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Buildings in a Test Tube: Validation of the Short-Term Energy Monitoring (STEM) Method

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Buildings in a Test Tube: Validation of the Short-Term Energy Monitoring (STEM) Method

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INTRODUCTION

Classical controlled, repeatable experimentation involving whole buildings is nearly impossible to do. It is therefore necessary to develop and validate field monitoring techniques that include mathematical methods to normalize for varying weather, and to account for the impossibility of knowing precisely the full thermal and physical characteristics of a building. Two mobile modular office units, one constructed with structural insulated panels and the other with standard 2X4 framing, 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. STEM is a method developed by NREL to determine key thermal parameters of a building in-situ, based on a three-day test sequence. By comparing the results from the indoor highly controlled tests to those from the outdoor STEM tests, we were able to determine the accuracy of the STEM method, and to quantify the guassian and bias uncertainties. In addition we completed successive STEM tests under a variety of outdoor weather conditions. This allowed statistical determination of the confidence intervals associated with single and multiple STEM tests. We also evaluated the accuracy of the STEM method related to determining thermal capacitance in a building by adding a known amount of thermal mass to one of the buildings, during a sequence of outdoor STEM tests.

The full length technical report on which this paper is based presents a detailed analysis of the differences in thermal performance between the SIP and frame units and also describes the validation of the STEM method. Here we focus on the validation aspects of the study (Judkoff et. al., 2000).

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 of typical frame construction. The second is as identical as possible to the first, except it is made of SIPs, 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. Table 1 shows the thermal and physical characteristics of each unit.

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 (Judkoff, 1986). 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.

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. BLC is defined as the amount of heat, in Btu/hr, required to maintain a 1°F temperature difference between the inside and outside. 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.

Data collected each hour was used in the BLC parameter estimation only if the following data filtration criteria 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.

This 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. In the indoor tests, BLC was measured by maintaining a constant temperature difference of about 30°F.[1] Under steady-state conditions, BLC = (Btu supplied)/ΔT, where $\Delta T = T_{inside} - T_{outside}$. These comparisons can be viewed as a validation study of the STEM technique.

Standard STEM 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 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 (ΔT) 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 2 and 3 list the BLCs from the outdoor and indoor tests, and 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 (see Table 3 for infiltration corrections). 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

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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 ΔT = 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.

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 3 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 2: Renormalized Parameters for the Frame Unit

(BLC values include infiltration which is higher in the outdoor tests than in the indoor tests)	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^{o}F set point)	282	1.14	1.09	1276
April 25-28 (70^{o}F set point)	249	1.11	1.17	1241
June 12-16 (105^{o}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 3: Renormalized Parameters for the SIP Unit

(BLC values include infiltration which is higher in the outdoor tests than in the indoor tests)	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 speeds were unusually high, or some other factors interfered with a robust determination of the BLC. Therefore, a set of systematic criteria was developed as previously defined in the STEM governing equations 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.

Figures 2a and 2b 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.

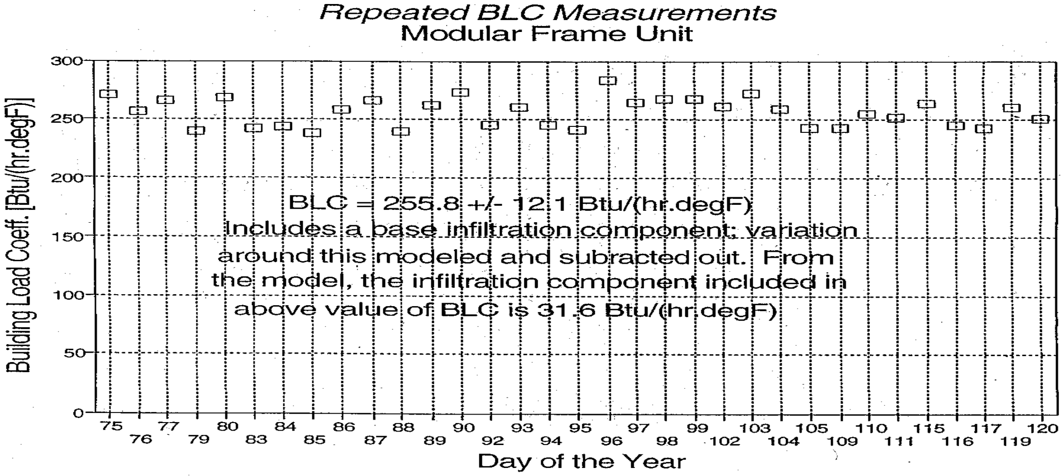

Figure 2a.

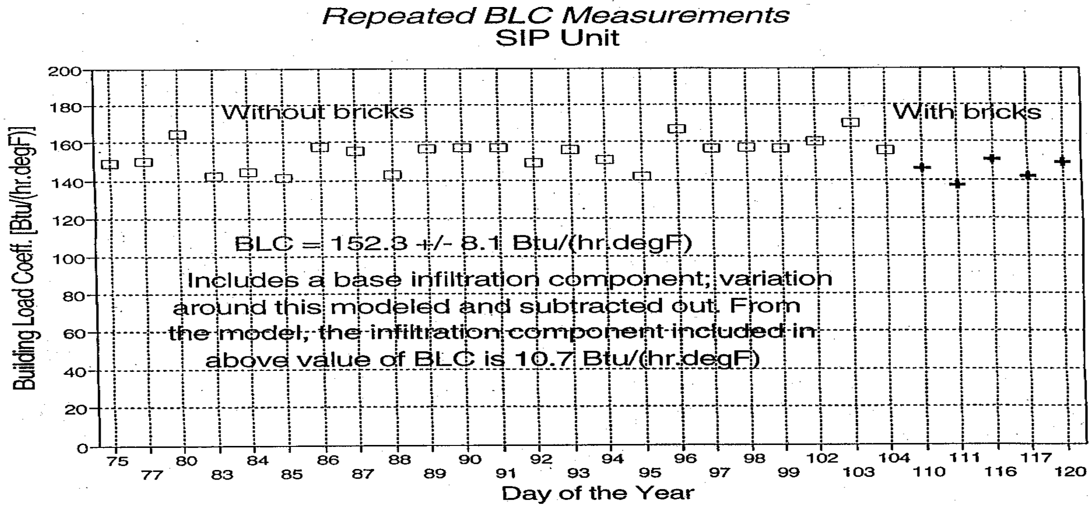

Figure 2b.

Indoor Versus Outdoor STEM Tests

Table 4 summarizes data from Tables 2 and 3 and Figures 2a and 2b. 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. Comparisons of outdoor to indoor results test both bias and gaussian uncertainty because the indoor steady-state conditions and the outdoor dynamic conditions are fundamentally different. 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 4: 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 4 labeled “Standard STEM Tests” shows the mean BLC from the STEM 3-day tests in Tables 2 and 3. 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 5 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 5: 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 5 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.

CONCLUSIONS

1. BLC measurements from outdoor STEM tests agree well with results from co-heating tests in an environmental enclosure under steady-state conditions.
2. Results averaged from multiple repeated outdoor STEM tests are very reliable for discerning differences in the BLC in the 5% range.
3. Results from single outdoor STEM tests should be used where the changes in BLC are expected to be greater than 10%.
4. 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.
5. 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.
6. The SIP building has an overall heat transmission coefficient about 40% less than that of the AAM frame building.
7. The SIP building has a leakage area about one-third that of the frame building.
8. Better integration of the mechanical equipment with the modules would be beneficial. The external heat pump units lose substantial heat through their cases.

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