A High-Quality Residential Data Set for Validation of Computer Simulation Models

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ABSTRACT

Four new identical unoccupied production homes have been operated for two years in Fort Wayne, Indiana, to compare the heating and cooling energy performance of alternative glazing systems with and without interior shading. The homes provide data for north/south and east/west glazing orientation and three glazing types with and without light- and dark-colored interior shades. The operation of each home is controlled and documented with a data logger, which also provides simulated internal sensible and latent gains. On-site weather measurements include wind speed, temperature, humidity, and high-quality solar radiation measurements of incident solar radiation on each building façade and horizontal.

For this paper, a data set has been prepared that will allow simulation program developers to test the ability of their models to accurately represent the hourly operation of typical production housing and the impact of alternate glazing and shading systems over an entire year. The data set includes an hourly weather file formatted to work with TRNSYS. A description of the homes, including plans, energy-related specifications, operational schedules, and measurements of air leakage and HVAC system characteristics is included. The data set includes measured hourly indoor temperatures, total heating and cooling loads, and energy consumption.

INTRODUCTION

Although many of today's residential building energy simulation software programs have at one time been calibrated using the BESTEST procedure (Judkoff and Neymark 1995a, 1995b), seldom does the opportunity exist to compare simulations to a detailed set of measured data from unoccupied houses. The houses in this case were constructed by a major glazing manufacturer for the purpose of researching the thermal comfort and energy impacts of window products. The houses, located in Fort Wayne, Indiana, are typical two-story production houses with full basements and forced-air HVAC systems. Construction was completed in the summer of 2004 and data measurements began in August of that year. The houses are identical except for the window glass, which can be changed in a matter of hours to facilitate different fenestration studies. Two of the houses face east and the other two houses face north (Figure 1).

INSTRUMENTATION

Each house is equipped with a multichannel scientific data logger that is used to collect data as well as control the HVAC system. Data are measured at 15-second intervals and averaged and stored every minute and hour. Information on accessing a floor plan showing the location of most sensors is provided in the Appendix.

Temperature sensors consist of a type T thermocouple extension wire with an initial calibration tolerance per ASTM E230 (ASTM 2003) and ANSI MC96.1 (ANSI 1982) of 0.5°C (0.9°F). Indoor air temperatures are measured using type T thermocouples enclosed within radiant shields aspirated with a small fan and suspended from the middle of each room, as shown in Figure 2. The attic and garage air temperatures are also measured this way. Black globe temperatures are measured on a limited basis using type T thermocouples enclosed within thin black glass globes, as shown in Figure 3.

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Figure 1 View of houses from the north.

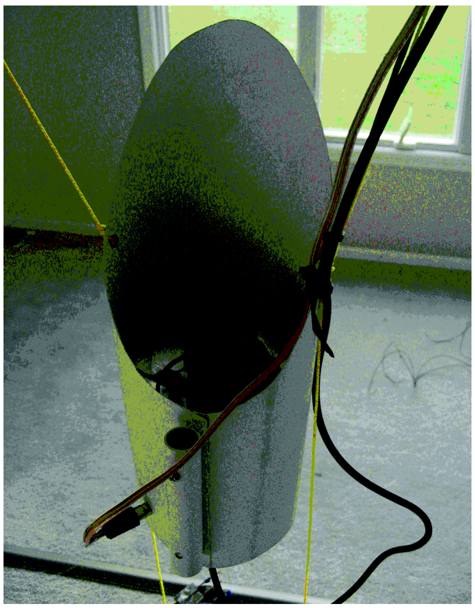

Figure 2 Shielded and aspirated thermocouple.

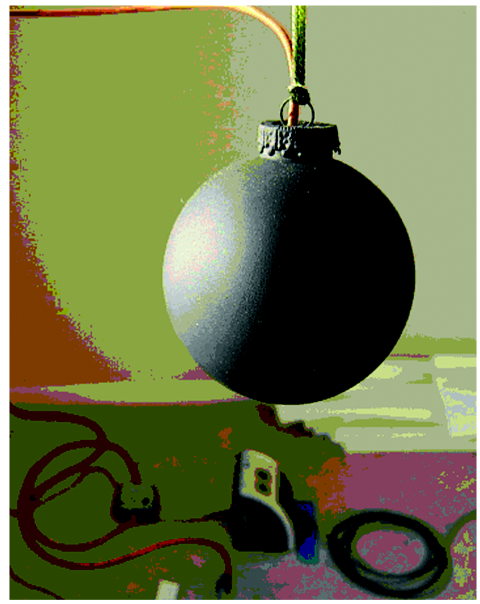

Figure 3 Thermocouple in black globe.

A limited number of interior window surface temperatures are measured for nighttime heating season studies, but readings during periods of direct solar radiation do not accurately represent the surface temperature. Two arrays of eight thermocouples are used to measure the supply air temperatures in each of the main ducts near the furnace, and measured airflows are provided for each main duct. Redundant outdoor temperature sensors were mounted on the north side of house 3235, as shown in Figure 4. A conventional louvered radiation shield was used for one enclosure while a second apparatus utilized an aspirated enclosure.

Humidity sensors have an operating range of 0% to 98% RH and an accuracy of ±3% (0%–90% RH) and ±5% (90%–98% RH). Indoor, outdoor, and return air humidities are measured.

Electrical energy is measured with true RMS AC watt-hour transducers with pulse output (solid-state relay closure) proportional to kWh consumed. The accuracy is 0.45% of reading plus 0.05% of full scale through the 25th harmonic. The following end uses are recorded as separate measurements as shown in Figure 5: whole-house, condensing unit, air handler, sump pump, vaporizer, and basement heaters.

Solar radiation is measured using two different pyranometers on a horizontal plane and for each cardinal direction on a vertical plane, as shown in Figure 6. One brand of pyranometers has a spectral range of 400 to 1100 nm, with an absolute error in natural daylight of ±5% maximum, ±3% typical. Sensitivity is 0.2 μV/W/m. The other type of pyranometer is fully compliant with ISO-9060 (EN 1990) and has a spectral range of 350 to 2800 nm with a nonlinearity of ±0.6% (<1000 W/m) and a directional error less than ±10 W/m (beam 1000 W/m). Sensitivity is 4–6 μV/W/m.

Wind speed is measured using a three-cup anemometer with a starting threshold of 0.45 m/s (1.0 mph) and an accuracy of 0.11 m/s (0.25 mph) or 1.5%.

Condensate from the air-conditioning system is measured using a tipping bucket.

RESEARCH HOUSE SPECIFICATIONS

The houses were built specifically for research purposes, and construction was closely supervised to ensure that all four houses were as identical as possible.

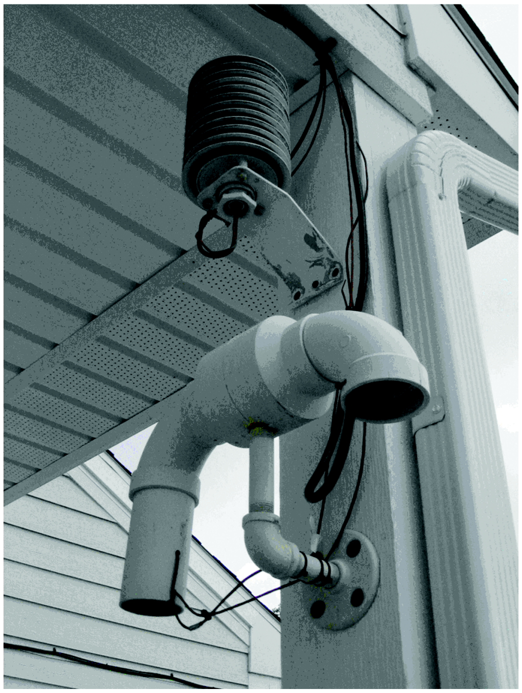

Figure 4 *Outdoor temperature and humidity sensors.*

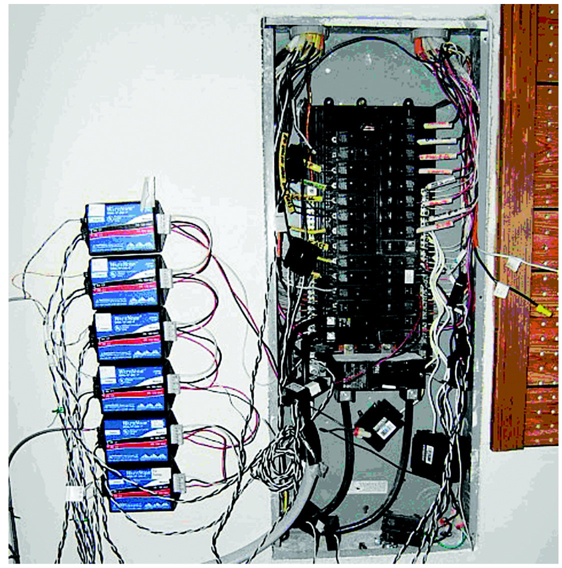

Figure 5 *Watt transducers.*

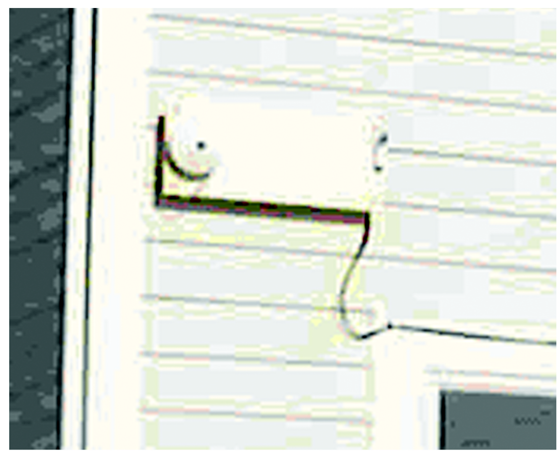

Figure 6 *Pyranometer installation.*

Drawings and Dimensions

Information on accessing a site plan, floor plans, and a typical building section can be found in the Appendix, although window dimensions on the drawings should be disregarded. Information on accessing a separate reference file containing dimensions and specifications for each window opening is provided in the Appendix. Ceiling heights are 2.4 m (8 ft.).

Building Envelope

Exterior above-grade walls consist of 13 mm (0.50 in.) foil-faced RSI-0.58 (R-3.3) polyisocyanurate rigid foam sheathing and 2 × 4 wood frame construction with 19 mm (0.75 in.) closed-cell polyurethane spray foam insulation (Figure 7) and RSI-1.94 (R-11) fiberglass batts in the wall cavity. But, due to compression of the fiberglass batt, the R-value is reduced by 24% (R-13.6 nominal). Building corners are sheathed with 13 mm (0.50 in.) structural fiberboard wall sheathing with a thermal resistance of RSI-0.23 (R-1.3). The overall thermal resistance of the exterior wall with a 20% framing factor is RSI-3.06 (R-17.4) at mid-wall locations and RSI-2.85 (R-16.2) at the corners. The house/garage wall has an overall thermal resistance of RSI-2.38 (R-13.5). Information about accessing calculations can be found in the file listed in the Appendix.

Basement walls consist of 0.20 m (8 in.). poured concrete insulated with unfaced RSI-1.94 (R-11) fiberglass batts in an interior frame wall covered with a polyethylene sheet on the inside surface of the insulation.

The basement ceiling is insulated with RSI-3.35 (R-19) fiberglass batts to enable the basement heating and cooling loads and energy use to be isolated from the rest of the house.

Attic insulation consists of RSI-6.7 (R-38) blown-in cellulose insulation. Roofs have asphalt shingles and the attic is vented.

Floors over unconditioned spaces such as the garage are insulated with unfaced RSI-3.3 (R-19) fiberglass batt insulation.

Measured airtightness for each house was very similar. Blower Door™ results were 385 ± 8 L/s at 50 Pa (815 ± 16 cfm at 0.20 in. w.c.). Detailed results can be found in the Infiltration.xls summary file listed in the Appendix.

Figure 7 *Application of closed-cell foam insulation.*

Fenestration

Three different glazing products are available for field studies. Glazing was changed according to the dates in Table 1. All window glazings were replaced according to the schedule except for the window in the second story of the front foyer, which remained a Low Solar Gain Low-E (LSLE) type for the entire year. A separate Microsoft® Excel® file with specific areas and window specifications for each window opening is listed in the Appendix.

- Clear: U = 2.51 W/m·K (0.442 Btu/h·ft·°F) and SHGC = 0.590
- Low Solar Gain Low-E (LSLE): U = 1.71 W/m·K (0.302 Btu/h·ft·°F) and SHGC = 0.342
- High Solar Gain Low-E (HSLE): U = 1.77 W/m·K (0.312 Btu/h·ft·°F) and SHGC = 0.484

Shading

Interior canvas window blinds were used periodically in each house to evaluate the effects of black or white blinds. Blinds were placed on all windows except in the second story of the front foyer. Window blinds were changed according to the schedule in Table 2. No blinds were used prior to July 20.

HVAC

Each house is equipped with a single-stage forced-air heating and cooling system consisting of a gas-fired furnace and a direct expansion (DX) "split" cooling system. Due to the variations in cooling loads caused by the characteristics of the different window glazings, the HVAC systems in the homes have different nominal cooling capacities, as shown in Table 3. Total airflows, as measured by the Duct Blaster™ method, were used to calculate the sensible cooling output of the system.

Table 1. Window Glazing Schedule

Time Period	House Number			
	10803	10905	3219	3235
12/17/04 to 10/9/05	HSLE	LSLE	HSLE	LSLE
10/11/05 to 12/31/05	Clear	LSLE	Clear	LSLE

Table 2. Interior Shading Schedule

Start Date	House Number			
	3219	3235	10803	10809
7/20	Black	Black	White	White
7/27	None	None	None	None
8/3	White	White	Black	Black
8/10	White	White	Black	Black
8/17	White	White	Black	Black
8/24	Black	Black	White	White
8/31	Black	Black	White	White
9/7	None	None	None	None

Cooling System Performance. The nominal efficiency rating of the cooling systems is 3.28 COP (11.2 SEER). Cooling system performance variables included in the data sets are shown in Table 4. The systems were typically controlled based on the calculated average of all the room temperatures, but individual room temperatures could also be used. Information about accessing a performance map file compiled from the manufacturer's engineering data and formatted for TRNSYS Type 756b (TRNSYS 2006) is included in the Appendix as well as the manufacturer's engineering data files for the equipment.

Heating system performance was not included as part of the study. Instead, room temperatures were precisely maintained by the data acquisition system via individual electric space heaters in each room using the thermocouple in the same room. The heating setpoint temperatures for the house and basement can be found in columns BZ and CA. The "enabled" status of the house and basement heating is located in columns EI and EL.

Ventilation is provided by a single-point supply system that continuously delivers 34 L/s (70 cfm) of unconditioned outdoor air directly into the living room. The status of the ventilation system is recorded in column FL.

Duct leakage to outdoors is 1% of system cooling airflow at 25 Pa (0.10 in. w.c.). The entire air distribution system is fully ducted and within conditioned space.

Table 3. HVAC System Nominal Cooling Capacities (kW [MBH]) and Airflows—(L/s [cfm])

House Number	10803	10905	3219	3235
Cooling capacity	14.1 (48)	10.6 (36)	14.1 (48)	10.6 (36)
Kitchen	67 (142)	52 (110)	54 (114)	54 (114)
Powder	11 (23)	9 (19)	9 (20)	9 (20)
Utility	9 (19)	9 (19)	8 (18)	8 (18)
Nook	59 (125)	34 (72)	17 (37)	17 (37)
Great room (left)	62 (131)	48 (101)	55 (117)	55 (117)
Great room (right)	8 (16)	8 (16)	13 (28)	13 (28)
Dining	56 (119)	36 (77)	28 (60)	28 (60)
Entry	9 (20)	12 (25)	7 (15)	7 (15)
Total, first floor	**281 (595)**	**207 (438)**	**193 (409)**	**193 (409)**
Bath	31 (65)	25 (52)	25 (54)	25 (54)
M. closet	17 (37)	32 (68)	19 (41)	19 (41)
M. bed (right)	46 (97)	9 (19)	9 (20)	9 (20)
M. bed (front)	48 (101)	38 (80)	39 (83)	39 (83)
Bed 4	57 (121)	44 (93)	44 (93)	44 (93)
M. bath	34 (72)	27 (58)	35 (75)	35 (75)
Bed 3	45 (96)	39 (83)	37 (78)	37 (78)
Bed 2	41 (86)	29 (61)	22 (47)	22 (47)
Total, second floor	**319 (675)**	**242 (514)**	**231 (491)**	**231 (491)**
Total (sum of outlets)	**599 (1270)**	**537 (1137)**	**417 (883)**	**425 (900)**
Total (Duct Blaster™)	**668 (1416)**	**489 (1036)**	**668 (1416)**	**498 (1055)**

Table 4. Cooling System Variables

Variable	Column	Units	Notes
Fractional runtime	AA	Fraction	
Cycles per hour	AB	Cycles/h	
Refrigerant liquid temp.	DR	°C	Coincident with operation
Refrigerant hot gas temp.	DS	°C	Coincident with operation
Set point temperature	ED	°C	°C
Deadband temperature	EE	°C	°C
Control temp. location	EF	Integer	0 = Tavg, 1 = Dining, 2 = Living, 3 = Kitchen, 4 = Laundry, 5 = BR2, 6 = BR3, 7 = BR4, 8 = MBath, 9 = MBR, 10 = Closet, 11 = Thermostat
Sensible load	GB	kWh	Calculated from one-time airflow measurement and continuously monitored supply and return air temperatures.
Latent load	GC	kWh	Calculated from tipping bucket measurement and a heat of vaporization constant of 0.594 kWh/kg.
Total load	GD	kWh	kWh

Domestic Hot Water

Domestic hot water was not part of the research program and therefore the water heater was not on.

DATA SETS

A data set for each house is available for the year 2005. The files are in Microsoft® Excel® format and contain hourly measurements of temperatures, energy use, humidity, HVAC equipment status, and artificial internal gains. Weather data collected from the four houses is compiled in a separate file.

Input Data

Input data consist of annual hourly records of local weather, internal sensible and latent gains, and temperatures of unconditioned spaces, such as the attic and the garage.

Weather. An annual hourly weather file for TRNSYS Type 109 (TRNSYS 2006) was compiled from the site-measured data and local wind direction data from the Fort Wayne International Airport. Missing data for wind direction were filled in using the last and next known wind direction values. Wind direction relative to north = 0°. See Table 5 for the weather data file format.

Internal Gains. An artificial internal gains schedule was implemented during the cooling season for each house using portable electric heaters controlled by the central data acquisition system. A target total sensible gain of 879 W (3000 Btu/h) was split equally between the kitchen and the master bedroom. Latent gains were achieved by using the apparatus shown in Figure 8, which was confined to the kitchen. Deionized water is dispensed automatically into a container and salt is added manually to maintain a known salinity. Two household vaporizers are used to evaporate approximately 9.3 L/day (2.5 gpd). Water volume and electrical power to the vaporizers is metered. Latent loads are based on the measured water volume and compared to the electrical energy measurement to determine additional sensible gains due to heat loss through the sides of the container. A heat-of-vaporization of 594 W/kg (921 Btu/lb) was assumed. The sensible fraction of the energy used is approximately 43% for the entire cooling season. This fraction is applied to the measured hourly energy use and the product is added to the sensible gain for the kitchen. Hourly internal sensible gains for each room can be found in columns HL through HU of the "data" worksheet in each data set. Total internal gains are found in column HV. Latent internal gains for the kitchen are found in column GT. Units are in liters for latent gains and kilowatt-hours for sensible gains.

Unconditioned space temperatures for the garage and attic are located in columns AP and AQ of the "data" worksheet in the data set. Surface temperatures of the basement floors and walls can be found in columns BA and BB. Basement wall temperature is measured at the interior face of the concrete, behind the insulation.

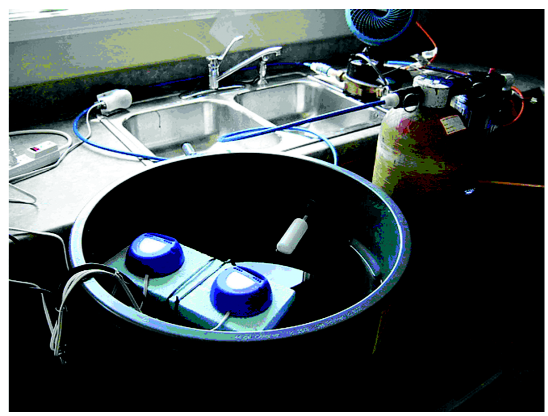

Figure 8 *Latent load apparatus.*

Table 5. Weather Data File Format

Column	1	2	3	4	5	6	7	8	9
Variable	Wind direction	Wind speed	Ambient temperature	Relative humidity	Global radiation				
					Horizontal	North	South	East	West
Units	degrees	m/s	°C	RH	W/m	W/m	W/m	W/m	W/m
Data	80	3.4	0.1	0.744	113.8	49.3	63.1	59.4	58.5

Table 6. Output Data

Variable	Column	Units	Notes
Room air temperatures	AE–AN	°C	
Indoor RH and coincident temperature	CE & CB	Fraction and °C	
A/C energy	S	kWh	Condensing unit only
Air handler energy	T	kWh	Cooling only
Basement heat energy	U	kWh	
Room heating energy	GY–HH	kWh	Does not include energy use for artificial internal gains

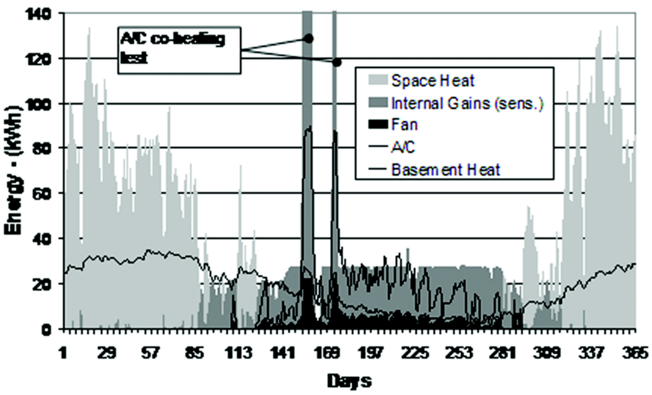

Figure 9 *Daily energy use—House 10803.*

Output Data

The majority of the data in the data set consists of output data such as indoor temperatures and humidity and energy consumption. Measured data for comparison to simulation outputs are listed in Table 6.

Figure 9 illustrates the major energy end uses for House 10803.

CONCLUSIONS

Four single-family homes were constructed in a mixed climate for the purpose of conducting building science research. Because the fenestration was predominately distributed on the front and back, the houses were oriented in pairs, with one pair facing north/south and the other facing east/west. Each house was equipped with a multichannel data acquisition and control system to record weather conditions, indoor air temperatures, humidity, and the resulting energy use of the heating and cooling system. Data were collected for a one-year period and compiled into hourly data sets for future evaluations and comparisons. Supporting documentation was compiled and made available to allow others to reconstruct building simulation models using various software packages.

ACKNOWLEDGMENTS

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APPENDIX

Reference Files

All reference files can be downloaded from www.ibacos.com.

Weather	FortWayne2005weather.txt
Drawings	
Site Plan	Site_Plan.pdf
Floor Plans	Floor_Plans.pdf
Wall Section	Wall_Section.pdf
Monitoring Plan	Monitoring_Plan.pdf
Data Sets	
House 3219	3219_2005.xls
House 3235	3235_2005.xls
House 10803	10803_2005.xls
House 10905	10905_2005.xls
Fenestration	Fenestration.xls
Exterior Walls	Fenestration.xls
Infiltration	Infiltration.xls
A/C Performance Map	AC_Performance.xls