{measured} - BLC_{Base\ Case}$
IHR fraction = $1 - \Delta BLC_{co\text{-}heat}/\Delta BLC_{tracer}$

Our experiment involved either pressurizing the building, in which case only exfiltration occurs, or de-pressurizing the building, in which case only infiltration occurs. Normally, under real conditions, approximately half the crack area of the building is under exfiltration, and half is under infiltration. Therefore, for our building, one can estimate that the infiltration heat recovery factor under normal conditions would be about 0.20. This is very similar to average findings of other studies. However, there is not much discussion in the literature on the effect of the directionality (infiltration versus exfiltration) of air flow on the infiltration heat recovery factor. Liu (1992) mentions the effect mostly in connection with an outdoor test cell exposed to solar energy. He notes that under these conditions, infiltrating air will carry more solar energy absorbed by the wall surface into the cell, and exfiltrating air will reject more of the solar energy to the outside. Liu also states that he found no dependence on directionality in his indoor tests with no solar radiation present.

Further work would be necessary to confirm our observations regarding the directionality of infiltration heat recovery. In real buildings, direction of flow can cause changes in effective crack area, geometry, and path length. For example, it is fairly common to calculate a different effective leakage area for blower-door tests done under pressurization versus depressurization. The most accurate blower-door protocols call for averaging the ELAs obtained under both conditions. We found very little difference in ELA obtained by pressurization versus that obtained by depressurization in this building. Our observations could also be explained if the ratio of diffuse flow to concentrated flow changed without effecting the overall ELA, though this seems unlikely.

### *Infrared Imaging Tests*

Both the frame and SIP units were inspected with an Inframetrics infrared imaging system. These inspections produced visual images of the surface temperatures of the units, indicating the surface heat flux. Scanning from the outside of the modules, characteristic differences between SIP construction and stud-wall construction were observed. The thermal “short circuit” caused by the studs was apparent. The SIP walls were observed to have a lower average temperature and nearly uniform temperature. Exterior surface temperatures of the studs and cavities were about 40°F and 37°F, respectively. Exterior surface temperatures of the spline joints and SIP panels were about 36°F and 31°F, respectively. Some wall cavities in the frame unit were found to have missing insulation, apparently overlooked during construction. SIP construction is less subject to this kind of quality-control problem because the insulation is integral with the structure. However, the spline joints must be carefully detailed in SIP construction.

One heat-loss problem observed in both units was the end-mounted heat pump unit. Even when the HVAC fan was not operating, the metal surface of the heat pump case appeared warmer than adjacent exterior surfaces, indicating higher heat loss rates. When the system fan was operating, the heat pump case temperature was about 9°F hotter than the SIP surface temperature. The efficiency of HVAC operation in both units could be improved by better insulating the heat pump case, or by moving the air handler inside the conditioned space.

## ***Outdoor Tests***

Both modular units were moved outside on February 15, 1994, and set up along an east-west axis with the front door and the majority of the windows facing due south. One objective of these tests was to provide a direct, side-by-side comparison of the heating and cooling energy used by the two units. Both units were heated with portable electric heaters until May. Air conditioning tests began in June and continued through August 15, 1994. A second major objective of the outdoor tests was to evaluate the accuracy and repeatability of STEM tests on both units. Repeatability was examined by conducting a standard 3-day STEM test on several occasions throughout the test period. In addition, each night of operation with portable heaters provided a repeated coheating test. Accuracy was examined by comparing the estimate of the BLC from the STEM tests with the BLC measured in the indoor tests.

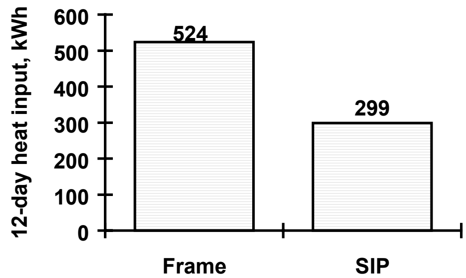
### *Heating Performance*

#### **Operation with HVAC Strip Heaters, February 27, 1994, through March 10, 1994**

Both units were operated for 12 days using their own HVAC units for heat. The heat pumps were turned off so that the heat was entirely from the 10-kW electric-resistance strip heaters. The fan was off except when the heaters were on. The average outside temperature during these 12 days was 42°F and the average inside temperature of both units was 72°F.

Figure 14 shows the electric heat used in both units. During this period, the power drops to near zero during many days when outside temperatures rise and solar gains through windows cause the inside temperature to rise above the thermostat set point. The total electricity used (which includes a small amount of electricity for the data logger and the fans) was 524 kWh for the frame unit and 299 kWh for the SIP unit. During this period, the SIP module used 43% less heating energy than the frame module.

Figure 14: Strip heaters

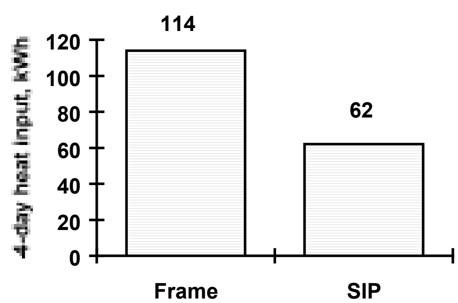



This period included one cold night following a cloudy day. The minimum outside temperature at 5 AM was 16°F, and the inside temperature was held at 70°F. The peak power at this time was 5.26 kW in the frame unit and 3.28 kW in the SIP unit. The peak for the SIP unit was 38% lower than for the frame unit.

**Operation with Portable Heaters Inside the Units, March 11–14, 1994**

Both units were operated for 4 days using the same portable electric-resistance units to supply heat that had been used during the inside tests. The HVAC fans were turned off. This test provides a more direct comparison of *shell loads* than the test during the preceding 12 days because heat losses from the HVAC unit and the ducts are minimized. Thus, it provides a more direct comparison of frame construction with SIP construction.

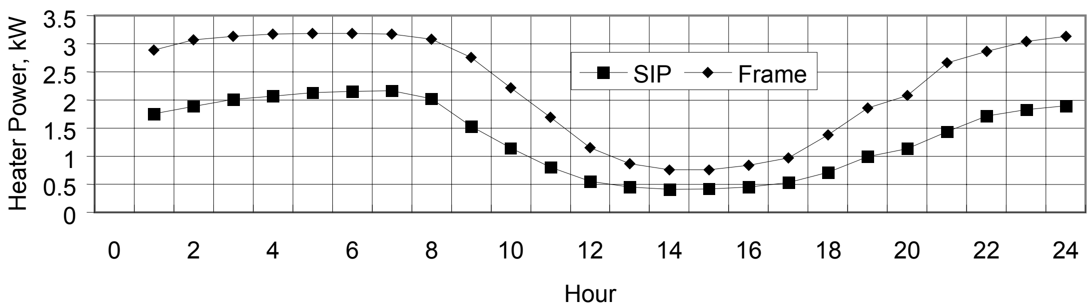
Figure 15: Co-heaters




The weather was sunny during these 4 days. The average outside temperature was 48°F, and the average temperature inside both units was 73°F. The total electricity used (which includes a small amount of electricity for the data logger and the fans) was 114 kWh for the frame unit and 62 kWh for the SIP unit (Figure 15). The SIP unit used 46% less energy than the frame unit.

Figure 16 shows the average hour-by-hour electric power used for heating with portable electric heaters for both units during a 1-week period in March. The weather was cold and sunny during this period, with typical nighttime lows of about 20°F and daytime highs in the 40s. The heating thermostat set point for both units was 71°F. The average peak electric power demand for the frame unit was 3.2 kW, and for the SIP unit was 2.2 kW. The peak demand occurred between 6 AM and 7 AM for both units. The average daily electric energy usage for heating was 53.9 kWh for the frame unit and 32.2 kWh for the SIP unit.

**Figure 16: Average Heating Power**
Days 58-64

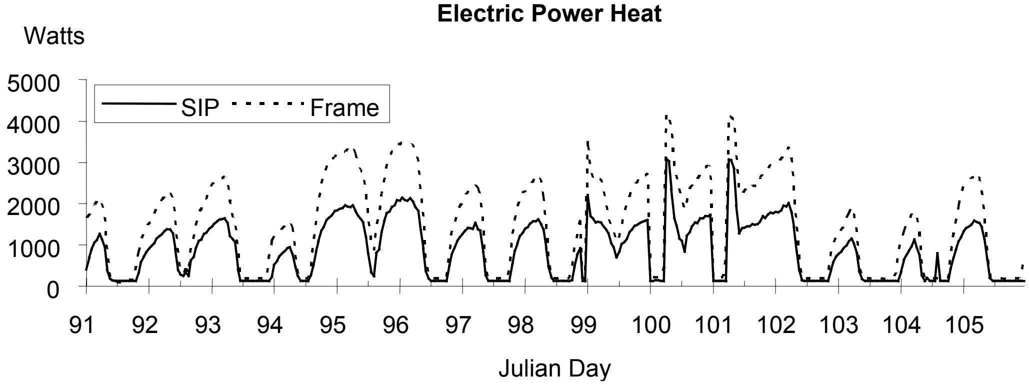



It is informative to compare the fractional reduction in BLC, peak demand, and energy use between the frame and SIP modules. In general these values should be similar, but not exactly the same because of solar energy and heat storage effects.

BLC savings fraction 1-(SIP/Frame) = 1-(150/240) = 0.37
Peak heating demand savings fraction = 1-(2.2/3.2) = 0.31
Total heating energy use savings fraction = 1-(32.2/53.9) = 0.40

The energy savings fraction is greater than the BLC savings fraction because the balance point temperature of the SIP unit is lower than that of the frame unit. It makes better use of internal gains and solar gains through windows. We cannot readily say why the peak demand savings fraction is lower than the BLC savings fraction for this period. For most periods the demand savings fraction averages about the same as the BLC savings fraction, as shown in Figure 17, which displays the electric heating power profiles for both units from April 1 through April 15. (The area in and around the NREL large-scale environmental enclosure is sometimes referred to as the CMFERT facility.)

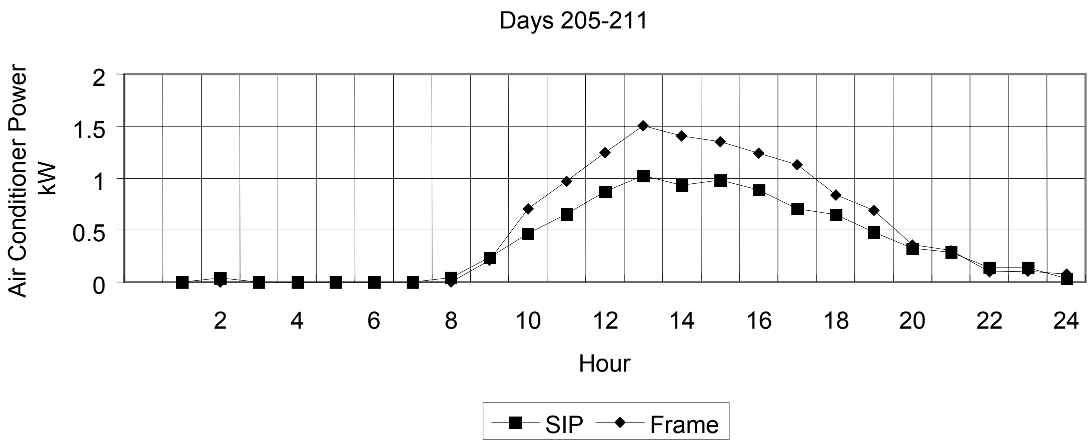
**Figure 17: CMFERT Outside Tests**
**Electric Power Heat**



## *Cooling Performance*

Figure 18 shows the average hour-by-hour electric power used for air conditioning for both units during a 1-week period in July. The weather was warm and sunny, with the average daytime high temperature being 89°F. Daytime relative humidity during the test period was typically less than 30% (and sometimes less than 10%). The cooling thermostat set point for both units was 71°F. Internal gains in each unit were approximately 100 W due to the data acquisition systems and mixing fans. The average hourly integrated peak electric power demand for the frame unit was 1.5 kWh/h, and for the SIP unit was 1.0 kWh/h. The peak demand occurred between noon and 1 PM for both units. The average daily electric energy usage for air conditioning was 12.2 kWh for the frame unit and 8.9 kWh for the SIP unit.

**Figure 18: Average Air Conditioner Power**




BLC savings fraction 1-(SIP/Frame) = 1-(150/240) = 0.37
Peak cooling demand savings fraction = 1-(1.0/1.5) = 0.33
Total cooling energy use savings fraction = 1-(8.9/12.3) = 0.27

The total energy savings fraction for air conditioning is smaller than the peak demand savings fraction. This is due to the higher conductivity of the frame unit. When outside temperatures are hotter than inside temperatures, more heat is conducted into the frame unit, but when outside temperatures are cooler than inside temperatures, the SIP unit loses heat more slowly than the frame unit. As expected, both these fractions are well below the BLC savings fraction. Tighter, better insulated construction generally will deliver more energy savings in the heating mode than in the cooling mode. This is because internal gains and solar gains transmitted through windows will dissipate relatively more slowly in the better-insulated building. Shading, internal heat reduction, and economizer ventilation are more effective strategies for the cooling mode than are insulation and air sealing. This is evident in the section on annual energy use extrapolations (Figures 22 and 23).

## *Outdoor Measured Infiltration Rates*

The net air exchange rate between the inside and outside air was measured using the tracer-gas system during most of the test period. Figures 19a and 19b show examples of the measured air exchange rates for both units, along with the wind speed and temperature difference for the same periods. Both units were heated with portable electric heaters during these periods. The infiltration rates, therefore, were not influenced by operation of the HVAC fan. When the HVAC fans operate in either the heating or cooling mode, the air exchange rates are nearly constant for both units.

**Figure 19a: Measured Air Infiltration**

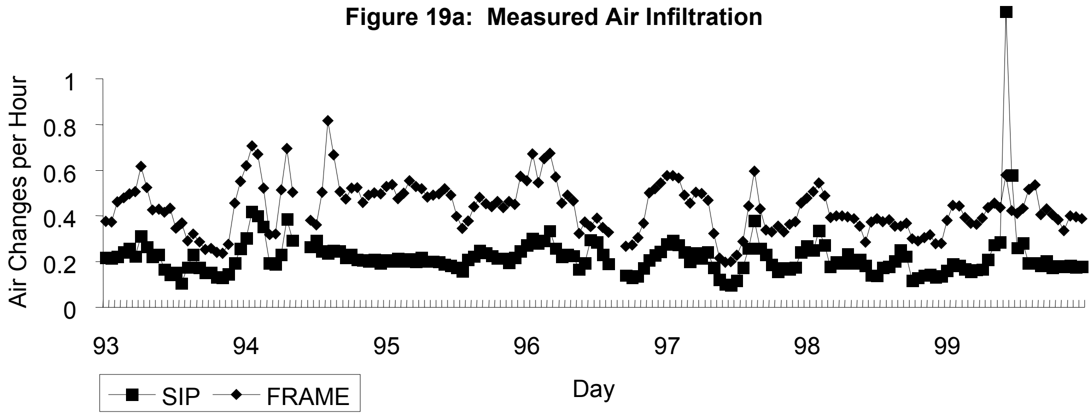
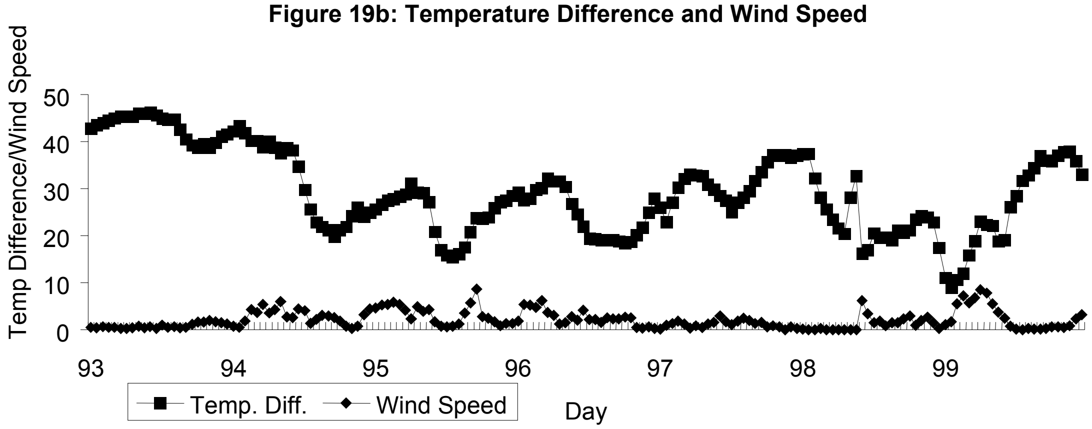
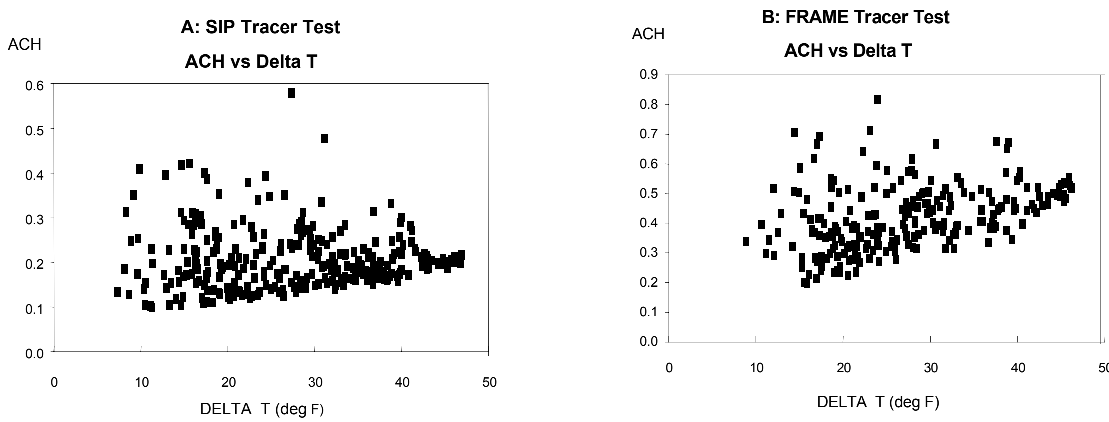


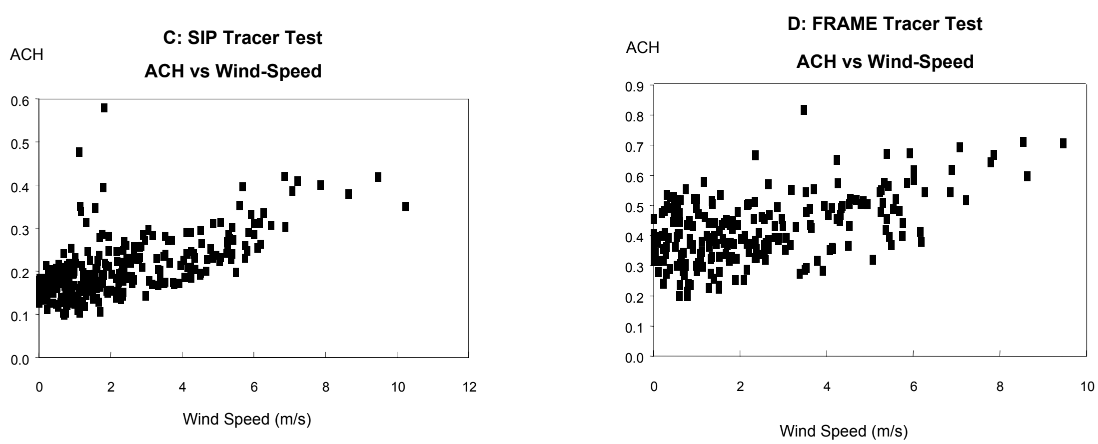

**Figure 19b: Temperature Difference and Wind Speed**



Figures 20a–d show correlations of infiltration rate to wind-speed and temperature difference for both units.

**Figures 20a–d**




## *STEM Test Results*

NREL has developed a technique for determining the key thermal parameters of a building from outdoor test results. The STEM method falls under the general class of techniques known as inverse methods. The concept is to calibrate, in a mathematically formalized manner, an hour-by-hour computer model of the building. The calibration is based on dynamic data taken during a brief test sequence, normally 3 days in duration. The model consists of several "macro-parameters" that represent physically logical combinations of numerous individual "micro-parameters." For example, the BLC is a macro-parameter consisting of all the micro-parameters that define the overall heat transmission coefficient of the building. These would be all the individual R-values of all the building shell components. "Lumping" the parameters facilitates a robust solution of the parameter-estimation portion of the technique. In the parameter-estimation routine, values for the macro-parameters are automatically adjusted until the residuals are minimized between the data measured in the test sequence and the values predicted by the model. To further ensure a robust solution (i.e., finding a global and physically reasonable minimum), the starting values for the lumped parameters are calculated based on a detailed building audit or a review of the building plans. The initial values are then renormalized based on the best fit to the data. Once the building's key thermal parameters are determined, the building's performance can be modeled forward in time using standardized weather data. The method, which is fairly complex, is described in some detail by Subbarao et al. (1990), Subbarao (1988a), Subbarao et al. (1988b), and Balcomb et al. (1993).

Three key building characteristics are determined from the analysis of data taken during a STEM test. These are the BLC, the effective building thermal mass, and the effective solar gains. The test protocol in its simplest form begins with a nighttime "co-heating" period during which inside air temperatures are maintained at a uniform and constant value to determine the BLC. During the daytime, the air temperatures are allowed to float above the set-point temperature in response to solar gains to determine the effective solar gains. During a subsequent nighttime period, the set-point temperature is changed to allow the air temperatures to change during the "cool down" part of the protocol to determine effective thermal mass or capacitance. Each portion of the protocol is intended to facilitate the accurate estimation of one of the fundamental parameters shown in the following formulation.

$$BLC = (Q_{electric} + Q_{corrections}) / (T_{in} - T_{out})$$

where:

| | |
|---|---|
| $Q_{electric}$: | is the electrical power needed to maintain the interior temperature |
| $T_{in}$: | is the interior temperature |
| $T_{out}$: | is the exterior temperature. |

The correction term is composed of several terms:

$$Q_{corrections} = P_{in} * Q_{in,storage} + P_{sun} * Q_{sun} + Q_{out,storage} + Q_{sky} + \Delta Q_{infiltration}$$

where:

| | |
|---|---|
| $Q_{in,storage}$: | is the heat flow due to interior temperature variations |
| $P_{in}$: | is the associated renormalization factor for $Q_{in,storage}$ |
| $Q_{sun}$: | is the heat flow due to solar radiation |
| $P_{sun}$: | is the associated renormalization factor for $Q_{sun}$ |
| $Q_{out,storage}$: | is the heat flow due to outdoor temperature variations |
| $Q_{sky}$: | is the heat flow due to the sky temperature depression below ambient |
| $\Delta Q_{infiltration}$: | is the infiltration heat flow over and above the base amount of infiltration included in STEM's definition of BLC. |

This part of the study was designed to evaluate the accuracy and repeatability of STEM results on both units. Repeatability was examined by conducting a standard 3-day STEM test on several occasions throughout the test period. In addition, each night of operation with portable heaters provided a repeated co-heating test. Accuracy was examined by comparing the estimate of the BLC from the STEM tests (taken outside under dynamic conditions) with the BLC measured indoors under steady-state conditions.

These comparisons can be viewed as a validation study of the STEM technique.

## *Standard Tests*

Standard STEM tests consisting of a full 3-day protocol were performed on both units on February 24–26, April 6–10, and April 25–28, 1994. The co-heating set point for these tests was 70°F. An additional test was done on the frame unit only on June 12–16, 1994. The co-heating set point for this test was 105°F. The additional test was run to check if comparable STEM results can be obtained under summer conditions. Originally, the STEM methodology called for winter testing. In theory, it should be possible to test in summer if a large enough temperature difference ($\Delta T$) between indoors and outdoors can be maintained. Heating system efficiency tests would not be advisable under these conditions because of fixed temperature settings in furnaces. However, cooling system efficiency tests are of interest under these realistic conditions. Tables 4 and 5 list the renormalized parameters for the frame unit and the SIP unit, respectively.

Parameters determined from these multiple standard STEM tests show maximum spreads, as defined by:

$$\text{Max } \Delta\% = [(\text{Max Value} - \text{Min Value})/\text{Mean}] \times 100$$

from about 9% to 18%. The average BLC for the frame unit from the STEM tests was 262 Btu/hr/°F, 9% higher than the BLC measured in the environmental enclosure. These values include infiltration, which is higher for the outdoor tests than for the indoor tests. The average BLC for the SIP unit was 150 Btu/hr/°F, 5% higher than the BLC measured in the environmental chamber. These values also include infiltration; however, infiltration in the SIP unit is much less than in the frame unit. The high-temperature STEM test (105°F set point) yielded parameters roughly equivalent to those from the typical STEM tests (70°F set point), indicating the feasibility of this technique for warm weather testing. It is interesting to note that the window descriptions were exactly the same for both units, but the SIP has lower $P_{sun}$ and $P_{in}$ values. This may be caused by reduced solar heat gains through opaque surfaces because of better insulation. It is also interesting that the SIP unit actually weighs more, but exhibits slightly less effective capacitance on average than the frame module. This may be because the capacitance associated with the exterior stress-skin of oriented strand board (OSB) is effectively unavailable to the interior of the unit due to the sandwich insulation design. In stud frame construction, relatively more of the capacitance of the wood may be thermally linked to the interior of the building.

***Adding Thermal Mass:*** On April 14, 1994, 1,000 paver bricks were placed in a single layer on the floor of the SIP unit. Each brick weighs about 4.5 pounds with a nominal specific heat of 0.21 Btu/lb/°F. The bricks covered approximately 40% of the total floor area. The unit was subjected to a standard STEM test sequence and the three primary parameters were determined with the STEM analysis. The STEM analysis was implemented using both the original audit description not including the bricks, and a revised audit description including the bricks. In theory, only those parameters related to thermal capacitance should change as compared to the parameters determined before the addition of the bricks. Table 5 shows the estimated primary parameters from this analysis. For the case in which bricks were not included in the audit, $P_{in}$ increases considerably, as expected, to correct for the fact that the audit description was not changed. For the case with the corrected audit input, $P_{in}$ remains very close to 1.0, also indicating, as expected, that no renormalization correction was needed. The effective diurnal thermal capacitance changed from an average of 1,280 Btu/°F for the lightweight tests to 2,265 Btu/°F, for a difference of about 985 Btu/°F. This is within about 4% of the nominal thermal capacitance of all of the bricks, which is about 945 Btu/°F. The other parameters, BLC and $P_{sun}$, changed by insignificant amounts, demonstrating that the renormalization properly accounted for the addition of the thermal capacitance represented by the bricks.

**Table 4: Renormalized Parameters for the Frame Unit**

| | BLC (Btu/hr/F) | $P_{in}$ | $P_{sun}$ | Effective Diurnal Capacitance (Btu/F) |
|---|---|---|---|---|
| Test Date (Conditions) | | | | |
| Feb. 24-26 (70°F set point) | 259 | 1.18 | 1.14 | 1317 |
| April 6-10 (70°F set point) | 282 | 1.14 | 1.09 | 1276 |
| April 25-28 (70°F set point) | 249 | 1.11 | 1.17 | 1241 |
| June 12-16 (105°F set point) | 259 | 1.32 | 1.06 | 1473 |
| Average | 262 | 1.19 | 1.12 | 1327 |
| Max Δ% | 13% | 18% | 10% | 17% |
| Indoor Test | 240 | | | |

**Table 5: Renormalized Parameters for the SIP Unit**

| | BLC (Btu/hr/F) | $P_{in}$ | $P_{sun}$ | Effective Diurnal Capacitance (Btu/F) |
|---|---|---|---|---|
| Test Date (Conditions) | | | | |
| Feb. 24-26 (no brick) | 151 | 0.78 | 0.90 | 1181 |
| April 6-10 (no brick) | 166 | 0.91 | 0.76 | 1381 |
| April 25-28 (brick) (no brick in audit) | 148 | 1.30 | 0.83 | 1970 |
| April 25-28 (brick) (brick in audit) | 149 | 1.07 | 0.82 | 2265 |
| Average (no brick) | 158 | 0.85 | 0.83 | 1281 |
| Max Δ% (no brick) | 9% | 15% | 17% | 16% |
| Indoor Test (no brick) | 150 | | | |

### *Repeated STEM Tests*

The BLC is the single most influential parameter for predicting the thermal performance of the building fabric. To test the repeatability and accuracy of the STEM method for determining the BLC, both units were heated with portable heaters at a constant set point of about 71°F from March 15, 1994, through May 15, 1994. Because this is the same operating condition as the coheating portion of the STEM protocol, nearly every night during this period provided data from which the BLC could be estimated by the STEM analysis. On a few occasions, nighttime temperatures or wind speed was unusually high, or some other factors interfered with a robust determination of the BLC. Therefore, a set of systematic criteria was developed for accepting or rejecting co-heating data during this period. Such filtering criteria are a necessary part of outdoor testing. The fundamental idea is to select those periods that provide the strongest signal-to-noise ratio for the parameter of interest. This minimizes reliance on mathematical modeling to correct for noise or other confounding signals in the experiment. For example, co-heating data is used between about 1 AM and sunrise for BLC determination. This is the period in the diurnal cycle when the outside world behaves most like an environmental chamber. That is, temperatures tend to be most steady, winds tend to be most attenuated, and the confounding influence of solar energy and stored energy is minimized.

*STEM Data Filtering Criteria*

For each hour between 1 AM and 6 AM during a co-heating test, the BLC can be computed as:

$BLC = (Q_{electric} + Q_{corrections}) / (T_{in} - T_{out})$

where:

| | |
|---|---|
| $Q_{electric}$: | is the electrical power needed to maintain the interior temperature |
| $T_{in}$: | is the interior temperature |
| $T_{out}$: | is the exterior temperature. |

The correction term is composed of several terms:

$Q_{corrections} = P_{in} * Q_{in,storage} + P_{sun} * Q_{sun} + Q_{out,storage} + Q_{sky} + \Delta Q_{infiltration}$

where:

| | |
|---|---|
| $Q_{in,storage}$: | is the heat flow due to interior temperature variations |
| $P_{in}$: | is the associated renormalization factor for $Q_{in,storage}$ |
| $Q_{sun}$: | is the heat flow due to solar radiation |
| $P_{sun}$: | is the associated renormalization factor for $Q_{sun}$ |
| $Q_{out,storage}$: | is the heat flow due to outdoor temperature variations |
| $Q_{sky}$: | is the heat flow due to the sky temperature depression below ambient |
| $\Delta Q_{infiltration}$: | is the infiltration heat flow over and above the base amount of infiltration included in the definition of BLC. |

Data collected each hour was used in the BLC parameter estimation only if the following conditions were met:

Windspeed ≤ 12 mph
$T_{in} - T_{out} \geq 20\ ^{o}F$

$|Q_{in,storage}| + |Q_{sun}| + |Q_{out,storage}| + |Q_{sky}| \leq Q_{maximum}$

where:

$Q_{maximum}$ = 1000 Btu for the frame unit
$Q_{maximum}$ = 800 Btu for the SIP unit.

These constraints functioned to filter out those effects that tend to mask or create noise in determining the parameter of interest (BLC).

Figures 21a and 21b display the individual estimates of BLC for the frame and SIP units, respectively, for each repeated test. The X-axis in each graph displays the days for which the co-heat hours met the filtration criteria. The average of all tests for the frame unit was 256 Btu/hr/°F, with a standard deviation of 12.1 Btu/hr/°F and a standard error of 2.1 Btu/hr/°F. Eliminating one obvious outlier from the 33 data points, the total spread in results was 14%. The average of all tests for the SIP unit was 152 Btu/hr/°F, with a standard deviation of 8.1 Btu/hr/°F and a standard error of 1.5 Btu/hr/°F. The highest BLC for the

SIP unit was 170 Btu/hr/°F and the lowest was 142 Btu/hr/°F, giving a total spread of 18%. These statistics suggest that there is about a 68% chance that the BLC determined from a single STEM test will fall within ±5% of the mean BLC obtained if it were possible to do multiple tests. If it is possible to do multiple tests, then we can have 95% confidence that the sample mean BLC will fall within about ±2% of the actual mean. These statistics do not include experimental bias errors associated with non-random instrument inaccuracy, experimental design, and sensor placement.

These BLC estimates include part of the infiltration heat exchange equal to the average infiltration over all co-heat hours. The variation around this component is modeled and subtracted out. From the model, the infiltration component included in the BLC estimate for the frame unit is 31.6 Btu/hr/°F, and for the SIP unit is 10.7 Btu/hr/°F.

**Figure 21a**

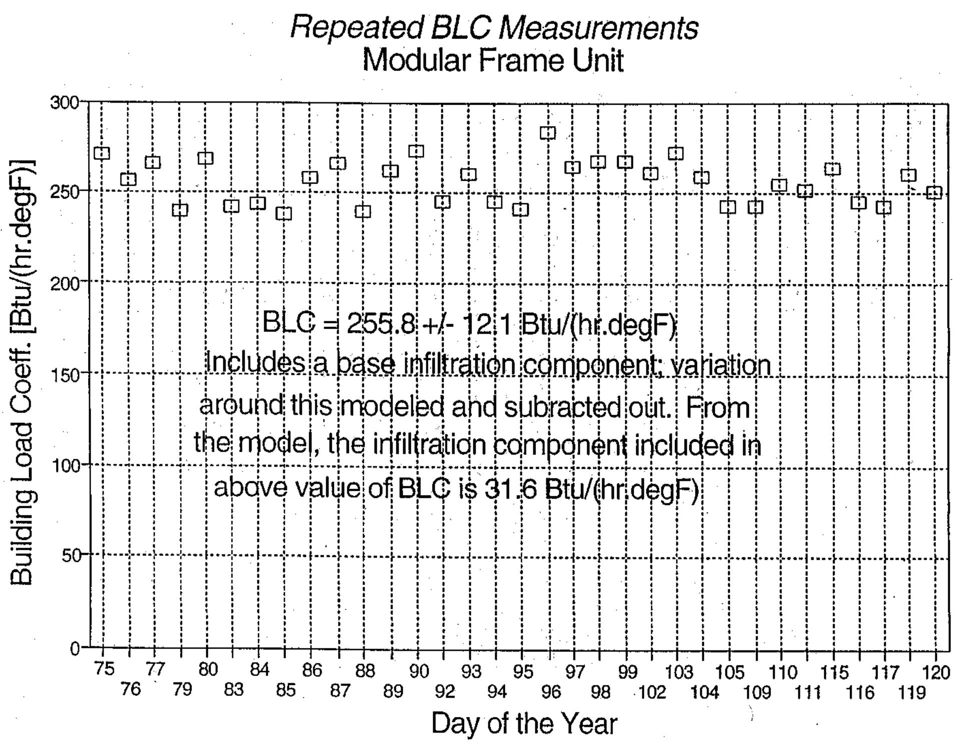
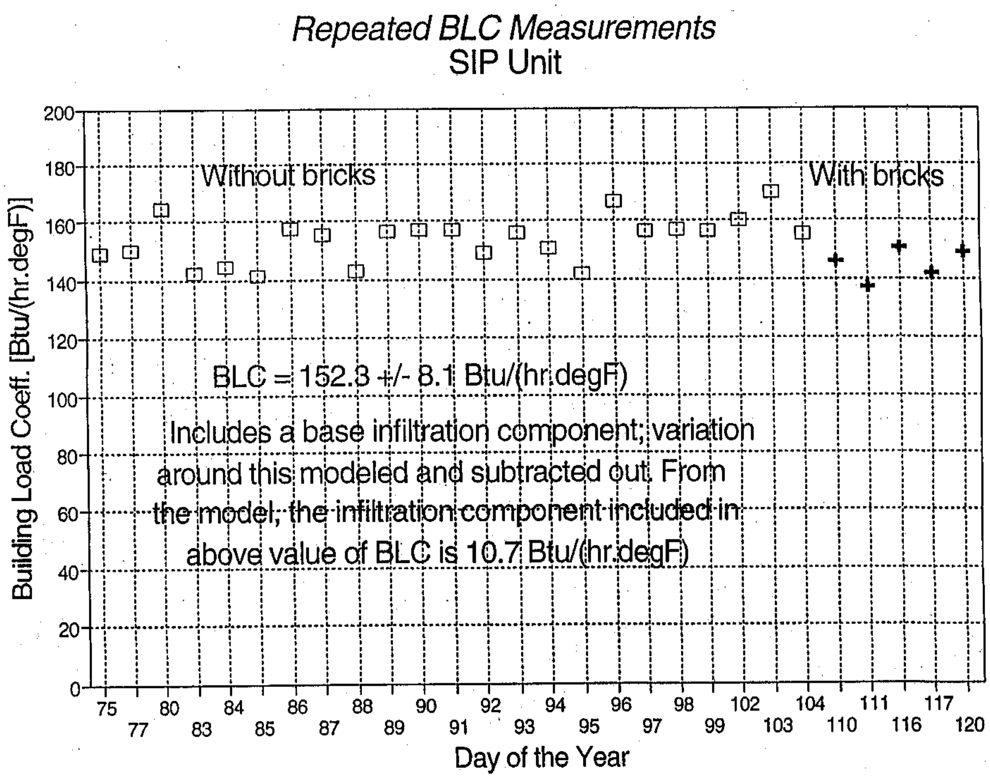


**Figure 21b**




## *Indoor Versus Outdoor STEM Tests*

Table 6 summarizes data from Tables 4 and 5 and Figures 21a and 21b. The summary compares the BLCs for the two office modules determined by three different methods. In the first method, co-heat tests were conducted inside an environmental enclosure under steady-state conditions. Eleven separate co-heat tests were conducted on the SIP module, and 10 separate tests were done on the frame module. Infiltration readings were taken during the co-heat tests by measuring the decay in concentration over time of sulfur hexafluoride ($SF_6$) with a B&K Specific Vapor Analyzer. These results may be considered the "truth standard" for validation of the outdoor STEM tests. Here we have discounted bias error because the bias errors from instrumentation inaccuracy, spatial and temporal discretization, and experimental design will be similar for both the indoor and outdoor tests. Bias errors, except for instrumentation error, are difficult to assess in the context of a whole-building test. Because of the relatively small number of samplings in the indoor tests, a Student's T distribution was used to determine the confidence intervals.

**Table 6: Indoor and Outdoor BLC results**

| (Btu/hr/$^{o}$F) | Mean of Indoor Co-heat Tests | Mean of Outdoor Co-heat Tests | Mean of Outdoor Standard STEM Tests |
|---|---|---|---|
| Frame BLC (no infiltration) | 226 ±2.8 (95% Confidence) (SD=3.9) (Std error=1.2) (T=2.26) | 224 ±4.2 (95% Confidence) (SD=12.1) (Std error=2.1) | 230 ±22.2 (95% Confidence) (SD=14) (Std error=7) (T=3.18) |
| SIP BLC (no infiltration) | 143 ±2.3 (95% Confidence) (SD=3.4) (Std error=1.0) (T=2.23) | 142 ±3 (95% Confidence) (SD=8.1) (Std error=1.5) | 147 ±13.4 (95% Confidence) (SD=8.4) (Std error=4.2) (T=3.18) |
| Frame BLC (infiltration) | 240 | 256 | 262 |
| SIP BLC (infiltration) | 150 | 152 | 158 |

In the second method, 46 repeated outdoor co-heating tests were done over a 46-day period. The STEM analysis method was used to correct the directly measured BLCs for the non-steady-state conditions associated with outdoor testing. The $P_{in}$ and $P_{sun}$ terms, being relatively fixed characteristics of the building, were calculated once at the beginning of the test sequence using the standard 3-day STEM protocol. The rest of the STEM terms were measured each hour and used to determine the BLC for that hour. The infiltration component was determined as explained in the previous section. The number of outdoor tests were sufficient to use a normal distribution for determining the confidence intervals. The BLCs from the indoor and outdoor tests for the SIP and frame modules are very close, indicating that the STEM technique successfully corrects for the unavoidably dynamic conditions prevalent in outdoor testing.

The column in Table 6 labeled "Standard STEM Tests" shows the mean BLC from the STEM 3-day tests in Tables 4 and 5. In these tests, all STEM correction terms are determined and applied during the 3-day test protocol. The small number of standard tests requires using a Student's T distribution with only three degrees of freedom. When only a small number of tests is possible (in this case n=4), the 95% certainty band is about ±10% of the BLC. However, it is reassuring to note that the mean BLCs from these few tests fall within, or very close to, the 1 Standard Deviation band for both the indoor and outdoor tests.

### *Annual Energy Extrapolations*

***STEM Versus Audit:*** The STEM results provide calibrated simulation models of the modular offices. These can be used to predict performance over an entire year, using recorded hourly values of temperatures, solar gains, and other weather variables. These calculations use standard assumptions for the conditions inside the building, such as thermostat settings and heat produced by lights, people, and equipment. The results provide an indication of both the required seasonal heating and cooling and peak loads. The SUNREL building energy computer program was used to perform the simulations (Judkoff et al. 2000).

Table 7 shows the predicted annual heating load, hourly integrated peak load, and savings for the audit and renormalized models. The weather data used to calculate the annual performance is the Denver typical meteorological year (TMY). Internal gains are 0.0 Btu/hr for these simulations. The "standard" thermostat is set at 70°F for every hour of the year. The "set-back" thermostat is set at 60°F from 11 PM until 7 AM, and is set at 70°F from 7 AM until 11 PM for every day of the year. The cooling thermostat is set at 85°F for every hour of the year. These set points are not intended to represent optimum performance, but are selected to indicate a range of expected performance.

**Table 7: Summary of Annual Heating Performance**

| | Standard Thermostat | | Set Back Thermostat | |
|---|---|---|---|---|
| | Annual (million Btu) | Peak (Btu/hr) | Annual (million Btu) | Peak (Btu/hr) |
| Frame: | | | | |
| Audit | 24.1 | 15,710 | 20.2 | 25,770 |
| Renormalized | 34.3 | 20,850 | 28.8 | 32,720 |
| | | | | |
| SIP: | | | | |
| Audit | 15.9 | 11,370 | 13.6 | 24,020 |
| Renormalized | 18.3 | 11,960 | 15.5 | 21,780 |
| | | | | |
| Savings: | | | | |
| Audit | 8.2 | 4350 | 6.6 | 1750 |
| Renormalized | 16.0 | 8890 | 13.3 | 10,940 |

The results in Table 7 indicate the value of reconciling the audit model with measured data using the STEM analysis. Although the parameter adjustments were not large for either unit, the *savings* determined for the renormalized model are nearly twice those predicted with the audit model. The important point is that the savings were significantly different using the renormalized model, not that they were larger. The corrections provided by the STEM analysis could change the savings estimates in either direction depending on the accuracy of the audit model and the simulation algorithms.

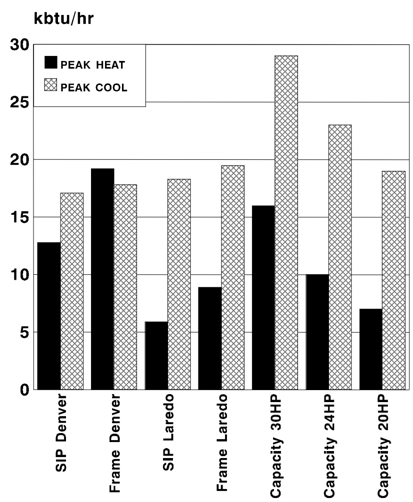
***Equipment Sizing:*** Here we explore the feasibility of downsizing the compressor in the SIP unit as discussed previously in the HVAC section. Figures 22 and 23 show the results of an annual simulation of the performance of the SIP and frame modules in Denver, Colorado, and Laredo, Texas. Denver has cold winters (6,000 heating degree days base 65), and Laredo has hot summers (4,137 cooling degree days base 65). The SUNREL building energy computer program was used to perform the simulations. Key modeling assumptions, representing a worst case scenario for cooling, were as follows:

- Approximately 4W/ft$^2$ of internal load (2 kW), on from 7 AM to 5 PM Monday through Friday
- Units oriented with their most heavily glazed facades due west
- Windows always shut
- Five occupants requiring 75 CFM during office hours (about 1 ACH)
- Natural infiltration rate of 0.25 ACH in SIP unit and 0.7 ACH in frame unit during unoccupied hours.

Figure 22 shows the peak heating and cooling loads predicted with SUNREL and the rated equipment capacities based on manufacturer's information. For the SIP module, the capacity in the heating mode of the 2.5-ton heat pump (Crispaire 30HP Classic I) exceeds the peak annual hourly heating load by 25%. We used the rated capacity at an outside temperature of 1$^o$F (the ASHRAE 97.5% design temperature for Denver) = 16,000 Btu/hr. In the cooling mode, the rated capacity of the heat pump at 100$^o$F (the ASHRAE 97.5% design temperature for Laredo) = 28,600 Btu/hr. This exceeds the peak cooling load in the SIP module by 56%. The data indicates that it may be possible to downsize the heat pump for the SIP module in locations with climates similar to or warmer than that of Denver. The Marvair Model 24HP appears adequate to meet peak demand with very little use of the backup resistance strip heater (approximately 1 week per year). Further analysis using an equipment simulation model would be necessary to trade off the added energy cost associated with using the strip heater versus the first cost savings and part-load ratio efficiency improvements associated with downsizing the equipment.

**Figure 22.**

**PEAK HEATING & COOLING IN 2 CLIMATES**

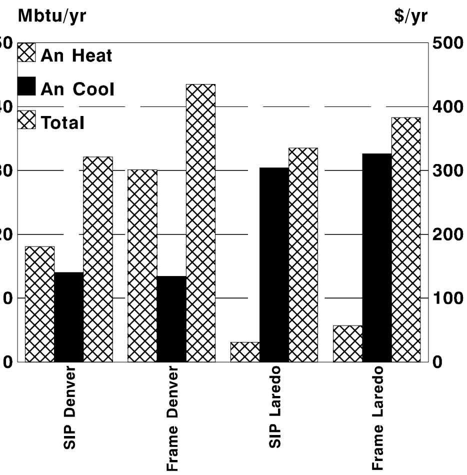



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PEAK HEAT | 12.8 | 19.2 | 5.9 | 8.9 | 16 | 10 | 7 |
| PEAK COOL | 17.1 | 17.8 | 18.3 | 19.5 | 29 | 23 | 19 |

Internal gains = 2kw or about 4w/ft2

**Figure 23.**

**Envelope Loads & Energy Costs**
**Annual Heating & Cooling In 2 Climates**




| | | | | |
|---|---|---|---|---|
| An Heat | 18.1 | 30.1 | 3.1 | 5.7 |
| An Cool | 14 | 13.4 | 30.4 | 32.6 |
| Total | 32.1 | 43.5 | 33.5 | 38.3 |

Electricity = $20/Mbtu
Heat Pump & A/C in-situ COP = 2
Internal gains = 2kw or about 4w/ft2

Figure 23 shows the annual heating and cooling loads and energy costs predicted with SUNREL in Denver and Laredo. It is worth noting that the SIP module has about the same cooling load as the frame module because much of the cooling load is from internal sources and from the transmission of solar energy through windows. In general, we have found that increased insulation and air tightening significantly reduce heating loads, but have little effect on cooling loads. To reduce cooling loads, other strategies are necessary, including solar load avoidance, economizer cooling, window management, and internal load management.

## Conclusions

- The AAM SIP building has an overall heat transmission coefficient about 40% less than that of the AAM frame building.
- The SIP building has a leakage area about one-third that of the AAM frame building.
- The SIP building would comply with the 1993 HUD thermal standards anywhere in the United States.
- The Schult cold-zone frame home performed as well as the SIP building, and much better than the AAM frame building, by using 2” x 6” walls with R-19 fiberglass batts, R-19 chopped cellulose in the ceiling, and R-22 fiberglass in the floor.
- In general, the primary advantage of the SIP construction compared with frame construction was the reduction in envelope thickness and air leakage.
- The SIP design allows all ductwork to be entirely within the thermal and pressure envelope of the building.
- The Schult frame design also placed the ductwork inside the insulation, and partially inside the pressure envelope. (The ductwork in the SIP unit was above the ceiling; the ductwork in the Schult frame unit was below the floor.)
- It appears possible to downsize the mechanical equipment for the SIP module.
- Better integration of the mechanical equipment with the modules would be beneficial. The external heat pump units lose substantial heat through their cases.
- Cooling loads could be reduced by using solar-load avoidance, economizer cooling, window management, and internal load management strategies.
- Using heat recovery for ventilation air should be investigated. The ASHRAE ventilation standard for five occupants would increase heat loss in the SIP module by about 46% and in the AAM frame module by about 29% when the venting system is on.
- Annual winter heating requirements for the SIP unit should be about 40%–45% less than in the AAM frame unit, depending on climate. Peak heating loads should be about 33% less.
- Annual summer cooling requirements for the SIP unit would be only slightly less than for the frame unit (because the cooling loads are mostly from solar gains and internal heat).
- BLC measurements from outdoor STEM tests agree well with results from co-heating tests in an environmental enclosure under steady-state conditions.
- Results averaged from multiple repeated outdoor STEM tests are very reliable for discerning differences in the BLC in the 5% range.
- Results from single outdoor STEM tests should be used where the changes in BLC are expected to be greater than 10%.
- Summer STEM tests are feasible for determining the BLC and for in-situ cooling equipment efficiency tests, but not for heating equipment efficiency tests in units with fixed internal thermostat settings.
- STEM is very effective at determining changes in thermal mass. The correction terms were well behaved whether or not the mass was included in the initial audit.

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13. ABSTRACT *(Maximum 200 words)*
Two modular office units were tested at the National Renewable Energy Laboratory (NREL) to establish each unit's thermal performance. The two units were nearly identical in appearance, but one was built with structural insulating panels (SIP), and the other was built using standard frame construction. The primary objective of these tests was to compare the thermal performance of buildings using SIP and standard frame construction. Both units were tested under carefully controlled steady-state conditions in the NREL large-scale environmental enclosure. They were then moved outdoors where Short-Term Energy Monitoring (STEM) tests were performed, and long-term heating and cooling energy use was measured. A secondary objective was to evaluate the accuracy of the NREL STEM method by comparing the results of outdoor STEM tests to steady-state indoor test results. STEM is a method developed by NREL to determine key thermal parameters of a building in-situ, based on a 3-day test sequence. The indoor test facility also provided the opportunity to investigate the phenomenon of infiltration heat recovery in a real building, under carefully controlled conditions, to evaluate the stability of the "concentration decay" method of tracer gas-based infiltration monitoring, and to compare the blower-door method with the tracer-gas technique in determining infiltration.

This project was a cooperative effort with the Structural Insulated Panel Association, the Modular Building Institute, All-American Modular (AAM, the manufacturer of the units), and GE Capitol (the owner of the units). Richard Harmon, the president of AAM, requested NREL's assistance in exploring the feasibility of converting his manufacturing process to SIP construction. His engineering staff needed to assess which comfort and energy benefits might be associated with this new technology. AAM manufactured the two units, and NREL tested the modules for 8 months.

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