# USE OF CALIBRATED SIMULATION FOR THE EVALUATION OF RESIDENTIAL ENERGY CONSERVATION OPTIONS OF TWO HABITAT FOR HUMANITY HOUSES IN HOUSTON, TEXAS

Jeff S. Haberl, Ph.D., P.E. [1]
Associate Professor
Energy Systems Laboratory
Department of Architecture
Texas A&M University

Tarek Bou-Saada [2]
Engineer
Houston Lighting & Power
Houston, Texas

Veronica Soebarto, Ph.D.[3]
Lecturer
Department of Architecture
University of Adelaide, Australia

Agami Reddy, Ph.D. [4]
Associate Professor
Department of Civil & Arch. Engineering
Drexel University, Philadelphia, PA

## ABSTRACT

This paper describes a project where selected energy conservation measures in two Habitat for Humanity houses in Houston, Texas were measured using side-by-side measurements of identical houses and calibrated simulation. The measures include shell tightening, improved A/C efficiency, modifications to the DHW heater, and solar screens. To perform the analysis both houses were instrumented with hourly data loggers for more than one year to record energy use and environmental conditions and the data analyzed using several methods including an inverse fourier series method and calibrated DOE-2 simulations. The results indicate that several of the

when all confounding factors were removed using simulation. The confounding factors that needed to be normalized with the simulation included: the weather conditions, differences in the life styles of the two houses, and omissions in the construction of the houses (Bou-Saada, et al. 1998). This paper discusses the instrumentation installed in the houses and the efforts that were undertaken to calibrate the DOE-2 simulation to the energy efficient house. The paper by Haberl et al. (1998) discusses the results of simulating the ECRMs.

## INTRODUCTION

Several new Habitat for Humanity houses have been built in a sub-division in North-East Houston as shown in Figures 1 and 2. The energy efficient house had a number of energy saving features incorporated into it to lower utility costs to the homeowner. Since these features also increased the price of the house, the specific objective of this project was to evaluate whether the individual energy improvement features are cost effective or not. For this purpose two houses were build side-by-side which were as identical a possible except that one of the houses had specific energy saving features built in while the other house was of standard construction. These two houses are referred to as the Energy Efficient (EE) house and the Standard Efficiency (SE) house, respectively.

In order to evaluate the cost-effectiveness of the individual measures, monitoring was initiated to measure the relevant parameters beginning in May

conserving features using calibrated computer simulation models to normalize for differences in occupant behavior and other discrepancies.

The construction plans of the two houses are identical, consisting of 1,100 ft$^2$ of floor area with an attic space. In each house, there are three bedrooms, a living area, a kitchen/dining area, a utility room, and a bathroom. Both the houses have forced-air, central air-conditioning with cooling provided by a vapor-compression air conditioner and heating provided by a natural gas furnace. The domestic water heating is also accomplished with natural gas. The differences in the building and equipment features of both houses, as well as the cost increase in incorporating the individual features are summarized in Table 1 which include the retrofits and estimated costs provided by Habitat for

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[1] Associate Professor and Associate Director, Energy Systems Laboratory, Department of Architecture, Texas A&M University.
[2] Currently at Houston Lighting and Power. Formerly, Mr. Bou Saada was a Research Associate, Energy Systems Laboratory.
[3] Currently, Lecturer, Department of Architecture. Formerly, Dr. Soebarto was a Research Associate at the Energy Systems Laboratory.
[4] Currently, Associate Professor, Department of Civil and Architectural Engineering, Drexel University. Formerly, Dr. Reddy was the Assistant Director of the Energy Systems Laboratory.

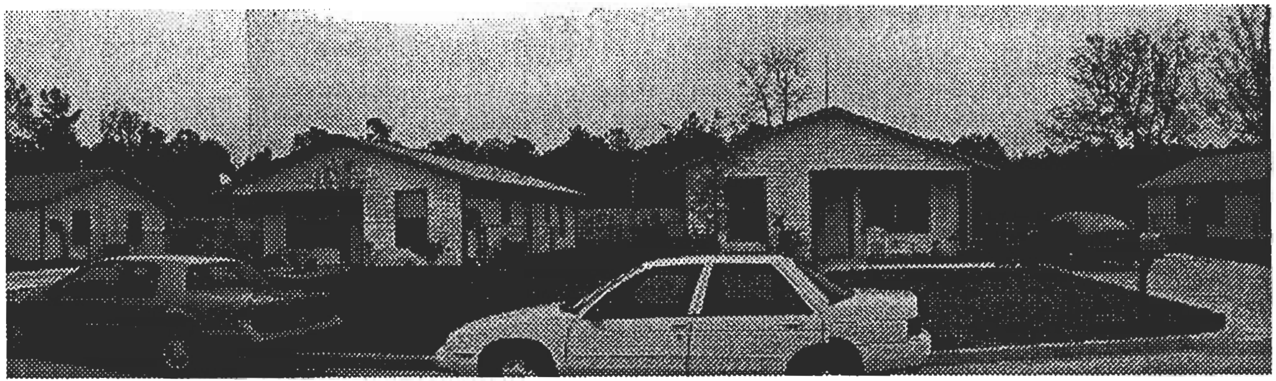

***Figure 1.*** *Front view of the two side-by-side Habitat for Humanity houses in Houston. The standard efficiency house is on the left and the energy efficient house is on the right.*

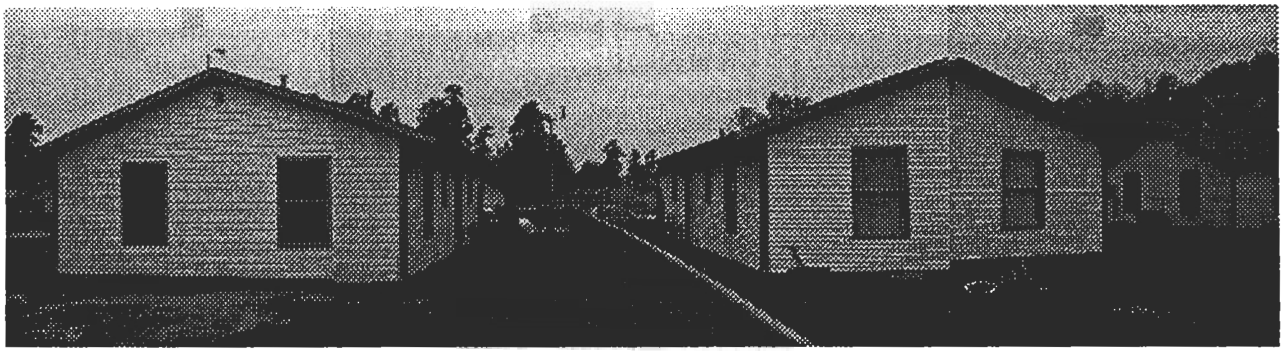

***Figure 2.*** *Back view of the two side-by-side Habitat for Humanity houses in Houston. The local weather station that was constructed can be seen between the energy efficient house (left) and the standard efficiency house (right).*

Humanity. The $1,300 in additional energy efficiency measures can be broadly classified into four categories:

1. shell tightening, which consists of improved duct insulation/sealing and shell tightening (both of which cost $150),
2. window upgrades, which include single pane clear glass windows with solar screens installed at a cost of $300,
3. a smaller water heater placed in the attic of the EE house (versus in the utility room of the SE house), which includes the roof pitch having to be increased thus costing an additional $200 (with insulated water lines) that increased the cost in total by $375, and
4. a more efficient HVAC system, with a programmable thermostat in the EE house that cost an additional $475. This includes upgrading the A/C in the EE house to SEER 12 from SEER 10 in the SE house.

The other major difference in the houses was the fact that the Standard Efficiency house had a gas oven and range while Energy Efficient house had a electric range and oven.

## ANALYSIS APPROACH

In order to analyze the effect of the energy conservation retrofits it was decided to instrument the houses with a modest suite of sensors and a data acquisition system and record hourly data through both the heating and cooling seasons. Table 2 includes a list of the channels that were chosen for monitoring. In both houses whole-building electricity use, air conditioner electricity use, and the electricity use of the HVAC blower was recorded. In the energy efficient house the electricity use of the kitchen was also recorded[5]. Supply and return temperatures and humidities the HVAC unit were also recorded in an attempt to ascertain the in-situ efficiency of the air conditioner. The temperature difference across the DHW was also recorded along with ambient temperature, humidity, wind, and solar radiation. Data

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[5] The standard efficiency house used a gas stove in the kitchen.

were retrieved weekly from the data logger, inspected for data quality and loaded into a data base for later analysis. All sensors were calibrated before and after the experiment to assure that significant sensor drift had not occurred.

Figures 3 and 4 present a sample of the data that was collected. In Figure 3, the electricity use of both air conditioners is shown versus ambient temperature. The impact of the reduced electricity use of the 12 SEER air conditioner in the Energy Efficient house versus the 10 SEER air conditioner in the Standard Efficiency house can be clearly seen as a 500 Watt reduction in the electricity use shown in Figure 3.

Figure 4 shows comparisons of the indoor return air humidity (upper graph), temperature (middle graph), and blower electricity use for both houses (lower graph) through the cooling and heating seasons. It is clear to see from the data that the homeowners in the houses operated their houses in very different manners. In the Standard Efficiency house the homeowner manually set back the temperature in both the summer and winter when they went to work and the house was unoccupied. In the cooling season this allowed temperatures to approach 80 F when the house was unoccupied during the day, while in the heating season, temperatures dropped to 55 F when the HVAC was manually set back.

In the Energy Efficient house the HVAC system ran continuously, which accounts for the very tight band of indoor temperatures between 65 and 75 F. The few points where the temperature dipped below 65 F represent only infrequent periods when the homeowner allowed the temperature to drop because the HVAC system had not been switched into the "heating" mode before going to bed. Humidity profiles in both houses are similar with humidities ranging in the 50 to 70% range in the summer and dropping as low as 20% in the winter. In the SE house there does appear to be slightly more variation in the humidity due to the wide temperature swings during the setback period.

The blower electricity use profiles in Figure 4 indicate that two speed blowers were installed in both houses with a lower speed for the heating mode. Also, in the SE plot there are bands of both zero electricity use and maximum electricity use which point to the manual on/off switching that the homeowners used to shut down the system when they were are work, turning it on again when they came house. In the EE plots the A/C never ran continuously for an hour since the A/C was always on. Hence the lack of peak blower electricity use.

Numerous site visits were also made to inspect the construction of the building and perform additional tests as needed to obtain "as-built" parameters for the simulation such as the air conditioner efficiency. Blower door tests were also conducted to ascertain the shell tightness.

Unfortunately, during the numerous site inspections it was discovered that the contractor never completed the installation of the access doors to the closet that housed the HVAC unit. This had the effect of allowing a direct passage to the attic since the ceiling of the closet that houses the HVAC unit was directly open to the attic to allow for combustion air for the HVAC unit. Blower door tests on both houses under this condition resulted in more air changes per hour than the blower door could measure, which unfortunately, represented the actual condition of the Energy Efficient house for a number of months.

In the Standard Efficiency house the homeowner covered the opening with a piece of 1/2" polystyrene mainly to cover up the noise that the unit was making. Therefore, the actual leakiness of the envelope in both houses could not be measured without covering the access doors with masking tape. Blower door tests on both houses with the access doors taped showed almost identical results which was a 0.75 air change rate.

## MONTHLY UTILITY BILL COMPARISON

During the data collection portion of the project a preliminary analysis was performed on the monthly utility bills to determine if the anticipated energy savings were visible in the monthly utility bills. Unfortunately, the utility bills indicated the Energy Efficient house was consuming more energy than the Standard Efficiency house. This can be seen when one inspects Figure 5 (electricity use), Figure 6 (natural gas use) and Table 3 which provides statistical indications of how the variation in monthly utility bills is captured with the 3 parameter models. In these figures and tables it is clear that the Energy Efficiency house consumed considerably more electricity than the Standard Efficiency house. Figure 4 points to one of the reasons why, namely that the Energy Efficient house occupants kept indoor temperatures quite a bit cooler in the summer and warmer in the winter. Natural gas use was similar at both houses in spite of the fact that the EE house had a gas stove in the kitchen.

*Table 1. Energy saving features of Houston Habitat for Humanity houses.*

| Building Feature | Standard House | Energy Eff. House | Cost Increase |
|---|---|---|---|
| **Improved Insulation and Shell Tightening** | | | |
| Ceiling Insulation | R-30 | R-30 | - |
| Wall Insulation | R-13-16 | R13-16 | - |
| Duct Insulation/Sealing | R-4/tape | R-6/mastic | $100 |
| Air Infiltration | Medium | Tight, tape exterior | $50 |
| Sealing Ext. Envelope | Yes | Yes | - |
| **Window Upgrades** | | | |
| Type | Single pane | Single pane | - |
| Frame | Aluminum | Aluminum | - |
| Shading Coefficient | Clear | Clear | - |
| Solar Screens | No | Yes | $300 |
| **Water Heater Placed in Attic** | | | |
| Type | 40 gallon, natural gas | 29 gallon, natural gas | - |
| Location | Conditioned space | Attic | $100 |
| Electronic Ignition | No | Yes | - |
| Insulated Lines | No | Insulate lines | $75 |
| Roof Pitch | - | Increased pitch | $200 |
| **More Efficient HVAC System** | | | |
| AC Type | 10 SEER, 2 ton | 12 SEER, 2 ton | $400 |
| Heating Type | | 80% AFUE electronic ignition | - |
| Thermostat | Non-programmable | Digital programmable | $75 |
| **Other** | | | |
| Ceiling Fans | Livingroom + bedrooms | Livingroom + bedrooms | - |
| Attic Ventilation | Ridge/soffit vents | Ridge/soffit vents | - |
| **Total ECRMs** | | | |
| | | Grand Total | $1,300 |

*Table 2. List of installed monitoring equipment.*

| House Metering | EE House | SE House | Device | Units |
|---|---|---|---|---|
| Whole-building electricity use | Y | Y | digital Watt trans. | kWh/h |
| Air conditioner electricity use | Y | Y | “ | kWh/h |
| Electric oven electricity use | Y | N | “ | kWh/h |
| HVAC blower electricity use | Y | Y | “ | kWh/h |
| Attic dry bulb temperature | Y | Y | 1000 Ohm RTD | $^{0}$F |
| Indoor/return air dry-bulb temp. | Y | Y | “ | $^{0}$F |
| Indoor/return air relative humidity | Y | Y | thin film RH sensor | % RH |
| Indoor/supply air dry-bulb temp. | Y | Y | 1000 Ohm RTD | $^{0}$F |
| Indoor/supply air relative humidity | Y | Y | thin film RH sensor | % RH |
| DHW supply water temperature | Y | Y | 1000 Ohm RTD | $^{0}$F |
| DHW cold water feed | Y | Y | 1000 Ohm RTD | $^{0}$F |
| **Outdoor Weather Station** | | | | |
| Global solar radiation | $Q_{sol}$ | | PV-type pyranometer | W/m$^2$ |
| Air relative humidity | $RH_0$ | | thin film RH sensor | % RH |
| Wind speed | v | | contact anemometer | mph |
| Air dry-bulb temperature | $T_0$ | | 1000 Ohm RTD | $^{0}$F |

***Table 3.*** *Statistical Parameters for the 3 Parameter Models. These tables display the statistics of the 3 parameter change-point models that were used to analyze the monthly utility bills for both houses. The upper table shows the statistics for the electricity use and the lower tables show the statistics for the natural gas use.*

*Electric model cooling statistics*

| Cooling | SE House | EE House |
|---|---|---|
| Slope | 20.68 | 40.95 |
| Intercept | 299.98 | 413.56 |
| CV(RMSE) | 24.1% | 21.5% |
| RMSE | 102.80 | 142.75 |
| $R^2$ | 0.64 | 0.79 |

*Natural gas model heating statistics*

| Heating | SE House | EE House |
|---|---|---|
| Slope | -3.68 | -2.69 |
| Intercept | 16.82 | 14.22 |
| CV(RMSE) | 13.9% | 15.7% |
| RMSE | 4.07 | 4.41 |
| $R^2$ | 0.96 | 0.95 |

Several additional features are also evident in the monthly utility bills that helped guide the calibrated simulation analysis. First, it was clear that the natural gas use and electricity use in both houses had strong weather dependencies which can be seen in the sloped portions of the 3 parameter regressions (Kissock et al. 1993). Second, the natural gas use for both houses was well described by the 3 parameter model with $R^2$ of 0.96 and 0.95 for the SE and EE houses, respectively. Monthly use of natural gas in the summer appears slightly higher in the SE house which may be a combination of the gas cooking and DHW ECRM. The Energy Efficient house had a slightly higher change-point temperature which confirms the characteristics of the measured indoor temperatures.

On the other hand the electricity use for both houses was only partially explained by a 3 parameter model as evidenced by the $R^2$ of 0.64 and 0.79 for the SE and EE respectively [6]. The one feature that does stand out about the differences in the electricity use in the two houses is that the Energy Efficient house used considerably more electricity for non-weather-dependent purposes (i.e., cooking, lighting, etc.) as is evident in the increased baseline use (413.56 kWh/mo for the EE vs 299.98 kWh/mo for the SE). This was expected since the Energy Efficient house contained an electric range and oven whereas the Standard Efficiency house had a gas range and oven.

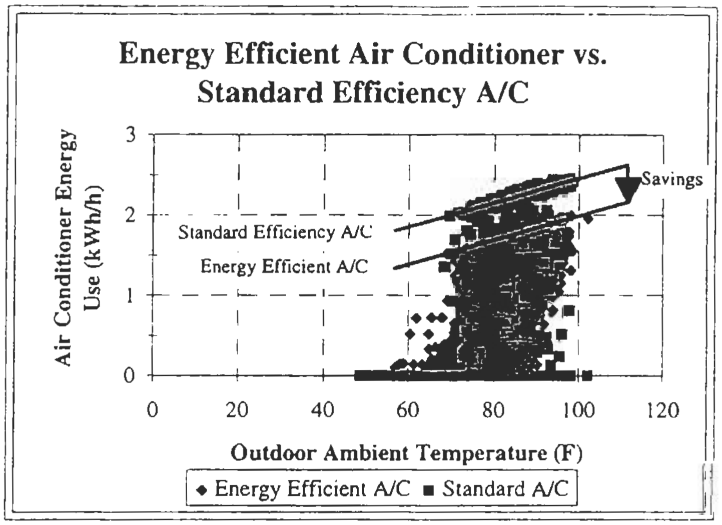

***Figure 3.*** *Electricity use of the Air Conditioners. This figure shows the electricity use of the air conditioners[7] in both the Energy Efficient and Standard Efficiency house.*

In conclusion, a simple monthly analysis of the electricity use and natural gas use of the two houses begins to shed light on the differences in the energy use characteristics of the two houses. However, as we will indicate later, these differences are not normalized for differences in lifestyle and therefore were not useful in determining whether or not the energy conservation retrofits were saving energy as expected.

## CREATING A CALIBRATED DOE-2 MODEL

A calibrated DOE-2 model was created for the baseline house in order to normalize for the confounding factors, such as the occupants, construction differences, etc. This section describes the calibration process. The calibration process includes:

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[6] Which may be indicating that the SE house had more temperature setbacks (based on interviews with the occupants) whereas the EE house had the thermostat always in one setting.

[7] This represents only the compressor and the condenser fan.

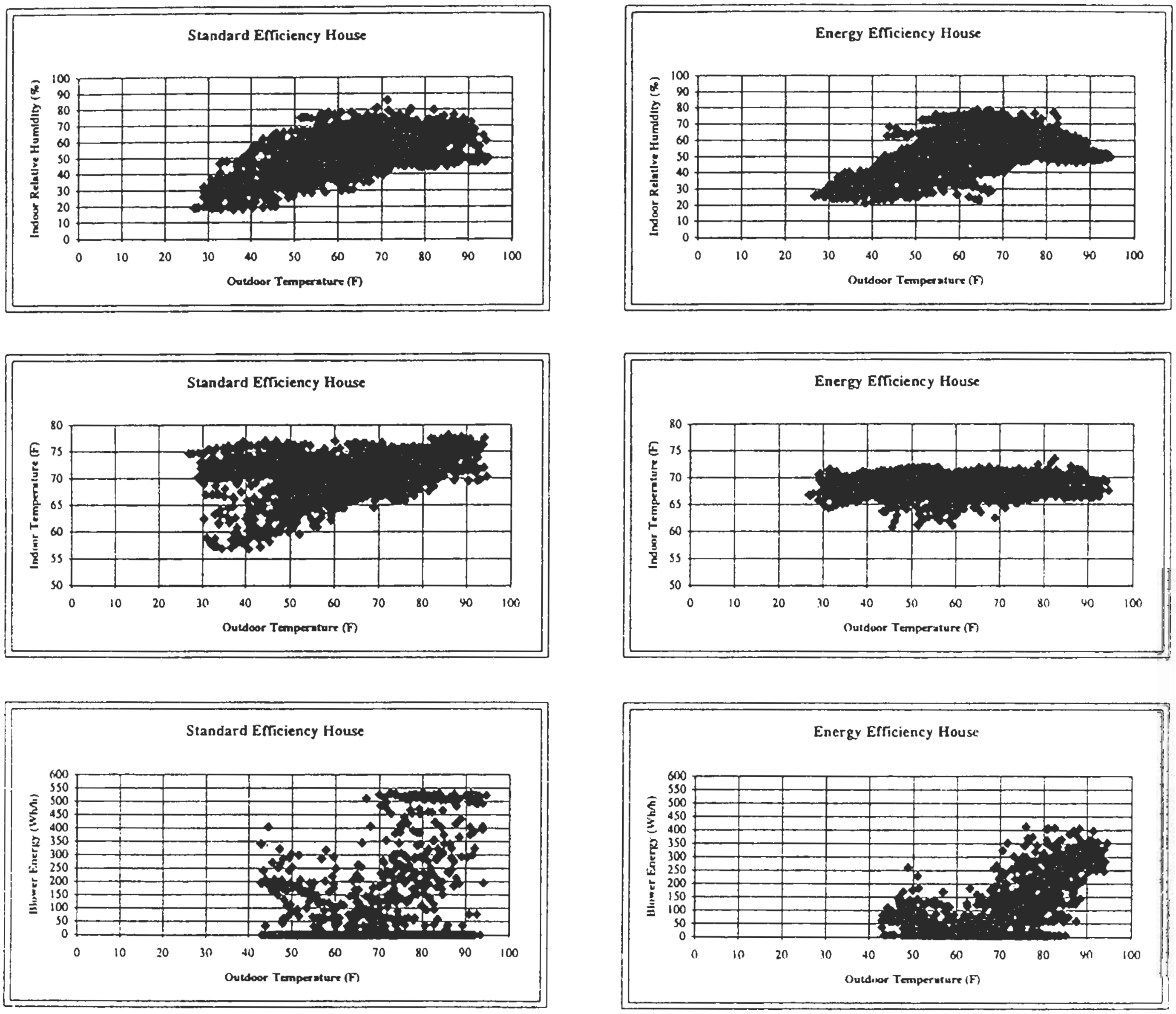
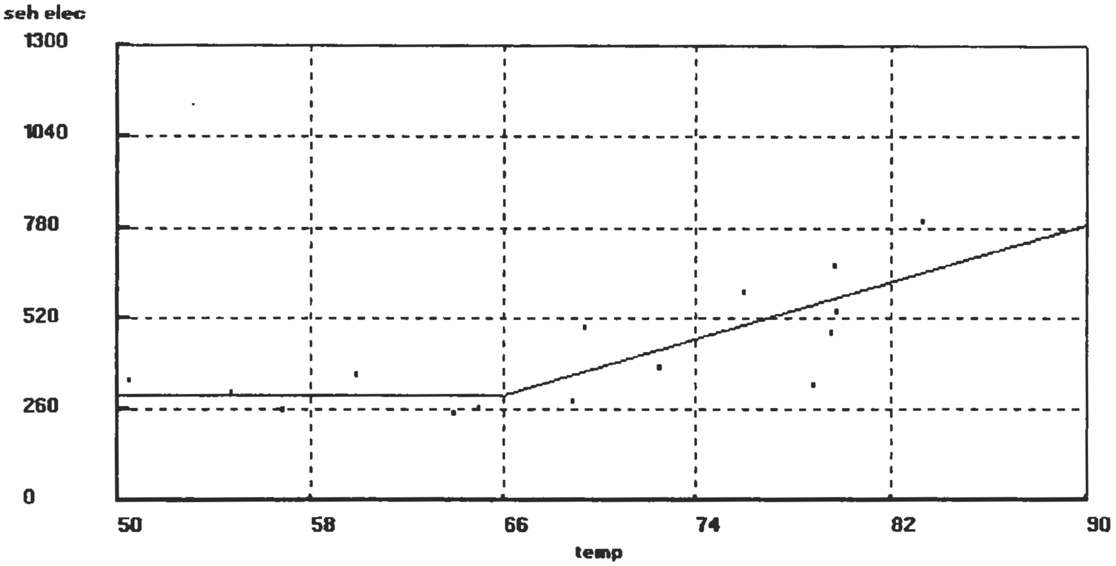


*Figure 4. Indoor Environmental Conditions and Fan Electricity Use for Both Houses. These graphs display comparative environmental conditions for both houses, including the temperature and relative humidity measured at the return air grill.*

1. confirming the building geometry with the an architectural rendering program (Huang 1993);
2. confirming the envelope materials/assemblies;
3. creating input parameters for space conditions using on-site data;
4. developing energy use profiles from hourly monitored, data;
5. entering the HVAC systems parameters using manufacturer's data, clamp-on measurement, hourly monitoring; and
6. fine-tuning the input data until the simulated results match measured data within an acceptable range.

**Building Geometry Data.** The building geometrical data were obtained from the architectural drawings. The data were also confirmed with site observation and measurements. After the building geometrical data were input into the DOE-2 model, an architectural

*Standard Efficiency House (SE) Electricity Use*



*Energy Efficient House (EE) Electricity Use*

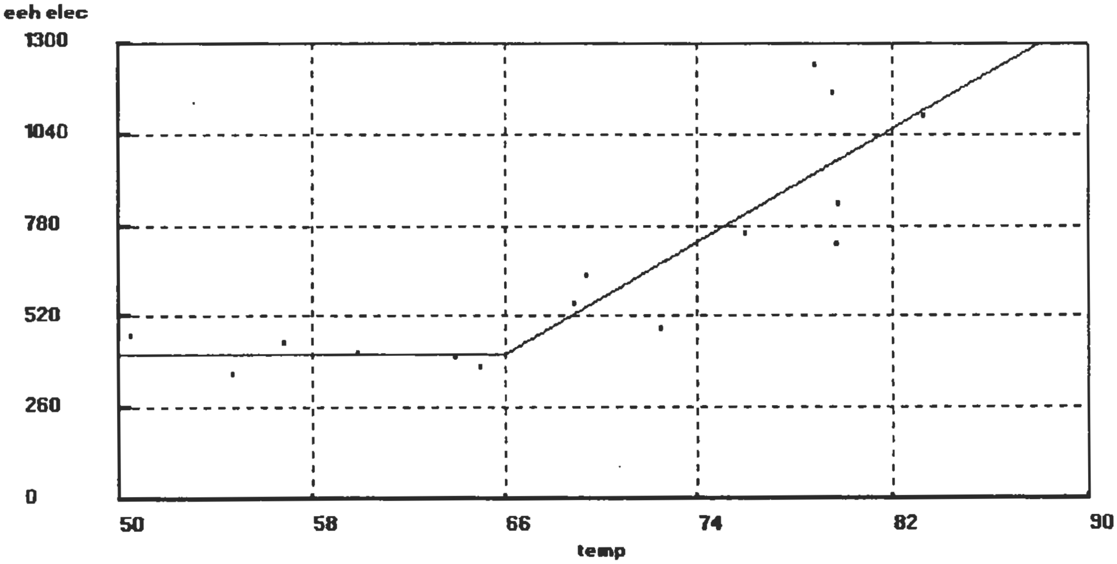
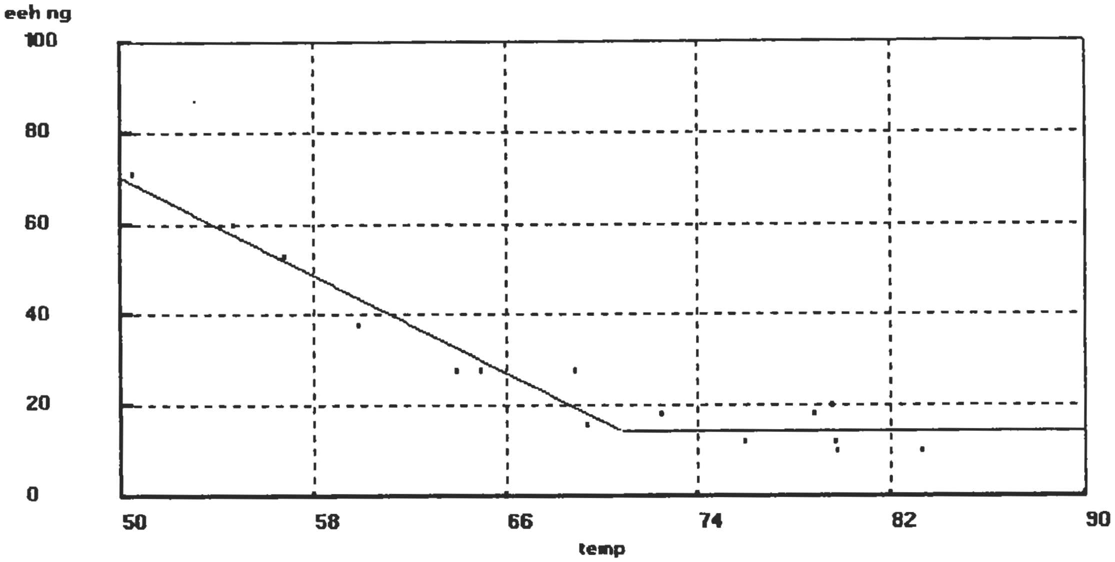


***Figure 5.*** *Monthly Electricity Utility Data for the SE and EE Houses. These figures display the results of a 3 parameter analysis of the monthly electricity use for the SE house (upper graph) and EE house (lower graph).*

rendering program, (Huang 1993), was used to check the accuracy of the geometrical data in the DOE-2 model. Figure 7 shows an architectural rendering of one of the houses using the program (Huang, 1993) that sketches the actual BDL input file and hence was used to verify the placement and orientation of the building's walls, roof, windows, and doors. The adjacent houses were simulated as "building shades" which were represented as opaque shades in the DOE-2 model.

*Energy Efficient House (EE) Natural Gas Use*



*Standard Efficiency House (SE)Natural Gas Use*

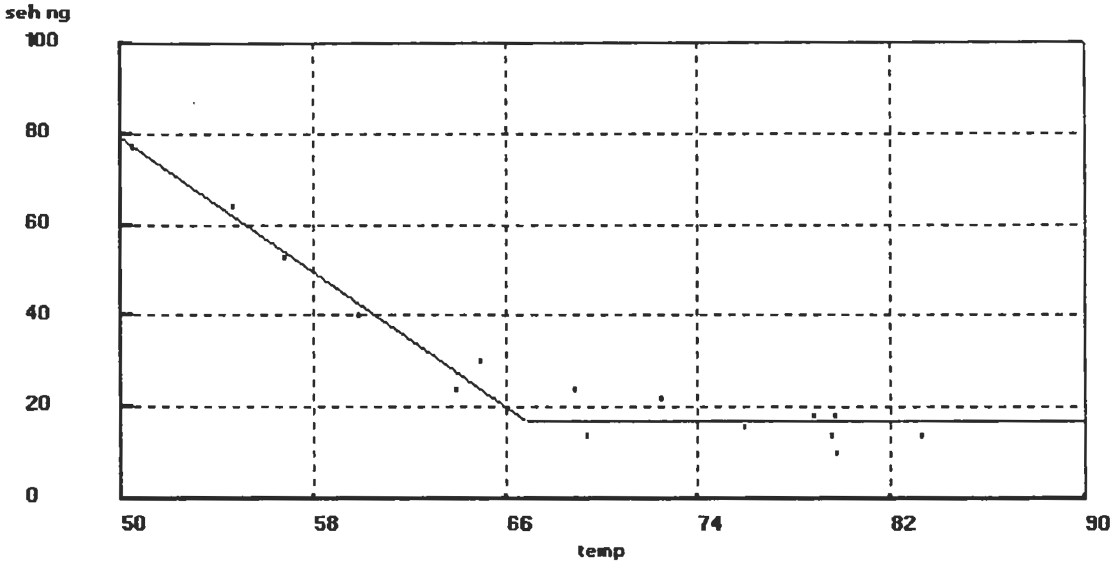


***Figure 6.*** *Monthly Natural Gas Utility Data for the SE and EE Houses. These figures display the results of a 3 parameter analysis of the monthly natural gas use for the SE house (upper graph) and EE house (lower graph).*

**Building Envelope Data.** The building envelope data were obtained from the architectural drawings, and confirmed with site observation and measurements. In the simulation, the thermal properties of the building envelope were defined based on the thermal property data published by several sources (LBL 1980; 1981; 1982; 1989). Later, these values were fine-tuned to calibrate the simulation model to measured data. Table 4 presents the summary of the envelope materials and thermal properties. Note that the wall studs were simulated as separate material assemblies. The "wall area" of the studs were calculated by adding the area of all outside surfaces of the studs.

The windows in the EE house are single pane clear glass with solar screens. The shading coefficients used in the DOE-2 program were based on solar transmittance measurements taken on-site with a photovoltaic-type sensor. These measurements, combined with manufacturer's data yielded shading coefficients that were used in the program.

**Zone Description.** The building was zoned into one conditioned living space (1,048 sq. ft.) and one unconditioned attic space directly above, which includes a small area over the porch (1,104 sq. ft.). The living room, kitchen, three bedrooms, bathroom, and utility room were simulated as one conditioned zone.

**Use Profiles.** Electricity used by lights and receptacles are the weather-independent loads in the building. Therefore, to calibrate the simulated electrical consumption, it is essential to first calibrate these weather-independent loads so that the calibration process could then be focused on matching the weather-dependent loads only.

The electricity usage profiles for lighting and receptacles were developed from hourly measured data for each calibrated period. The simulated electricity use for these loads was later compared to measured data to assure that these loads matched measured data. The hourly electrical consumption (in kWh/h) was obtained by subtracting measured fan and A/C electricity use from the measured whole-building electricity use. Figure 8 shows the measured lighting and receptacle electricity use compared to the simulation model for the period of March 17-30, 1997.

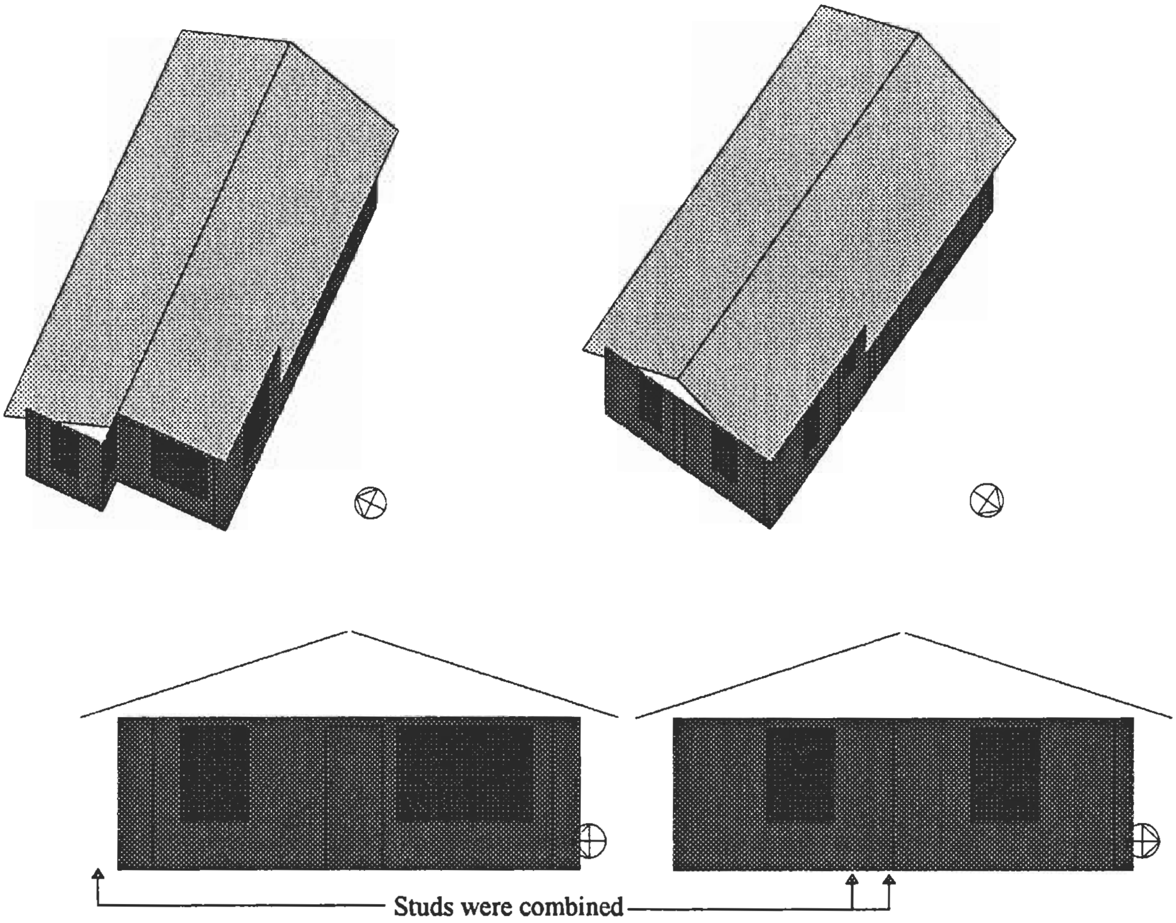
Measured indoor temperatures, obtained by monitoring the return temperature in the living space, were used to define the simulated space temperatures. Figure 9 shows an example of the simulated indoor temperature versus the measured indoor temperature for the calibration period of March 17-30, 1997. The coincident ambient temperatures are also indicated in the figure as a dashed line to provide a visual comparison of the effect of the ambient temperatures on the zone temperatures.

**HVAC Systems.** The HVAC system in the EE house was simulated using data from the following sources: site visits to read the nameplate data, manufacturer's data, on-site and clamp-on measurements, and hourly monitoring. Nameplate data from the manufacturer was also used to define the custom DOE-2 system performance curve-fits. Manufacturer's data on the HVAC systems and water heater are summarized in Table 5. On-site measurements include: clamp-on measurement of the fan electricity use (kW), and measurement of the supply air-flow rate (CFM)

**Fine-tuning (calibrating) the Simulation Model.** The calibration of the simulation model to match measured data included the following steps:

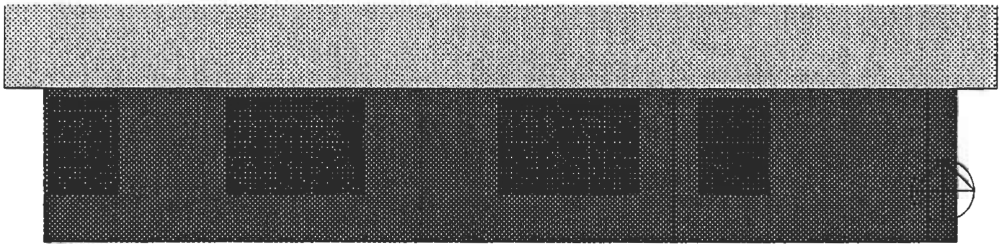
1. Develop a simulation input file based on a calibrated simulation as discussed.
2. Prepare the DOE-2 weather file based on on-site hourly monitoring of the outdoor temperature, relative humidity, average wind speed, and solar radiation.
3. Simulate the building for several short periods -- two weeks during the winter/swing season, and two weeks during summer season.
4. Use measured monthly average ground temperature (i.e., City of Houston water temperatures).
5. Compare the weather-independent components to the measured data to assure that they represented the actual weather-independent electricity use.
6. Compare the whole-building, fan, and AC electricity use to measured data.
7. Compare the indoor (living space) temperature to measured data.
8. Compare the attic temperature to measured data.
9. Tune the input parameters that affect the discrepancies. These include tuning and/or entering:
    - Thermal properties of the floor,
    - Custom weighting factors (furniture included),
    - Roof absorptivity,
    - Window shading coefficient,
    - Thermostat settings,
    - Performance curve-fit a for the cooling system, and
    - Fan supply kW.

**Example Calibration Results for March 1997.** To analyze whether the simulation matched the measured data, several evaluations were performed. First, time series plots of measured and simulated results were developed for the following components: (1) indoor temperature, (2) electricity use for lighting and receptacles, (3) whole-building electricity use, and (4) AC electricity use. Hourly values of the measured and simulated results were also plotted against outdoor temperatures. Finally, the hourly root mean squared error (RMSE) and CV(RMSE) of the whole-building electricity and indoor (space) temperature were calculated for each calibration result.



Front Elevation

Back Elevation



Side Elevation

***Figure** 7. Energy-efficient house as input in DOE-2 model and viewed with DrawBDL program*

Besides using data as discussed above, the calibration for this period included inputting and/or adjusting the following input parameters:

- AC system performance curve-fit, developed from the manufacturer's data
- Custom weighting factors -- that is, to take the furniture into account, for example:

  FURN-FRACTION = 0.3 (30% of floor is covered by furniture)

  FURNITURE-TYPE = HEAVY (estimated from the weight of furniture)

  FURN-WEIGHT = 2.5

- Floor conductance, from 0.7576 to 1.0417,
- Infiltration rate, from 0.3 (estimated) to 0.75 (measured),
- Attic infiltration rate and ceiling weight.

Figures 9 to 11 show the results of the calibration in March 1997. These figures clearly show that the simulation is closely tracking the zone and attic temperatures, and does a reasonable job at tracking the measured electricity use during this period. When developing a calibrated simulation of a building it is important to demonstrate that the simulation matched the measured data for the same period. Once this is accomplished the simulation input file declared "calibrated" and is then modified to represent average schedules and annual energy is simulated using average year weather data.

A closer look at Figures 9-11 reveals that there was very good agreement between the simulated and measured zone temperature and the simulated verses measured whole-building electricity use. However, there appears to be less evidence of agreement with the simulated verses measured attic temperature during the late evenings as shown in Figure 10 where it can be seen that the measured temperatures in the evening do not dip down as low as the simulated temperatures. Since the attic is an unconditioned zone that also has an insulating layer between it and the house this could be indicating any one of several things, including: i) higher temperatures due to the presence of the water heater in the attic, ii) the possibility of having a greater thermal connection between the attic and the house (i.e., the open hatch between the furnace and the house), iii) potentially too much infiltration and/or to much heat loss in the simulation model.

During the site visits it was noted that the approximately 2x4 ft. door which is supposed to cover the furnace (which sits in a closet that is directly connected to the attic through the top of the closet) was never installed in the EE house. In the winter time, when the attic becomes colder than the house, this could be a very strong mechanism for transferring heat between the utility room and the attic which would keep the attic a few degrees warmed than simulated.

The results of the staged calibration process are presented in Figures 12 and 13 and Table 6. In the first phase no curve fits or custom weighting factors were used. In the second phase an HVAC curve fit is entered which more accurately represented the unit. Unfortunately, this worsened the CV(RMSE) of the electricity use and interior temperature. In phase three custom weighting factors are added to more accurately represent the thermal mass in the building which decreased the CV(RMSE) of both the electricity and interior temperature, light furniture was used. In phase four the conductance of the floor was raised to couple the space more strongly to the concrete slab and heavy furniture was used which improved the CV(RMSE) of the electricity use and the temperature. In phase five the air-change rate was changed to 0.4 from 0.3 which improved the CV(RMSE) of both the electricity use and the interior temperature. In phase six the air-change rate was returned to 0.3 with only a modest decrease in the CV(RMSE) of the interior temperature. In phase seven internal electric loads were adjusted using actual electricity use profiles. In phase eight the air-change rate was increased to 0.75 with a small improvement in the CV(RMSE) of the electricity use and no change in the CV(RMSE) of the interior temperatures. Finally, in phase nine the attic infiltration rate and floor weight were adjusted to improve both the CV(RMSE) of the electricity use and the interior temperature.

It is clear from the results that the first five modifications to the input file produced the most differences in improving the accuracy of the simulation for the March test period. These included:

1. adding a custom curve fit for the HVAC system,
2. adding custom weighting factors for the house,
3. modifying the furniture fraction,
4. modifying the air change rate, and
5. modifying the floor conductance.

Modifications VI through XI also produced additional improvements to the accuracy of the simulation but these had a smaller impact on the calibration process.

These included modification of the air change rate, and adjustments to the attic and infiltration and ceiling weight.

At this point the model was declared "calibrated" and the input file for the model was then prepared to evaluate the energy savings from the energy conservation retrofits that were applied to the EE house. To accomplish this the input file was modified in the following ways (Bou-Saada et al., 1998):

1. the schedules were changed to represent average schedule which reflected the average occupancy for the house,
2. the space temperatures were set to reflect the different scenarios that were being simulated,
3. average weather year data were used for the whole year to calculate the annual energy use.

When improved air conditioner (SEER=12), actual window shading, and actual infiltration were combined the annual cooling energy use was reduced by 23.5%, the fan energy use remained constant, and the heating energy use increased by 1.4%. The total annual savings for the combined ECRMs represented a 11.0% reduction in the annual electricity use and a 0.8% increase in the annual natural gas use, which results in a 7.9% reduction in the total utility bills, a $71 reduction in total utility costs. These results confirm that the A/C ECRM worked as expected. However, for various reasons, the solar shading, DHW modification and house tightening could not be verified with the simulation (Haberl et al. 1998).

## SUMMARY

This paper described a project where selected energy conservation measures in two Habitat for Humanity houses in Houston, Texas were measured using side-by-side measurements of identical houses and calibrated simulation. The focus of this paper included the description of the instrumentation installed in the houses and the efforts that were undertaken to calibrate the DOE-2 simulation to the energy efficient house. The calibrated DOE-2 simulation was needed to remove the confounding effects that masked the savings from the energy conservation retrofits. These confounding effects are evident when one inspects the monthly utility bills which indicated that the Energy Efficient house was consuming more energy than the Standard Efficiency house. The results of the calibrated simulation show that the improved air conditioner did save the intended amount of energy once the confounding effects are removed in the simulation. Additional details about the calculation of savings with the calibrated simulation can be found in Bou-Saada et al. (1998) or in the paper by Haberl et al. (1998).

## ACKNOWLEDGMENTS

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*Table 4. Envelope material/assembly of the Simulated Energy-Efficient House*

| Component | Assembly (out-in) | Thickness ft | Conduct. $\frac{Btu\text{-}ft}{hr\text{-}ft^2\text{-}F}$ | Density $\frac{lb}{ft^3}$ | Sp. Heat $\frac{Btu}{lb\text{-}F}$ | R-Value $\frac{hr\text{-}ft^2\text{-}F}{Btu}$ |
|---|---|---|---|---|---|---|
| Roof | Fiberglass shingles | | | | | 0.21 |
| | Plywood 1/2" | 0.0417 | 0.0667 | 34 | 0.29 | - |
| Ceiling | Blown insulation 18" | 1.5 | 0.025 | 6 | 0.20 | - |
| | Frame, wood 3.5" | 0.2917 | 0.0667 | 32 | 0.33 | - |
| | Gypsum board 1/2" | 0.0416 | 0.0926 | 50 | 0.20 | - |
| Wall | Vinyl siding | | | | | 0.0004 |
| | Styrene 1/2" | 0.0417 | 0.0200 | 1.8 | 0.29 | - |
| | Plywood 1/2" | 0.0417 | 0.0667 | 34 | 0.29 | - |
| | R-11 batt insulation* | 0.2957 | 0.0250 | 6 | 0.20 | - |
| | Gypsum board 1/2" | 0.0416 | 0.0926 | 50 | 0.20 | - |
| | *) for the studs, wood 3-1/2" is used instead of the batt insulation | | | | | |
| Floor | Concrete 4" | 0.3333 | 0.7576 | 140 | 0.20 | - |
| | Linoleum tile | - | - | - | 0.30 | 0.21 |
| Doors | Metal sheet | 0.0050 | 26.0 | 480 | 0.10 | - |
| | Polyurethane 1.25" | 0.1042 | 0.0133 | 1.50 | 0.38 | - |
| | Metal sheet | 0.0050 | 26.0 | 480 | 0.10 | - |

*Table 5. Summary of the HVAC systems in the standard and energy-efficient houses.*

| SYSTEM | Standard-efficient house | Energy-efficient house |
|---|---|---|
| 1. Cooling | Goodman<br>Model # CK24-1B (outdoor)<br># U-30 (indoor)<br>SEER = 10 | Carrier<br>Model # 38BR024-30 (outdoor)<br># CD5BA024 (indoor)<br>SEER = 12 |
| 2. Heating | Goodman<br>Model # GNP 050-3<br>Input = 45,000 Btu/hr.<br>Output = 36,000 Btu/hr. | Resco<br>Model # GB1AAV024045, C series<br>Input = 44,000 Btu/hr.<br>Output = 35,000 Btu/hr. |
| 3. Water heater | Rheem<br>Model # 21V40-7<br>Natural Gas<br>Input 34,000 Btu, 40 gallon | State<br>Model # PRV-30-NOLSO<br>Natural Gas<br>Input 28,000 Btu, 29 gallon |

***Table 6.*** *RMSE and CV(RMSE)*[8] *of whole-building electricity use and indoor temperature from adjusting input parameters, for the period of March 17-31, 1997*

| Phase | Input Parameters | RMSE and CV(RMSE) of WBE | RMSE and CV(RMSE) of Temp |
|---|---|---|---|
| I | Fan = 0.36 kW, no HVAC curve-fit, no custom weighting factors, air changes = 0.3, floor conductance = 0.7576 Btu/ft2-hr-F | 0.52 kWh<br>(45.71%) | 0.97 F<br>(1.43%) |
| II | Fan = 0.36 kW, with HVAC curve-fit, no custom weighting factors, air changes = 0.3, floor conductance = 0.7576 Btu/ft2-hr-F | 0.54<br>(49.31%) | 1.02<br>(1.48%) |
| III | Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3, floor conductance = 0.7576 Btu/ft2-hr-F, light furniture | 0.43<br>(32.32%) | 0.91<br>(1.39%) |
| IV | Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3, floor conductance = 1.0147 Btu/ft2-hr-F, heavy furniture | 0.38<br>(25.37%) | 1.17<br>(1.58%) |
| V | Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.4 ACH, floor conductance = 1.0147 Btu/ft2-hr-F, heavy furniture | 0.30<br>(15.71%) | 0.95<br>(1.5%) |
| VI | Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3 ACH, floor conductance = 1.0147 Btu/ft2-hr-F, heavy furniture | 0.30<br>(15.71%) | 1.0<br>(1.46%) |
| VII | Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3 ACH, floor conductance = 1.0147 Btu/ft2-hr-F, heavy furniture, adjust other load | 0.25<br>(10.84%) | 1.0<br>(1.46%) |
| VIII | Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.75 ACH, floor conductance = 1.0147 Btu/ft2-hr-F, heavy furniture, adjust other load | 0.25<br>(10.62%) | 1.0<br>(1.46%) |
| IX | Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.75 ACH, floor conductance = 1.0147 Btu/ft2-hr-F, heavy furniture, adjust attic infiltration rate and ceiling weight | 0.24<br>(10.24%) | 1.03<br>(1.48%) |

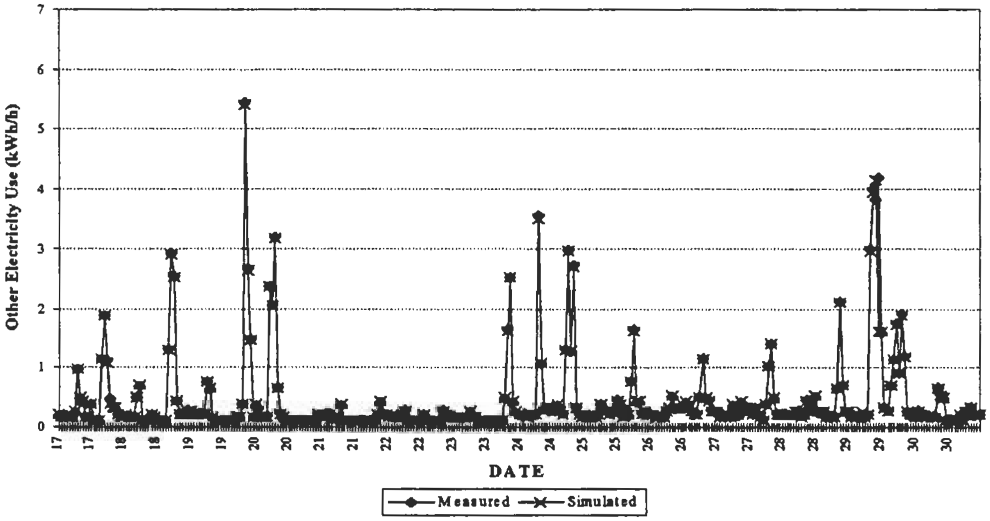

***Figure 8.*** *Simulated and measured lighting and receptacle electricity use.*

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[8] The hourly RMSE of Whole-Building Electricity is in kW, RMSE of indoor temperature is in degree F.

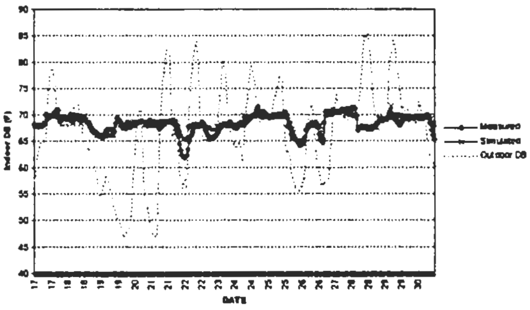

*Figure 9. Simulated and measured indoor temperature for the period of March 17-30, 1997.*

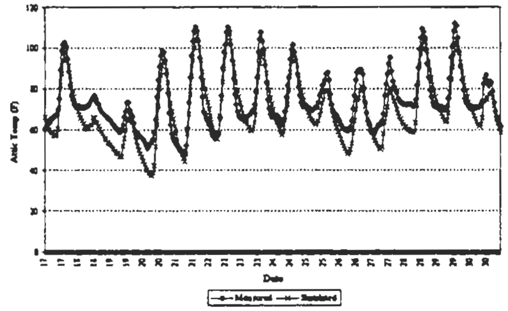

*Figure 10. Simulated and measured attic temperature, March 17-30, 1997*

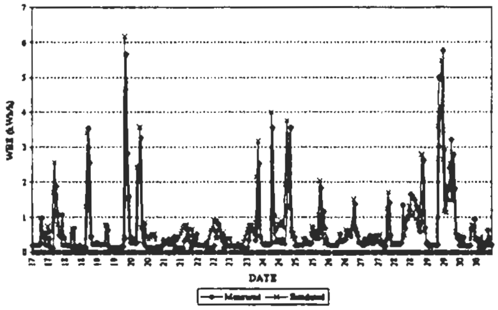

*Figure 11. Simulated and measured whole-building electricity, March 17-30, 1997*

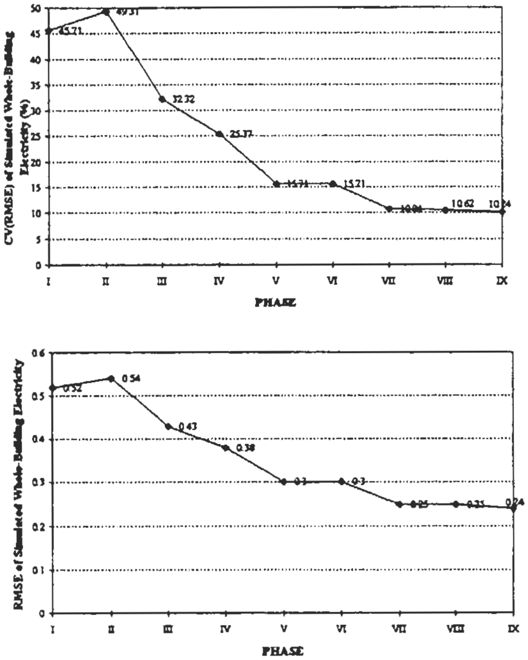

*Figure 12. Calibration results for March 17-30, 1997, as shown with: (a) the CV(RMSE) and (b) RMSE, of the Whole-building electricity use*

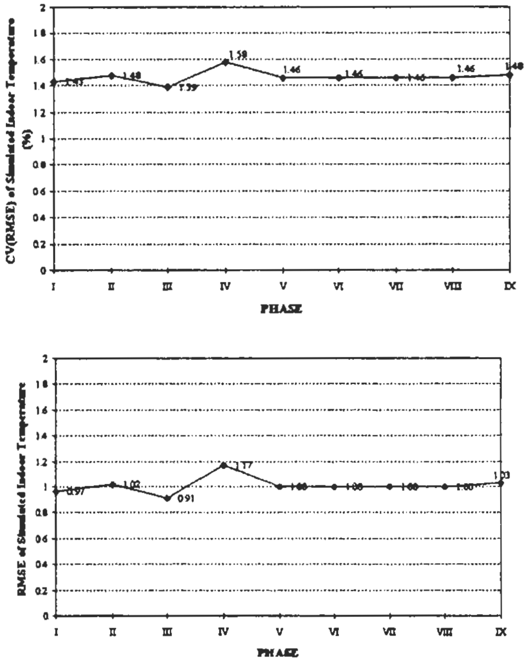

*Figure 13. Calibration results for March 17-30, 1997, as shown with: (a) the CV(RMSE), and (b) RMSE, of the indoor temperature*