Comparison of Measured and Calculated Residential Cooling Loads

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ABSTRACT

Sensible cooling extraction rates measured at four houses in Ft. Wayne, Indiana are compared to loads calculated with Manual J Eighth Edition (MJ8) and the ASHRAE Residential Heat Balance (RHB) methods. The houses have identical basic construction and are fitted with windows that allow glazing to be changed. Two of the houses have south-facing primary fenestration and the other two west-facing. This setup permits simultaneous measurements of four combinations of glazing and orientation. Data for July, 2005 are presented and related to calculated loads. There is acceptable correspondence for south-facing cases. For west-facing, both MJ8 and RHB produce conservative estimates of cooling requirements. Incident solar intensities derived with the ASHRAE clear sky model are shown to exceed virtually all observed values, causing high calculated solar gains for the west-facing cases that experience near-normal sun angles. An additional source of difference may be the steady-periodic assumption used in load calculation that masks any load reduction due to actual day-to-day variability. Comparison of RHB-calculated hourly loads to measured values for representative days shows only approximate correspondence, indicating the need for further model improvements.

INTRODUCTION

Correct calculation of heating and cooling loads is the essential first step for successful residential HVAC system design. As has been thoroughly documented, properly sized systems, compared to over-sized systems, have lower installation cost, perform better, operate more efficiently, and impose less demand on utilities (Proctor et al. 1995). The advantages of correct sizing apply especially to cooling systems.

A cause of over-sizing is lack of confidence in load calculation methods. That is, practitioners do not know (or do not believe) the accuracy of the procedures and thus use conservative assumptions and/or apply safety factors to calculated loads. Given the millions of air-conditioned homes that have been constructed, one might expect that end-to-end "closure" experiments would have identified and corrected weaknesses in loads methods. In fact, it is surprisingly difficult to make rigorous comparisons of calculated and actual building cooling loads. James et al. (1997) studied 368 occupied Florida homes and concluded that Manual J (7th edition) cooling loads (without safety factors) are accurate when actual window shading is modeled. In another study, Parker et al. (1998) reported on adjacent Lakeland, FL houses having identical plans but one having many experimental energy conserving features. Manual J (7th edition) calculated sensible cooling loads were lower than measured requirements for the standard house and higher for the experimental one. Comparative analysis identified handling of duct losses and glazing solar gain as probable sources of the discrepancies.

Multi-house experiments are ideal for controlled study of building performance and investigation of the validity of loads calculation procedures. Efforts of this type have been sponsored by Cardinal Glass Industries:

- A pair of houses in Roseville, CA was studied during 2001 and showed that the house fitted with low solar, low E (LSLE) glazing used 25% less cooling electrical

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energy and 33% less cooling electrical power than the reference house with clear double glazing (Wilcox and Larsen 2004; Wilcox et al. 2004). The paper also found acceptable agreement between calculated and measured cooling loads.

- Four identical houses in Ft. Wayne, Indiana were completed in 2004 and remain under study. These houses are thoroughly instrumented and have field-replaceable glazing (described below).

Data from the Ft. Wayne experiment is the basis for the current work.

Residential Cooling Load Calculation Methods

A load calculation procedure widely used in the U. S. is Manual J, published by the Air-Conditioning Contractors of America. This method has been in use for decades and has undergone periodic updates. The current version is the Eighth Edition (ACCA 2006), designated MJ8 in this paper. Manual J is a component-based procedure – formulas and tables specify the load contribution per unit area of a wide range of residential construction assemblies, taking into account design conditions and surface orientation. Given these factors, designated heat transfer multipliers (HTMs), the envelope load calculation is simply Σ(Component area × HTM). Additional gains are added for heat from appliances, occupants, and infiltration.

The Manual J component approach is simple and conceptually appealing. However, actual heat gains vary throughout the day and interact with building mass. The peak value of the combined gains is the nominal cooling load. The component approach embodies assumptions about when the peak will occur and can, at least in theory, be badly in error for atypical situations. MJ8 includes an hourly glazing gain procedure to better capture the peak, but this refinement does not eliminate the inherent limitations of a single-condition calculation.

A number of commercial software packages implement the MJ8 method and are sanctioned by ACCA. In this work, the Right-Suite Residential package was used to perform MJ8 calculations (Wrightsoft 2007).

In 2001, ASHRAE and ACCA undertook the research project *Updating the ASHRAE/ACCA Residential Heating and Cooling Load Calculation Procedures and Data* (1199-RP). This project adapted the heat balance method to residential applications (Barnaby et al. 2004, Barnaby et al. 2005). The resulting Residential Heat Balance (RHB) method is a first-principles, 24 hour procedure that can be performed on any day of the year with any design conditions. Hourly loads are calculated via rigorous energy balances and the design load is simply the peak of the overall daily profile. Xiao (2006) presents an extensive evaluation of RHB.

As part of 1199-RP, the RHB method was implemented as ResHB, a research-oriented FORTRAN 95 application based on the ASHRAE Loads Toolkit (Pedersen et al. 2001). As part of ASHRAE 1311-RP (Wright and Barnaby 2007), ResHB has been enhanced and is now designated HBX. HBX was used in the current work and will be available as part of the 1311-RP final report.

An important capability of RHB as implemented in HBX is explicit modeling of temperature swing – allowing the space temperature to temporarily exceed the nominal setpoint temperature. The resulting diurnal energy storage in building mass generally significantly reduces required cooling capacity. To determine the cooling load with temperature swing, HBX searches for the heat extraction rate that produces the specified swing above the setpoint. Cooling is assumed to operate continuously while the setpoint is exceeded. The model varies the cooling extraction rate until the maximum room temperature equals setpoint + swing. That extraction rate is the sensible cooling load, since it is the cooling power required to maintain space temperature within a comfortable margin of the nominal design set point.

The temperature swing effect has been understood for decades and was included empirically in prior ASHRAE and Manual J cooling load factors (for example, see ASHRAE 1972 Chapter 22, Part III, p. 440ff). Current ASHRAE procedures recommend against assuming a fixed setpoint for residential cooling calculations (ASHRAE 2005 Chapter 29).

TEST HOUSES

This work is based on four instrumented, unoccupied production builder houses located in a residential subdivision in Ft. Wayne, Indiana. The research nature of the buildings was established prior to construction, allowing documentation of materials and workmanship. Construction occurred during the winter of 2003-2004. Extensive effort has been made to ensure the houses are identical. The windows used are standard Andersen residential casement units with hardware that allows field-swapping of sash. Three glazing alternatives are available: clear and two low-e. The back of two of the houses face south and the other two face west. Thus, there are six possible combinations of orientation and glazing. Figures 1 and 2 show front and back views of one of the houses. Floor plans are shown in Figure 3. Additional photographs and construction details are available (see Wilcox 2007).

Particular care was taken to seal the homes to prevent air leakage differences. In addition, temporary forced-air ventilation systems are installed to provide identical ventilation flow at approximately normal ASHRAE Standard 62.2 rates. These supply-only ventilation systems provide 33 l/s (70 cfm) of unconditioned air to the open stair well area in the center of the 1st floor in each home, slightly pressurizing the houses. The internal pressure is sufficient to prevent additional infiltration under cooling conditions according to analysis of pressurization test results, virtually eliminating the infiltration rate uncertainty that plagues many whole-house experiments.

Each house is conditioned by a conventional forced-air split cooling system with a natural gas furnace. Two of the houses were equipped with 4 ton systems and the other two 3 ton (the larger systems ensured sufficient capacity for the clear glass configuration). Air handlers and duct trunks are located

Figure 1 *Test house, front (east or north) with vertical pyranometer at arrow.*

Figure 2 *Test house, back (west or south). (Note: pyranometer for this orientation is mounted on another house.)*
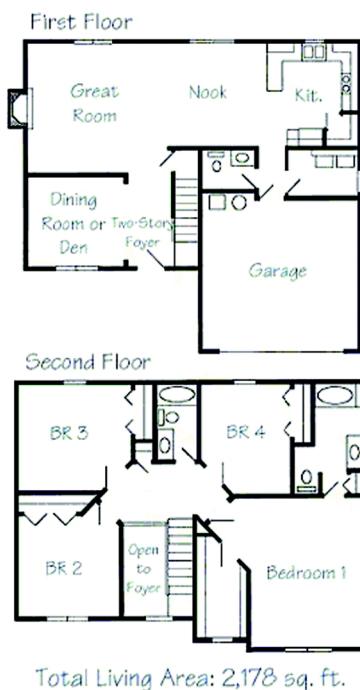
Figure 3 *Test house floor plans (back at top of each plan).*

in basements with branch ducts running up interior walls to floor registers at the perimeter. Duct systems were sealed using an aerosol approach; duct leakage of essentially 0 was verified by pressurization tests inherent in the sealing process (Aeroseal, 2007; Modera et al., 1996).

Extensive commissioning and verification ensured the houses perform comparably. The HVAC systems were adjusted to provide the same overall air flow rates relative to capacity and the same room-by-room distribution compared to calculated loads. Glazing systems were swapped among the houses four times during the first winter experimental period, demonstrating that the glazing systems provided substantially identical results regardless of installation location. Air-conditioner operation, including sub-cooling, was monitored and deviations from normal were repaired as they arose. The houses are unoccupied; access is carefully controlled. Data from days with significant human impacts are not included in this study.

All houses are heavily instrumented; outdoor and indoor conditions are recorded at 1 minute intervals. There are 5 high quality thermopile pyranometers (Kipp and Zonen 2006) installed to measure horizontal insolation and incident solar radiation on each of the 4 vertical orientations (see Figure 1).

Sensible HVAC system output is calculated from real-time air temperatures and air flow measured during commissioning using the plenum pressure matching technique. An array of nine thermocouples is installed in each of two branches of the supply duct system and the flow rate at each thermocouple was measured with an anemometer. Sensible output is calculated every 20 seconds during fan operation based on the overall system air flow and the temperature difference between the return duct near the furnace and the flow-weighted supply temperature. This result is adjusted by basement duct losses estimated from house-specific experimentally measured values, yielding the "measured load" for the house.

Basic geometry of the test houses is summarized in Table 1. Note that 95% of the fenestration area is on the front and back of the houses, with the back having the largest fraction. The backs of two of the houses face west, allowing study of what is typically the extreme exposure condition when low sun angles combine with near-peak dry-bulb temperatures. The houses are built to good quality U. S. production housing standards. Table 2 shows construction details. Of note is the exterior wall insulation system: a layer of spray foam is first applied to the sheathing between the studs and the remaining cavity is filled with fiberglass batt insulation.

As discussed above, three types of glazing were interchanged in the experimental program. Because of differences in size, the properties of individual windows are not identical for a given glazing type. As a modeling expedient, area-weighted average properties were used for all windows for

Table 1. Test House Attributes (As Modeled)

Attribute	Value
Conditioned Floor Area[2,3]	212.5 m^2 (2287 ft^2)
Volume[2,4]	550.4 m^3 (19435 ft^3)
Ceiling Height	2.44 m (8 ft)
Gross Exposed Wall Areas[5]	
Front	50.8 m^2 (547 ft^2)
Left	49.2 m^2 (530 ft^2)
Back	66.3 m^2 (714 ft^2)
Right	65.8 m^2 (708 ft^2)
Total	232.1 m^2 (2499 ft^2)
Window Areas, Including Frames (A_{pf})	
Front	11.2 m^2 (120.3 ft^2) (40%)
Left	0
Back	15.2 m^2 (163.6 ft^2) (55%)
Right	1.34 m^2 (14.4 ft^2) (5%)
Total	27.7 m^2 (298.2 ft^2)

[1]Some values not consistent with 3; see notes 2–4
[2]Modeled geometry is based on outside-to-outside dimensions (including wall and floor thicknesses).
[3]Modeled conditioned floor area includes "Open to Foyer" area on 2nd floor.
[4]Modeled volume includes thickness of interior floor between 1st and 2nd floor.
[5]Includes wall area between conditioned space and garage; does not include garage exterior walls.

Table 2. Test House Construction Details

Component	Construction	MJ8 code
Roof	Dark asphalt shingles (α_{solar} = 0.8) Building paper 13 mm (0.5 in.) OSB sheathing board 2 × 10 rafters 405 mm (16 in.) OC	16B-38ad (ceiling under vented attic)
Exterior Ceiling (Attic Floor)	2 × 10 joists 405 mm (16 in.) OC / RSI-6.7 (R-38) cellulose insulation 13 mm (0.5 in.) gypsum board	
Interior Ceiling/Floor	Carpet 19 mm (0.75 in.) T&G OSB 2 × 10 joists 405 mm (16 in.) OC 13 mm (0.5 in.) gypsum board	(not modeled)

Exterior Wall	Vinyl lap siding (α_{solar} = 0.6)
	13 mm (0.5 in.) OSB sheathing
	2 × 4 framing 405 mm (16 in.) OC with 2 layers of insulation in cavities:
	  • 19 mm (0.75 in.) closed cell polyurethane spray foam
	   (applied between studs to inside sheathing)
	  • RSI-1.9 (R-11) fiberglass batt insulation
	13 mm (0.5 in.) gypsum board
		12C-2sw
		(no exact equivalent defined by MJ8)

Interior Wall	13 mm (0.5 in.) gypsum board 2 × 4 framing 405 mm (16 in.) OC 13 mm (0.5 in.) gypsum board	(not modeled)
Exterior Floor (Over Garage and Basement)	Carpet 19 mm (0.75 in.) T&G OSB 250 mm (10 in.) engineered joists 405 mm (16 in.) OC / RSI-3.3 (R-19) batt insulation 13 mm (0.5 in.) gypsum board	19C-19bscp (over basement) 20P-19c (over garage)

each glazing type. These values are summarized in Table 3. Due to inaccessibility, the 1.75 m^2 (18.8 ft^2) window above the front door had LSLE glazing for all tested and modeled configurations.

DESIGN SENSIBLE COOLING LOADS

Baseline cooling load calculations were performed with MJ8 and RHB. Design conditions for these calculations are shown in Table 4. Standard calculation assumptions were used with the exception of infiltration and internal gain, which were modified to correspond to experimental conditions.

Calculated loads are presented in Table 5, along with inter-method ratios. RHB loads are smaller than MJ8 for the back-facing-south cases and about the same as MJ8 for west. For comparison, results calculated with temperature swing of 0 are also shown (in columns RHB-0). RHB-0 loads are *significantly* higher than RHB for all cases, illustrating the importance of the temperature swing assumption.

MEASURED LOADS

An uninterrupted sequence of measured data is available for the period June 25, 2005 – August 4, 2005. This date range spans the nominal July 21 design day, allowing measured results to be directly compared to calculated loads. During this period, two of the houses were fitted with HSLE glazing and two with LSLE, yielding four orientation / glazing combinations. Clear glass cases were not included during this period and are not considered in the following comparisons.

Table 6 shows basic weather statistics for the data period and shows the period is representative of typical Ft. Wayne July conditions for the purpose of peak load comparisons (energy consumption studies would require a more rigorous comparison). Values are also shown for July 10 and August 1, two days that have high measured cooling loads and conditions similar to the load calculation design conditions. Note that the design-day global horizontal radiation is higher than that observed on either representative peak day; in fact, it is higher than any observation during the data period.

Figure 4 shows measured sensible cooling loads plotted against outdoor temperature. Reference lines show the design temperature and the calculated cooling loads. Both MJ8 and RHB calculated loads for the south cases are reasonably consistent with observed house requirements, given that an occasional excessive gain will produce small (and short-lived) temperature excursions.

Both methods yield conservative or perhaps excessive estimates of the cooling requirements for the west cases especially for the HSLE glazing. It is also noteworthy that the variability of loads is greater for the west cases compared to south. Since the houses have 95% of glazing area on the front and back, the west configuration has much greater exposure to low sun angles that does the south, making overall gains more sensitive to variations in sky conditions.

The ASHRAE clear sky model is used for calculation of incident solar radiation in both MJ8 and RHB. In MJ8, inci-

dent radiation values are embedded in tabulated peak fenestration gain factors, derived using the "traditional" ASHRAE model (ASHRAE 2001). These factors depend on latitude and orientation; all other model parameters are fixed. RHB uses the updated-coefficient version of the clear sky model (ASHRAE 2005; Machler and Iqbal 1985). Figure 5 displays measured incident solar radiation and overlays the values used in the RHB load calculations. Note that in general, the calculated values correspond to extremely clear conditions, exceeding the observed intensity nearly every hour. In particular, the modeled peak intensity on the west façade is significantly higher than any actual observations.

Figure 6 shows hourly HBX calculated loads for the HSLE cases compared to the cooling requirements observed on representative peak days July 10 and August 1. There are only a few hours where the measured requirement exceeds the calculated load, especially for the west orientation. Selecting a cooling system with sensible capacity below the calculated result would result in small temperature excursions only on the hottest and sunniest days.

DISCUSSION AND CONCLUSIONS

Both traditional MJ8 and advanced RHB residential cooling load calculation methods assume worst case solar gains and thus yield conservative, perhaps excessive, overall cooling load estimates for buildings with high solar exposure. Both methods base their solar calculations on the ASHRAE clear-sky model. Comparing measured and calculated incident solar intensities for the Ft. Wayne site shows that the ASHRAE model predicts truly extreme intensities that infrequently occur. Temperature design conditions are normally selected with the understanding that they will be exceeded on some days; for example, the expectation is that the 1% condition will be exceeded about 88 hours per year. A similar assumption should be considered for solar intensity.

Given that the solar intensity on the west façade shows the most disagreement with observations, another area of suspicion is the method used to derive vertical surface intensity from horizontal solar. Model improvements may be needed for low sun angle conditions and/or reflected radiation.

Another pattern seen in Figure 4 is that MJ8 loads are consistently conservative (always larger than nearly every observation), while the RHB loads become increasingly conservative as solar exposure increases. Consistent results are desirable and further investigation is needed as to why RHB behaves in this fashion.

The hourly load profiles shown in Figure 6 show only approximate agreement between the RHB model and actual building behavior, leading to the conclusion that the thermal details are not accurately represented. Xiao (2006) identified inter-room heat transfer via air flow and partition conduction as weak areas in the RHB algorithm. Model enhancements may be required.

<center>**Table 3.   Test House Window Properties**</center>

Glazing Type[1]	U-Factor[2] W/m²·K (Btu/h·ft²·°F)			SHGC[2]			VT[3]	
	Min	**Max**	**Modeled**	**Min**	**Max**	**Modeled**	**Center of Glass**	**With Frame**
Clear Double (CLR)	2.56 (0.450)	2.57 (0.453)	2.57 (0.452)	0.584	0.619	0.608	0.81	0.62
High Solar Low E (HSLE)	1.77 (0.312)	1.79 (0.316)	1.78 (0.313)	0.474	0.502	0.495	0.78	0.60
Low Solar Low E (LSLE)	1.71 (0.301)	1.73 (0.305)	1.71 (0.302)	0.327	0.348	0.342	0.72	0.55

[1]The terms "high solar" and "low solar" indicate the relative amount of solar heat gain transmitted by the glazing. The low solar SHGC is 30% smaller than the high solar SHGC, while the U-factors and VTs are only slightly lower.
[2]Glazing is identical within each type; differences are due to size-related frame effects. Modeled values are area-weighted averages.
[3]Visible transmittance (VT) values were not used in modeling; they provide additional glazing characterization. All three glazing types are considered "high VT" (no perceptible tint).

<center>**Table 4.   Load Calculation Assumptions**</center>

Item	Value	Notes
Day of Year	July 21	Determines solar geometry
Maximum Dry Bulb	31.1°C (88°F)	ASHRAE annual 1% condition
Daily Range of Dry Bulb	11.1°C (20°F)	
Clearness Number	1	Default assumption for ASHRAE clear sky model
Ground Reflectance	0.2	Estimated for grass surroundings
Infiltration	33 l/s (70 cfm) (.21 ach)	Mechanical ventilation rate (see text)
Internal Gain	879 W (3000 Btu/h) continuous	Per experimental conditions (electric resistance heaters located in kitchen and Bedroom 1)
Occupants	0	Houses unoccupied.
Indoor Air Temperature	23.9°C (75°F)	Per experimental conditions
Temperature Swing	Base: 1.67°C (3°F) RHB-0 alternative: 0°C	Not alterable in MJ8

<center>**Table 5.   Calculated Sensible Cooling Loads at Annual 1% Design Condition**</center>

Glazing	Back Facing South			Back Facing West		
	MJ8 W (Btu/h)	**RHB** W (Btu/h)	**RHB-0**[1] W (Btu/h)	**MJ8** W (Btu/h)	**RHB** W (Btu/h)	**RHB-0**[1] W (Btu/h)
Clear Double (CLR)	5387 (18386)	4820 (16451) 0.89 × MJ8	6264 (21379) 1.16 × MJ8 1.30 × RHB	8289 (28291)	8482 (28949) 1.02 × MJ8	9928 (33884) 1.20 × MJ8 1.17 × RHB
High Solar Low E (HSLE)	4843 (16529)	4094 (13973) 0.85 × MJ8	5484 (18717) 1.13 × MJ8 1.34 × RHB	7232 (24682)	7282 (24853) 1.01 × MJ8	8606 (29372) 1.19 × MJ8 1.18 × RHB
Low Solar Low E (LSLE)	4274 (14586)	3308 (11290) 0.77 × MJ8	4699 (16038) 1.10 x× MJ8 1.42 × RHB	5900 (20138)	5600 (19113) 0.95 × MJ8	7029 (23990) 1.19 × MJ8 1.26 × RHB

[1]RHB-0 cases calculated with 0°C temperature swing (fixed indoor temperature); standard RHB temperature swing assumption is 1.67°C (3°F).

Table 6. Weather Statistics

Item	Long-Term Average[1]	Measured at Site			Design Day
		Data Period Average	July 10	Aug 1	
Dry Bulb Temperature					
Daily Maximum	29.2°C (84.6°F)	29.4°C (85.0°F)	31.4°C (88.6°F)	30.7°C (87.2°F)	31.1°C (88°F)
Daily Minimum	17.3°C (63.2°F)	19.0°C (66.2°F)	14.8°C (58.6°F)	18.5°C (65.3°F)	20.0°C (68°F
Daily Global Horizontal Radiation					
Average	6.06 kWh/m^2 (1.92 kBtu/ft^2)	6.18 kWh/m^2 (1.96 kBtu/ft^2)			
Clear Day	7.95 kWh/m^2 (2.52 kBtu/ft^2)		8.15 kWh/m^2 2.58 kBtu/ft^2)	7.32 kWh/m^2 (2.32 kBtu/ft^2)	8.31 kWh/m^2 (2.63 kBtu/ft^2) (Footnote 2)

[1]July values from Ft. Wayne data summary in NREL (1995)
[2]As calculated with ASHRAE clear sky model as implemented in HBX. See text.

An additional issue is the steady-periodic approach implicit in load calculations – the design day is assumed to repeat indefinitely. Typical residences have some multi-day storage capability, moderating loads at the beginning of a hot period. Repeating the same hot / sunny conditions overstates typical loads, at least in a climate like Ft. Wayne that normally has day-to-day variability even during hot weather. This effect should be investigated with longer simulations that model realistic day sequences. Ultimately, perhaps multiple day design sequences will replace the single 24 hr design day now used by ASHRAE load methods.

Finally, it is worth noting that a first-principles approach such as RHB is essential when reconciling observed and modeled results. Derived methods, such as MJ8, are based on many implicit assumptions, making them impossible to use experimentally for this type of study.

Future work suggested by this study includes extension to clear glass cases (expected to magnify the solar effects, perhaps allowing easier investigation) and comparison of measured to calculated latent loads. A large amount of additional data from the Ft. Wayne project remains to be analyzed and will contribute to further validation and refinement of residential load calculation procedures.

ACKNOWLEDGEMENTS

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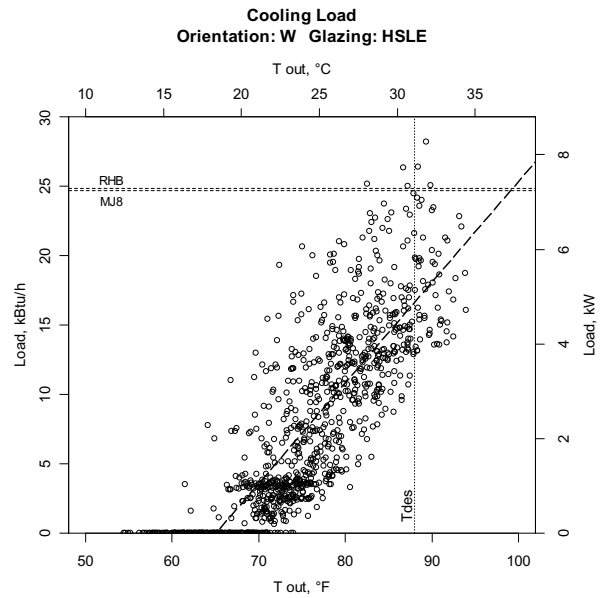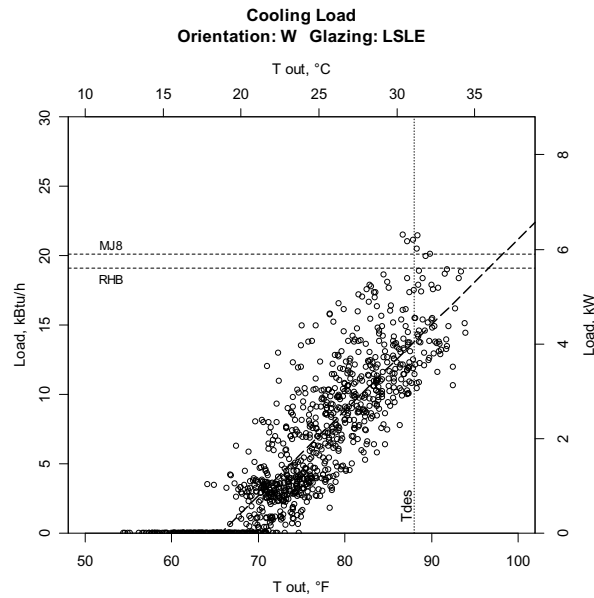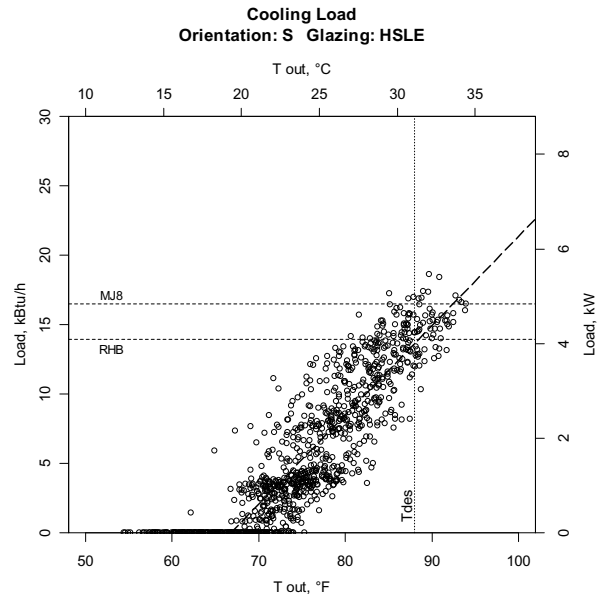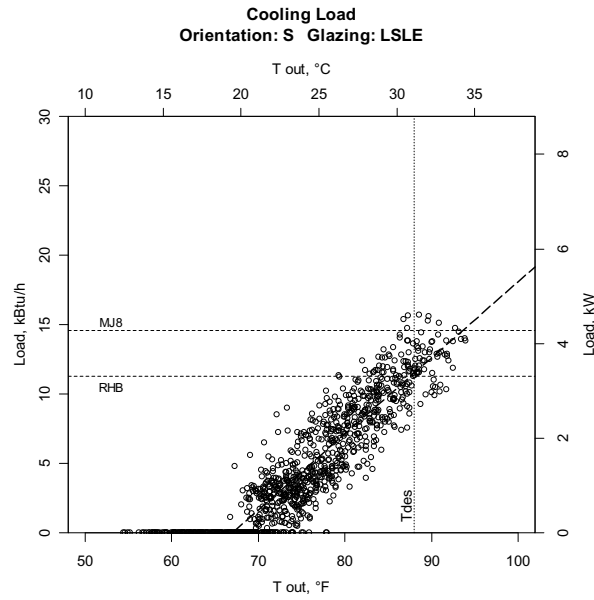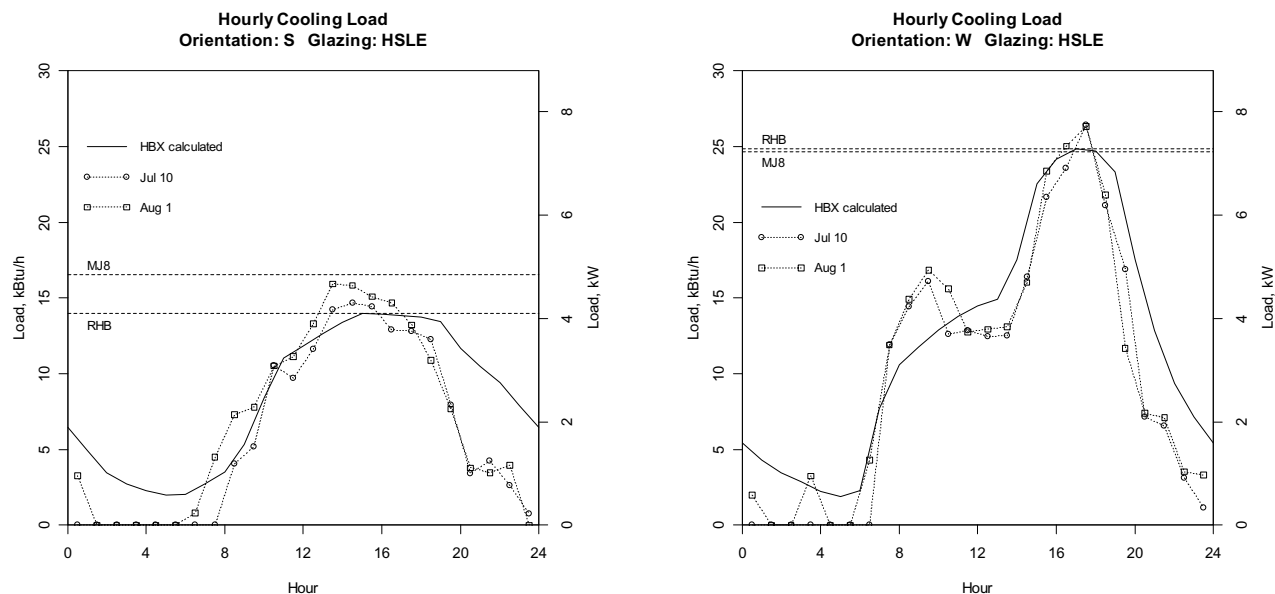
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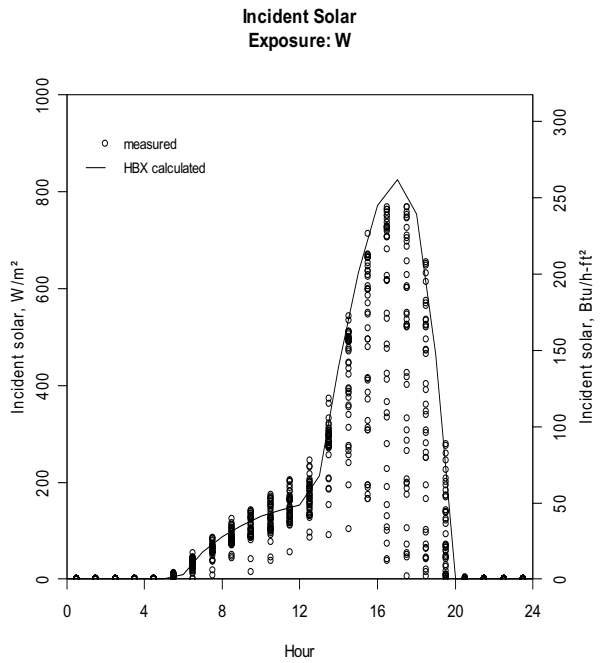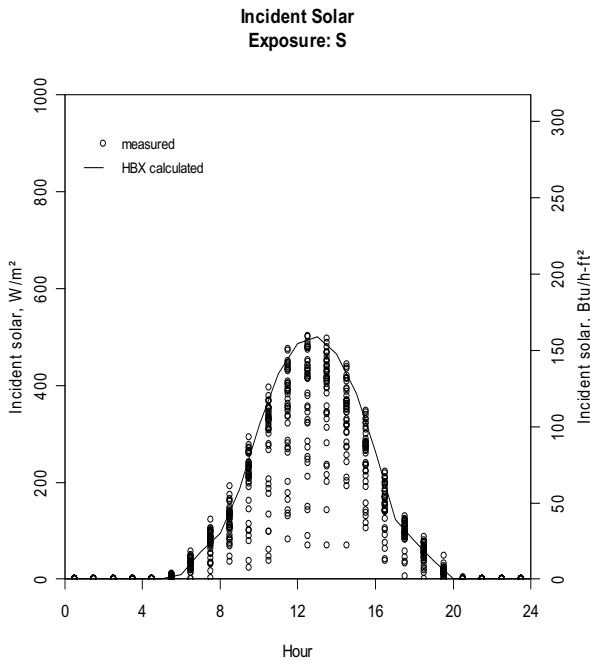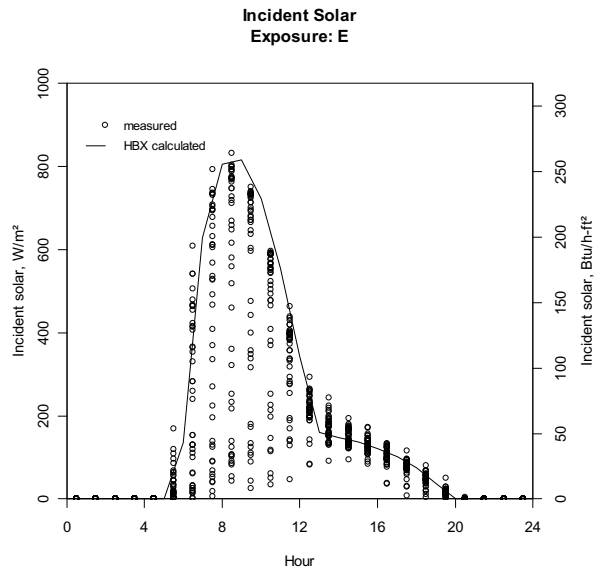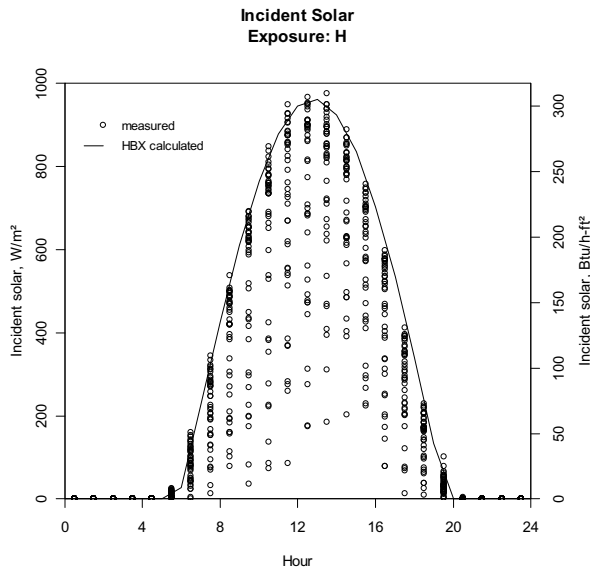
Figure 5   *Measured versus calculated incident solar radiation.*

Figure 6 *Representative day measured and modeled cooling loads.*

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