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System Interactions and Energy Savings in a Hot Dry Climate

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ABSTRACT

To evaluate opportunities for reducing cooling energy use in a hot dry climate, two new production houses located near Phoenix, Arizona, were studied: 1) a control home built with standard construction and 2) a prototype home with an integrated package of energy-saving features. The prototype's energy-saving features included spectrally selective windows, interior air handler location, low-loss ducts, and high efficiency air-conditioning equipment. Both houses were monitored while unoccupied for a period of several weeks during very hot weather to evaluate cooling energy use. A comparison of short periods of detailed data showed a cooling energy use reduction of approximately 40% during peak summer conditions.

Effects of the various energy-saving measures and their interactions were separated by a series of tests that focused on specific components of the overall cooling load. It is important to understand the interactions of shell measures with mechanical system measures to properly size equipment and minimize overall system costs. An experimental technique was also developed to directly measure the contribution of window solar gains to overall cooling loads.

Introduction

The Building America Program is an industry-driven program sponsored by the U.S. Department of Energy that applies systems engineering approaches to accelerate the development and adoption of advanced building energy technologies in new residential buildings. Building America works with four building industry teams, including the Consortium for Advanced Residential Buildings (CARB), to produce advanced residential buildings on a community scale. The systems incorporated in these houses are evaluated by conducting successive design, test, redesign, and retest iterations until cost and performance trade-offs yield innovations that can be implemented in production-scale housing.

The CARB team built a prototype house in 1997 near Phoenix, Arizona, with an integrated package of energy-savings features. This study describes the testing procedures used to evaluate the prototype and summarizes the results of the cooling load reduction strategies.

Objectives

The Building America Program uses performance testing to support the systems engineering process and provide rapid feedback on building performance for integration of systems innovations into production housing. The primary objective of this study is to evaluate the impact of energy efficiency measures integrated to reduce cooling energy use in a hot dry climate. The secondary objective is to develop simple short-term whole-building test procedures that evaluate the impacts of design changes on cooling energy use.

Description of Buildings

Two new production homes located near Phoenix, Arizona were studied: 1) a control home representing standard construction practice and 2) a prototype home with an integrated package of energy-saving features. These two ranch-style houses are nearly identical in design and located within several blocks of each other in a low-density residential development. They have the same floor plan with approximately 1650 square feet of floor area, including two bedrooms and two bathrooms. These one-story homes are framed on a slab-on-grade foundation with stucco exterior finish and red concrete tile roofs. Both houses have 274 square feet of window area with about 45% of the total window area in the back wall. These back wall windows are partially shaded by a patio cover.

Prior to testing, the interiors of both houses were fully finished. Approximately 40% of the floor areas were covered with ceramic tile and 60% covered with carpet. The prototype house also had operable interior blinds.

The control house employs standard construction materials and techniques including nominal 2 inch x 4 inch wood framing, fiberglass batt insulation, 1-inch polystyrene sheathing, and double-pane clear-glass aluminum-frame windows. The air handler in the control house is located in the garage with flex ducts in the attic space and a 10 seasonal energy efficiency ratio (SEER) air conditioner.

The prototype house incorporates several re-engineered features in its structural, heating, and cooling systems. Envelope changes include nominal 2 inch x 6 inch wall framing and limited use of steel studs. Windows with spectrally selective coatings (Carmody et al. 1996) were also installed to achieve a lower solar heat gain coefficient (SHGC). Mechanical system features include air handler relocation to an interior closet, shortened and highly insulated ducts, and a 12-SEER air conditioner. These load reduction strategies allowed the prototype’s the air-conditioning equipment size to be reduced by 25% relative to the control house. The prototype house also has a controlled ventilation system that consists of an outside air duct to the air handler return and separate intermittent central exhaust. To better evaluate the other energy-efficient features of the prototype house, both components of this ventilation strategy were disabled during the testing period.

A detailed summary of the differences between the control and prototype test houses is provided in **Table 1** (Tully 1997).

Methodology

The thermal performance of the two houses was measured for a period of several weeks in July and August 1997. This study compares the energy performance of the two houses while they were operating concurrently. During the test sequence, different measures were applied to the windows in each house to establish a variety of operating conditions. Side-by-side tests were conducted as the houses operated during identical weather conditions with different window features and air-conditioning systems. Comparisons are also made between the performance of each house with and without the applied window features (a sequential test) with similar but not identical weather conditions.

The primary measure of performance compared in these tests is the electricity used for air-conditioning. Hourly kilowatt-hours (kWh) were recorded. The hourly peak kW and daily total kWh are compared. The interior temperatures maintained by the air-conditioning systems were also measured. The interior thermostat setpoint temperature was approximately 72ºF in both houses.

Different window treatments were applied to the houses, either to create a limiting case of eliminating all solar gains through the windows or to test different practical window treatments.

Table 1. Characteristics of Test Houses

	Control	**Prototype**
Orientation (of back wall)	Southwest	Northwest
Walls	Wood frame throughout R-13 fiberglass insulation 1-inch polystyrene sheathing	Wood plus steel in-fill studs R-19 fiberglass insulation 1-inch polystyrene sheathing
Attic insulation	R-30 batt fiberglass	R-38 batt and blown fiberglass
Windows		
U-value:	0.78	0.47
SHGC :	0.74	0.37
Shading Coefficient:	0.70	0.44
Visible Trans.:	0.67	0.58
Glazing:	Double, clear	Double, low-e, low-SHGC
Frame:	Aluminum	Aluminum with thermal break
Treatments:	-	Blinds
Skylights:	-	2 (hallway & master bath)
Heating	Natural gas furnace 80 kBtu/h input	Hydronic combined with DHW 60 kBtu/h input, 48 gallons
Cooling	4.0 tons 10 SEER, 9.4 EER	3.0 tons 12 SEER, 11 EER
Distribution power (values measured in cooling mode)	660 W fan 1500 total supply CFM	350 W fan 1250 total supply CFM
Air distribution		
Air handler location:	Garage	Interior closet
Return ducts:	Ceiling grille with flex duct to plenum box, undercut doors	Low grille on closet wall, bedroom transfer grilles
Supply ducts:	Insulated R-5 flex duct in attic	Round steel ductwork under ceiling insulation
Supply registers:	Fixed blades in ceiling near outside walls	Adjustable blades in ceiling near inner partitions

Opaque exterior shades were constructed to completely block all beam radiation from entering the windows in each house. These shades were made using 0.75-inch thick sheets of foil-faced polyisocyanurate foam supported approximately 8 inches away from the exterior surface of each window. The shades were larger than the dimensions of the windows to block most of the incident radiation. The 8-inch supports allowed airflow between the shade and the glass to minimize changes in window U-value while blocking the solar gains. **Figure 1** shows a photograph of the control house with exterior shades applied. Comparing the air-conditioning energy use between the houses when the opaque exterior shades were applied, indicates the difference in air-conditioning system performance that results from design changes other than window glazing. Comparing the performance of each house with and without shades also indicates the maximum influence that window solar gains have on cooling energy use.

Figure 1. Photograph of control house with opaque exterior shades.

The prototype house was tested with interior blinds in the open position and in the closed position. **Figure 2** shows the prototype house with all the blinds closed. The control house did not have interior blinds, but it did receive a complete glazing change-out during the test. During the testing period, clear glazing in the control house was replaced with the same spectrally selective glazing used in the prototype house.

Figure 2. Photograph of prototype house with interior blinds fully closed.

Instrumentation

A portable thermal performance monitoring system was installed in each house. Each monitoring system included a Campbell Scientific CR10 data logger with a 32-channel multiplexer and a 16-channel digital output module. The sensors installed at each house included a complete weather station that measured ambient dry-bulb temperature, relative humidity, wind speed, and horizontal and vertical solar radiation. The air temperature in each room was measured using type-T thermocouples with the measuring junction mounted in a cylindrical radiation shield and positioned near the center of the room. Interior relative humidity was measured in two locations in each house. Total electric power was measured at the main service entrance using a Hall-effect watt transducer. During the testing period, heat-flux transducers were temporarily installed on the tile surface of the floor.

The data logger was programmed to sample each channel (except for electric power) at 30-second intervals. The electric power transducer was sampled at 1-second intervals. All data were averaged over a period of 1 hour and stored in the data logger memory. Periodically, data were transferred from the data logger to a computer.

Tracer gas decay tests were performed simultaneously in both houses to measure the net air exchange with outside air. The tracer gas was sulfur hexafluoride (SF_6) and the gas concentration was measured by Bruel & Kjaer (B&K) model 1302 multi-gas monitors. Tracer gas was injected periodically in the houses, and the decay of concentration was used to calculate a net air exchange rate expressed in air changes per hour (ACH). A sample of air from two to four points around each house was mixed to measure an average concentration. Small fans in each room operated continuously to establish fully mixed, single-zone conditions. To measure the natural air exchange rate, an independent 6-zone forced air cooling system was used to maintain constant interior temperatures without the standard air handler fan and ducts.

Results

Table 2 displays the weather conditions and performance measurements for each day during the test period used in the analysis. For the purpose of comparing daily cooling energy performance under similar weather conditions, weather similarity is judged by comparing daily average outside dry-bulb temperature and daily total horizontal solar irradiance. The variation in these weather conditions is given in **Table 3**.

Table 2. Summary of Measured Results

Day of Year 1997	Weather		Control			Prototype		
	Average Temp. °F	Horizontal Irradiance Btu/ft^2	Energy Use kWh	Peak Elec. kW	Window Treatment	Energy Use kWh	Peak Elec. kW	Window Treatment
199	96.7	2486	-	-	clear glass	-	-	spec. sel.*
200	93.6	1934	-	-	clear glass	-	-	spec. sel.
204	94.1	2462	82.1	5.18	clear glass	48.5	2.98	spec. sel.
205	97.1	2317	69.6	4.39	clear glass +ext shade	49.9	2.99	spec. sel.
209	93.5	2247	60.3	3.83	clear glass +ext shade	38.0	2.19	spec. sel. +ext shade
210	92.0	1873	55.2	3.50	clear glass +ext shade	36.0	1.98	spec. sel. +ext shade
212	95.3	2394	77.7	5.34	clear glass			
213	97.7	2422	84.5	5.60	clear glass			
216	94.0	2264	70.0	4.74	spec. sel.	46.0	2.95	spec. sel.
219	95.4	2029	74.1	4.87	spec. sel.	41.8	2.60	spec. sel. +blinds

* spec. sel. indicates spectrally selective coating on the window glazing.

Table 3. Summary of Variation in Weather

Analyzed Results	Days Averaged	Daily Average Temp. Diff. (T_{out} - $T_{setpoint}$) °F	Horizontal Irradiance Btu/ft^2·day
Normal Operation	204, 205, 212, 213, 216	23.6 ± 9%	2372 ± 5%
Exterior Shades	209, 210	20.8 ± 4%	2060 ± 9%
Window Treatments in the Control House	204, 209, 210, 212, 213, 216, 219	22.6 ± 14%	2242 ± 16%
Window Treatments in the Prototype House	204, 205, 209, 210, 216, 219	22.4 ± 12%	2199 ± 15%
Air Change Rate	199, 200, 204, 205, 212, 213	23.7 ± 9%	2336 ± 17%

The electric power used to operate the air-conditioning system (including the fan) under normal conditions on typical days in July and August for the control and prototype houses is compared in **Figure 3**. The graph shows the hourly electric power usage for each hour beginning at 6:00 a.m. Each point on the graph represents the average of 3 days with similar weather conditions. During this period, the windows in both houses were not shaded. Note that the measured power is nearly constant for hours 15:00 through 19:00 in the control house, and 16:00 through 18:00 in the prototype house, causing the load shape to appear clipped. During these periods, both air conditioners operated continuously and the room temperatures drifted above the thermostat set point (see **Figure 8**), indicating that the thermal cooling loads were not met in either the control or prototype house. As shown in **Table 4**, the peak electric demand in the prototype house is approximately 2.4 kW less than in the control house, a reduction of 45%. Average daily energy use for the prototype house is reduced by 33.4 kWh/day or about 40%. These savings result from the entire package of measures implemented in the prototype house.

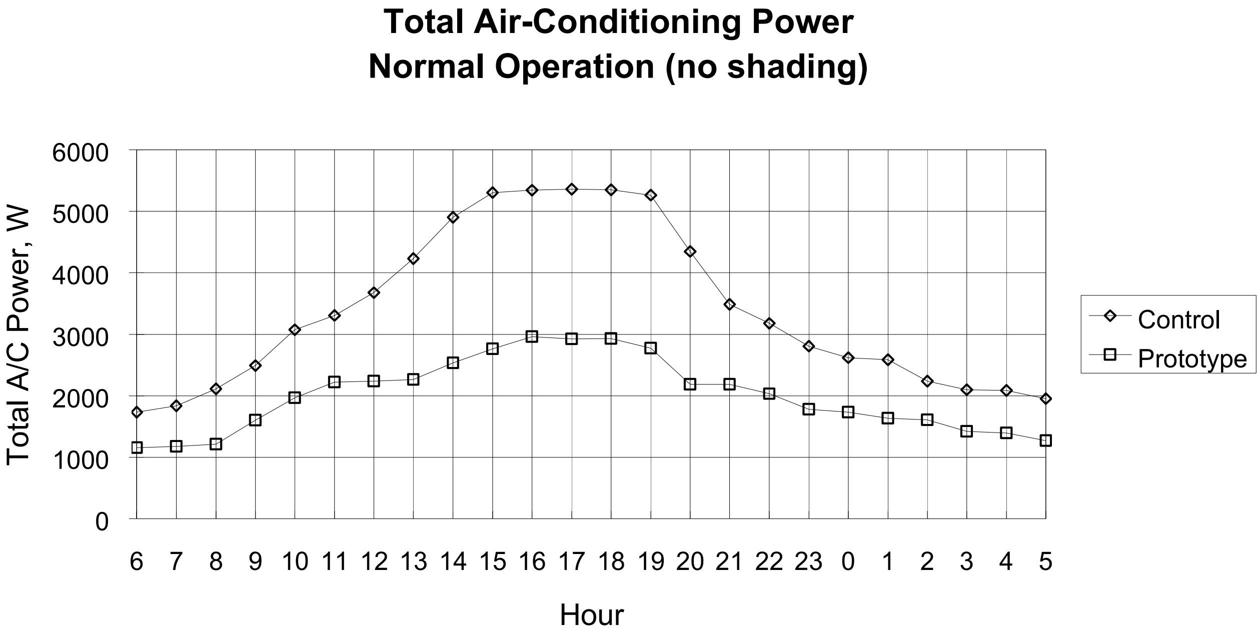

Figure 3. Hourly electricity consumption for air-conditioning during normal operation.

Table 4. Summary of Test Results with Normal Operation

	Control	Prototype	Reduction
Days Averaged	204, 212, 213	204, 205, 216	
Daily Energy Use kWh/day	81.4	48.0	33.4 (41%)
Peak Electricity kW	5.36	2.96	2.40 (45%)

Figure 4 shows the average daily load shapes for the control and prototype houses when the opaque exterior shades were applied to both houses. This side-by-side comparison demonstrates the performance improvement attributable primarily to the differences in the air-conditioning systems by limiting the differences in window solar heat gain. The indicated difference also includes the effects of window U-value as well as wall and ceiling insulation. Because of these effects, the net difference attributable to just the cooling system improvements is slightly smaller than indicated here. As shown in **Table 5**, the peak demand in the prototype house compared to the control house is reduced by about 1.4 kW or 41%, and the daily total electric energy for air-conditioning is reduced by about 21 kWh or 36%. Note that the load shapes for both houses are not clipped (as in **Figure 3**) and that interior temperatures do not drift significantly above the set point (see **Figure 8**). This indicates that the air-conditioning systems were fully meeting the thermal loads when the window solar gains were completely eliminated.

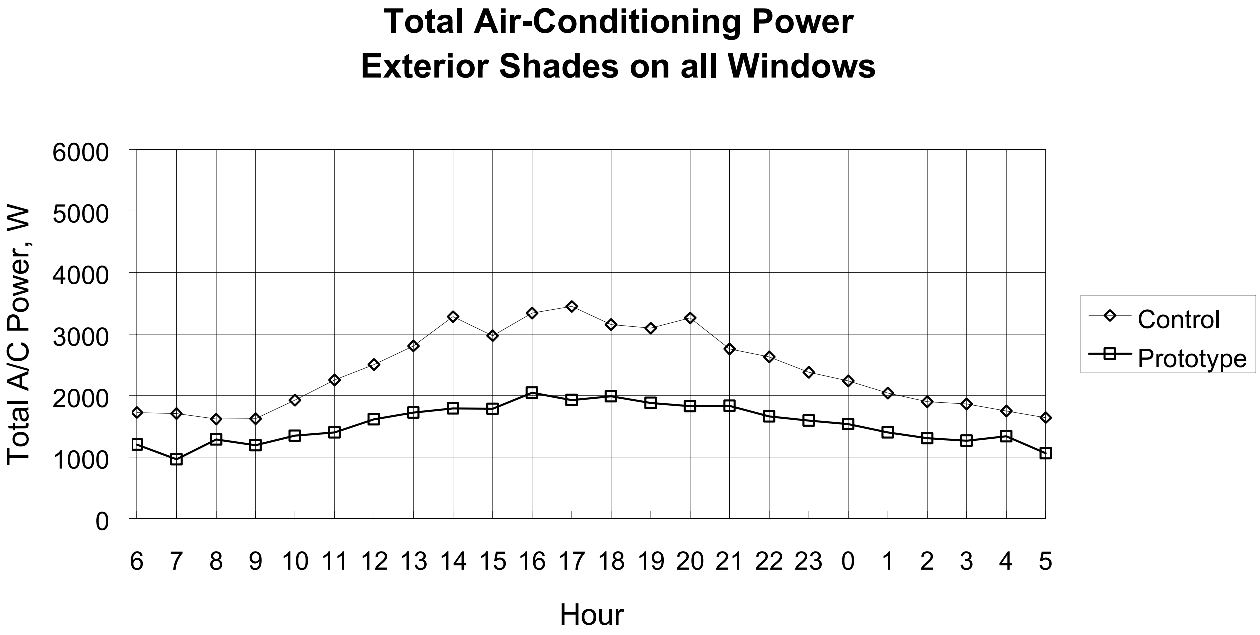

Figure 4. Hourly electricity consumption for air-conditioning with opaque exterior window shades.

Table 5. Summary of Test Results with Exterior Shades

	Control	**Prototype**	**Reduction**
Days Averaged	209, 210	209, 210	
Daily Energy Use kWh/day	57.9	36.9	21.0 (36%)
Peak Electricity kW	3.45	2.05	1.40 (41%)

Figure 5 displays the measured air-conditioning load shape for the control house with three different window conditions. The top curve in the graph represents the energy use for air-conditioning with clear glazing and no shading (same as in **Figure 3**). The bottom curve represents the energy use with the opaque exterior window shades in place (same as in **Figure 4**). The middle curve represents the air-conditioning energy use when the clear glass windows are replaced with spectrally selective glazing. When comparing clear glazing to the shaded condition, it is apparent that window heat gain accounts for a significant part of the total load. As shown in **Table 6**, total shading reduces the air-conditioning peak demand by about 1.8 kW and the daily total energy by about 24 kWh/day. Compared to unshaded clear glass windows, the spectrally selective glazing reduces peak demand by about 0.5 kW and reduces daily total cooling energy use by about 10 kWh/day. Note also that with spectrally selective glazing, the existing air conditioner has adequate capacity to meet the cooling load. The savings due to spectrally selective glazing would have been greater if the load shape for the unshaded clear glass windows case was not clipped.

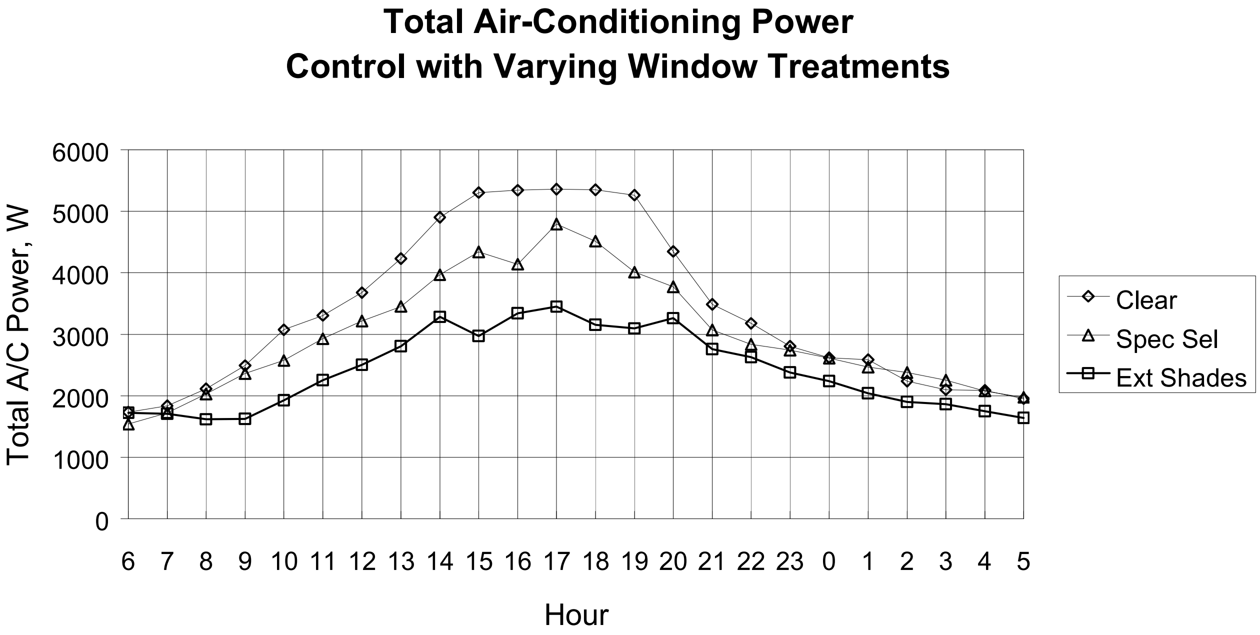

Figure 5. Hourly electricity consumption for control house with varying widow treatments.

Table 6. Summary of Test Results with Window Treatments in the Control House

	Clear	**Spectrally Selective**		**Exterior Shades**	
			Reduction		Reduction
Days Averaged	204, 212, 213	216, 219		209, 210	
Daily Energy Use kWh/day	81.4	71.7	9.7 (12%)	57.9	23.5 (29%)
Peak Electricity kW	5.26	4.79	0.47 (9%)	3.45	1.81 (34%)

Figure 6 compares measured air-conditioning load shapes for three different window treatments in the prototype house. The top curve represents the air-conditioning energy use for the unshaded spectrally selective glazing (same as **Figure 3**). The middle curve represents energy use for the spectrally selective glazing with operable interior blinds fully closed. The bottom curve represents energy use with the opaque exterior shades applied (same as **Figure 4**). As shown in **Table 7**, total shading reduces the air-conditioning peak demand by about 0.9 kW and the daily total energy by about 11 kWh/day. Interior blinds reduce peak demand by about 0.4 kW and daily total cooling energy use by about 6 kWh/day, compared to unshaded spectrally selective glazing. Note also that with interior blinds closed, the existing air conditioner has adequate capacity to meet the cooling load. (That is, the load shape is not clipped.)

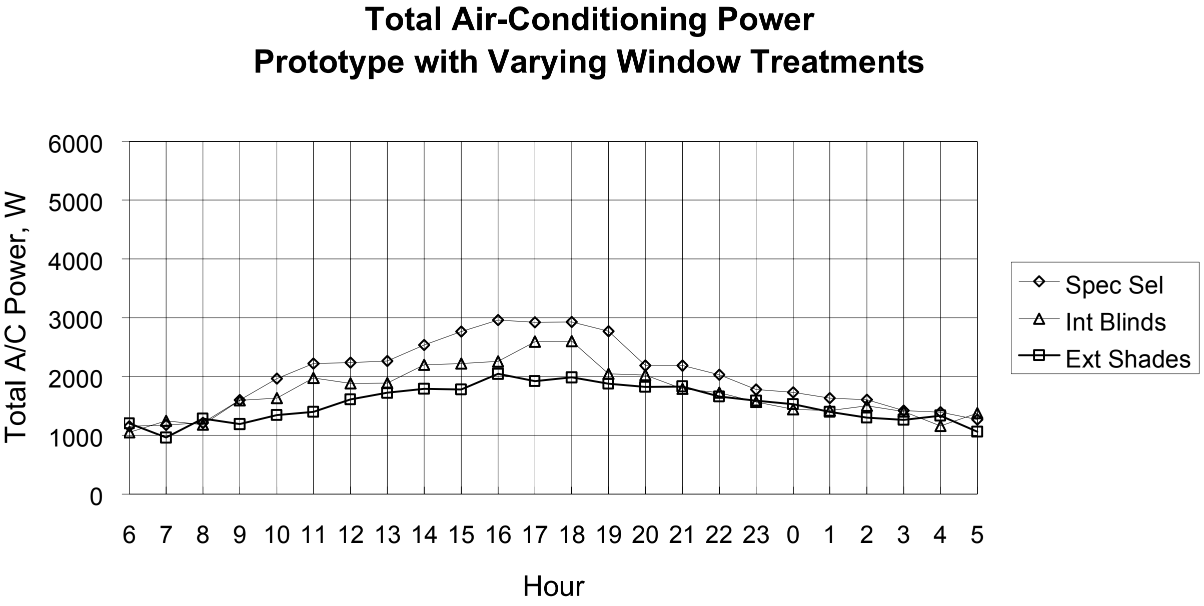

Figure 6. Hourly electricity consumption for prototype house with varying widow treatments.

Table 7. Summary of Test Results with Window Treatments in the Prototype House

	Spectrally Selective	**Blinds**		**Exterior Shades**	
			Reduction		Reduction
Days Averaged	204, 205, 216	219		209, 210	
Daily Energy Use kWh/day	48.0	41.8	6.2 (13%)	36.9	11.1 (23%)
Peak Electricity kW	2.96	2.60	0.36 (12%)	2.05	0.91 (31%)

Figure 7 shows the measured air exchange rate for the control and prototype houses in a typical 24-hour period under normal operating conditions. The graph also shows the measured natural air exchange rate for the prototype house. The control house air exchange rate varies from about 0.20 ACH at night to 0.50 ACH during the hottest part of the day. The prototype house ACH varies from about 0.13 at night to about 0.25 in the afternoon. Blower door tests indicated that leakage areas of the shell of the two houses were not significantly different. Most of the reduction in the prototype house air exchange rate is attributed to the improved air-distribution system and, specifically, to reduced duct leakage. The air exchange rate difference between the control and prototype houses increases as the air-conditioning system fan operating time increases. The natural ACH (under constant interior temperature with no fan operation) varies from 0.08 at night to 0.14 during the afternoon. **Table 8** shows the daily average air exchange rate. The control house has a daily average air exchange rate of 0.34 ACH, the prototype house has a daily average air exchange rate of 0.20 ACH, and the daily average natural air exchange rate is 0.11 ACH.

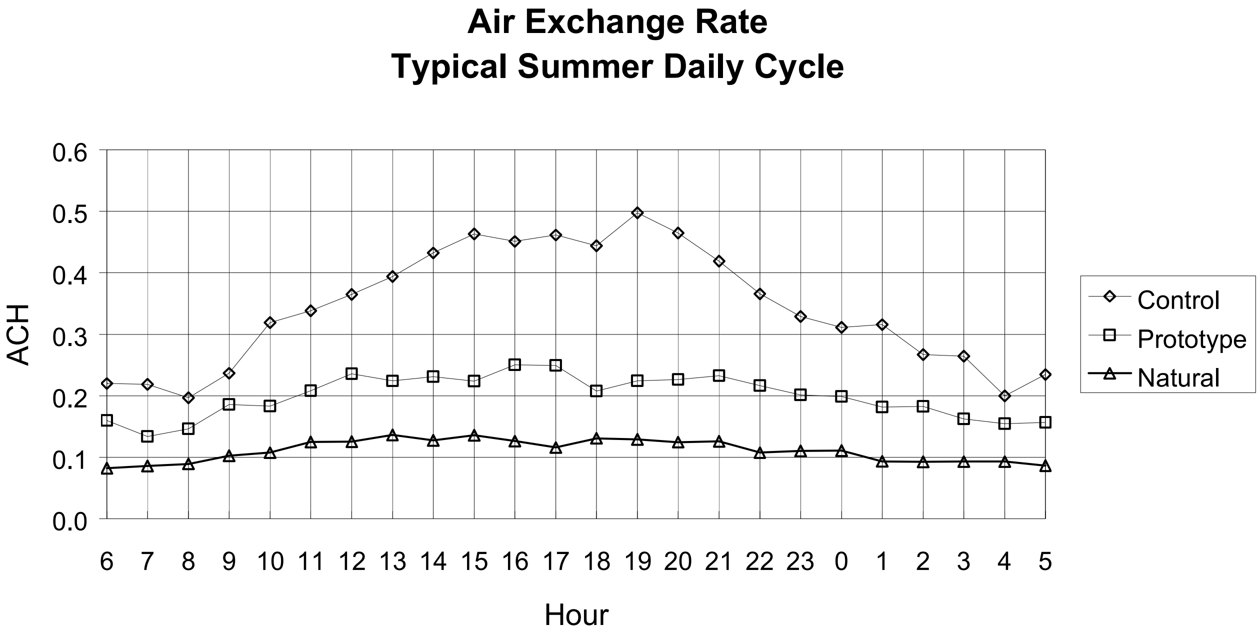

Figure 7. Hourly air exchange rate on a typical summer day.

Table 8. Summary of Air Change Rate Test Results

	Control	**Prototype**	**Natural** (prototype)
Days Averaged	204, 212, 213	204, 205	199, 200
Average Rate ACH	0.34	0.20	0.11
Range ACH	0.20 – 0.50	0.13 – 0.25	0.08 – 0.14

Figure 8 shows a time series graph of the measured interior room temperatures in the control house with three different glazing options. Each day exhibits a 24-hour variation, which we attribute to thermal lag of the thermostat and non-uniform air temperature of the rooms. When the windows are shaded with opaque exterior shades, the maximum variation in interior temperature is about 3°F. With clear unshaded glazing, the maximum daily variation is approximately 8°F. The rooms with east facing windows experience peak temperatures early in the day while west facing rooms experience even higher peak temperatures in the afternoon. The temperature excursions associated with clear glass windows might be judged as uncomfortable by occupants who might then be expected to apply window treatments to reduce solar gains. The temperatures shown in the last 2 days demonstrate that spectrally selective glazing mitigates the overheating problem associated with clear glazing.

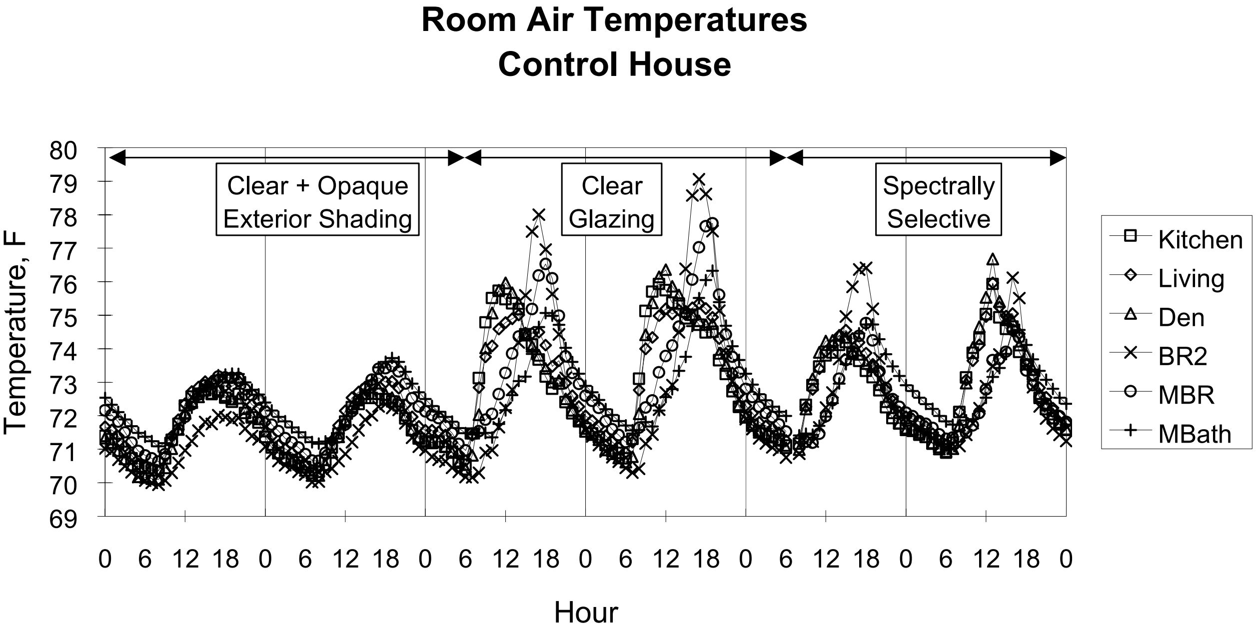

Figure 8. Hourly average room air temperatures for various window conditions in the control house.

The overall impacts of the design changes on daily cooling energy use are summarized in **Figure 9**. The window upgrade in the control house, from clear to spectrally selective glazing, results in a daily energy use savings of about 12%. The largest relative cooling energy use reduction is a result of the air-conditioning system upgrade, consisting of reduced duct losses and improved equipment efficiency. The upgrade in air-conditioning equipment efficiency alone reduces energy use about 20% (accepting that differences in SEER actually result in proportional differences in seasonal energy use). The combination of spectrally selective glazing and interior blinds is nearly as effective as opaque exterior shading.

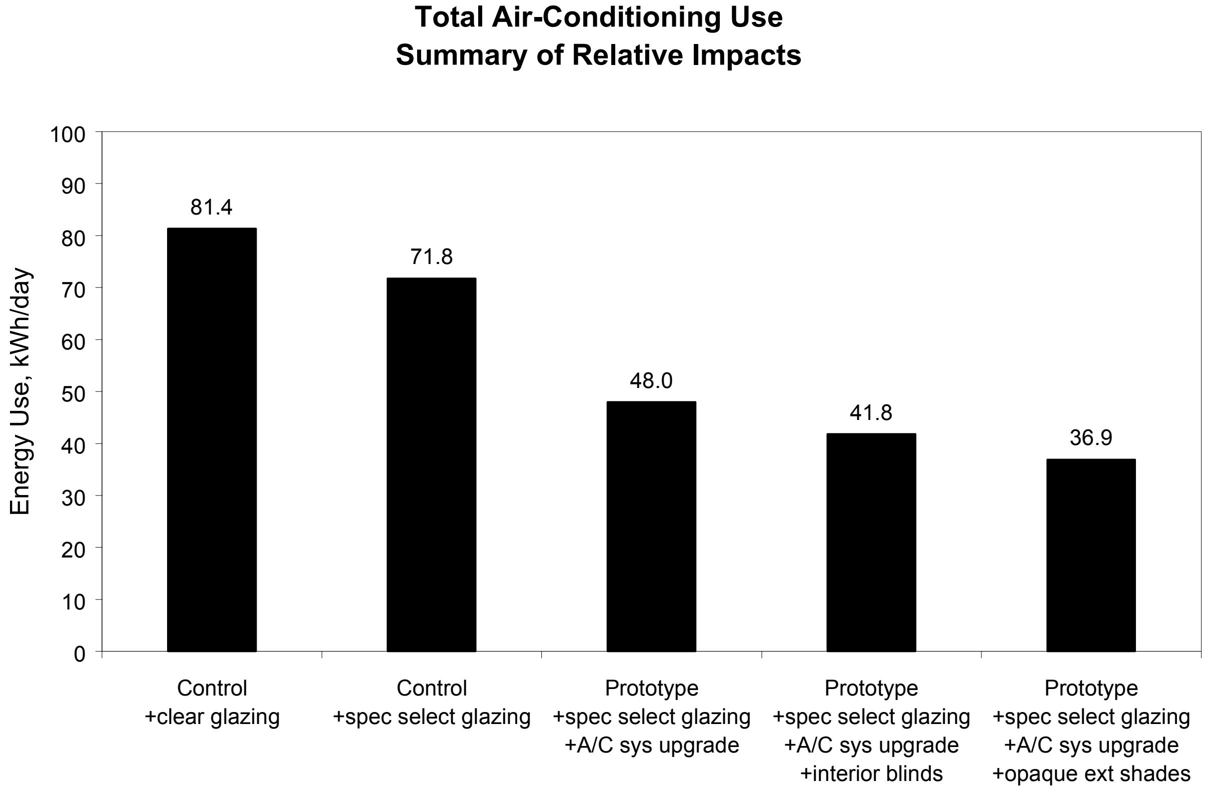

Figure 9. Daily electricity usage as a function of envelope and equipment performance.

Conclusions

Simple short-term testing techniques, including side-by-side and sequential protocols, were used to compare the performance benefits associated with integrated energy efficiency design changes in a residential building. In normal operation, the prototype saved 33.4 kWh/day compared to the control house, a reduction of about 40%. The peak demand was reduced by 2.4 kW, or more than 40%. When all the windows were totally shaded, the prototype saved approximately 21 kWh/day or 36% and reduced peak demand by 1.4 kW or about 40%, compared to the control house. This difference demonstrates the savings that result from improved performance by the prototype air-conditioning and air-distribution system. The prototype air-distribution system reduced unintended air exchange with the outside by 0.1–0.25 ACH compared to the control house. Spectrally selective windows reduced air-conditioning load by 12% and improved comfort, as demonstrated when the glazing was changed in the control house.

During peak cooling conditions, when the windows of both houses were unshaded, the standard-sized air-conditioning systems did not meet the peak cooling load in either house. Both air conditioners operated continuously for several hours while the room air temperatures drifted.

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