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Energy Savings and Peak Demand Reduction of a SEER 21 Heat Pump vs. a SEER 13 Heat Pump with Attic and Indoor Duct Systems

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BA-PIRC

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Energy Savings and Peak Demand Reduction of a SEER 21 Heat Pump vs. a SEER 13 Heat Pump with Attic and Indoor Duct Systems

Prepared for:

Building America

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Definitions

ADS	Air Distribution System
AHU	Air Handler Unit
BARBD	Building America Research Benchmark Definition
Btu	British Thermal Unit
COP	Coefficient of Performance – heating or cooling energy produced divided by the electrical energy input
CFM	Cubic Feet Per Minute
DHW	Domestic Hot Water
ECM	Electronically Commutated Motor
EER	Energy Efficiency Ratio -- Btus of cooling produced per Wh of electrical energy consumed
FPL	Florida Power & Light
FSEC	Florida Solar Energy Center
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilating & Air conditioning
kBtu/h	One Thousand British Thermal Units Per Hour
kWh	Kilowatt Hour
MELs	Miscellaneous Electric Loads
MH Lab	Manufactured Housing Laboratory (on FSEC campus)
NREL	National Renewable Energy Laboratory
RESNET	Residential Energy Services Network
RH	Relative Humidity
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
SHR	Sensible Heat Ratio
TMY	Typical Meteorological Year

Executive Summary

A new generation of fully variable-capacity HVAC units has come on the market, and they promise to deliver very high cooling efficiency. They are controlled differently than standard single-capacity systems. Instead of cycling on at full capacity and then cycling off when the thermostat is satisfied, they can vary their capacity over a wide range, thus staying “on” for nearly twice as many hours per day as the single-capacity systems. These types of systems have a greater impact on conductive losses of the duct system because cold air dwells in the ductwork (typically located in the attic) for longer periods of time.

Experiments were run in an unoccupied 1600 ft^2 house—the Manufactured Housing (MH Lab) at the Florida Solar Energy Center (FSEC)— to evaluate the delivered performance as well as the relative performance of a SEER 21 variable capacity heat pump versus a SEER 13 heat pump. The performance was evaluated with two different duct systems: a standard attic duct system and an indoor duct system located in a dropped-ceiling space. The design cooling load of the MH Lab is 1.5 tons, excluding any loads created by ductwork. The installed heat pumps are 3-ton units.

The two heat pumps were installed in the MH Lab house with the air handler units (AHUs) located side-by-side in the utility room. Each AHU could be attached to either the attic or indoor duct system. Instrumentation was installed to record the energy use of the various heat pump components as well as other appliances. Various temperature and humidity sensors were installed to record the heat pump system operation and environmental conditions indoors and in the attic. Weather data of temperature, relative humidity, solar radiation, rainfall, wind speed, and wind direction were recorded. Static pressures and air flows were measured in real time for each air handler and plenum.

Automated controls were implemented to activate various internal loads (both sensible and latent heat) to simulate occupancy of a three-person family. The oven, dishwasher, and showers were automatically cycled on and off at prescribed times to provide realistic internal loads as if the house were occupied.

The SEER 21 heat pump, which has a variable capacity compressor (varying in speed from 15 to 60 Hz and in capacity from 40% to 118% of nominal) and variable speed air handler fan operation, has the following two cooling modes: 1) standard control and 2) humidity control. In standard control, the system air flow varies generally in proportion to cooling capacity, with the exception that at lower capacity levels the air flow rates remain relatively high, moving air at about 700 cfm per ton. In humidity control mode, the air flow rate drops precipitously during lower capacity operation, moving only about 190 cfm per ton at the lowest system capacity.

A total of six experimental cooling configurations were examined: 1) SEER 13 unit with attic ducts, 2) SEER 13 unit with indoor ducts, 3) SEER 21 unit with attic ducts, 4) SEER 21 unit with indoor ducts, 5) SEER 21 with attic ducts and RH control set to 45%, and 6) SEER 21 with indoor ducts and RH control set to 45%. Heating experiments were also implemented using configurations 1 through 4.

Statistical analysis was used to develop best-fit lines and equations that characterize the relationship between daily cooling and heating energy use and outdoor minus indoor temperature. Least-squares, best-fit regression equations were developed. Coefficients of determination (r^2) values in the range of 0.85 to 0.97 provide high confidence in the predictive value of these best-fit lines and equations.

Statistical analysis was also performed to examine cooling and heating peak demand. Least-squares, best-fit regression equations were developed to characterize the relationship between peak hour energy use and the differential temperature of outdoor minus indoor temperature.

Experiments were run for both cooling and heating seasons, examining seasonal energy consumption and peak demand for both heat pumps and both duct systems.

Cooling seasonal savings. Based simply on SEER ratings, the SEER 21 unit should save 38.1% in seasonal cooling energy. Experiments were performed using both standard control and RH control (45% setpoint) for the SEER 21 unit. Simulations were implemented using the best-fit equations andTMY3 data for Miami, Orlando, and Atlanta. Based on the MH Lab experimental results, the SEER 21 unit fell short of its seasonal cooling energy rating by a small margin.

- With <u>indoor ducts</u>, analysis found that the SEER 21 system produced about 36% in seasonal cooling energy savings compared to the SEER 13 system in Miami and Orlando (about 28% in Atlanta) when using standard control and about 33.5% seasonal cooling energy savings compared to the SEER 13 system in Miami and Orlando (about 25% in Atlanta) when using RH control.
- With <u>attic ducts</u>, analysis found that the SEER 21 system produced about 36.5% in seasonal cooling energy savings compared to the SEER 13 system in Miami and Orlando (about 33% in Atlanta) when using standard control and about 34% seasonal cooling energy savings compared to the SEER 13 system in Miami and Orlando (about 31% in Atlanta) when using RH control.

Cooling peak demand savings. Based simply on EER ratings (95°F out, 80°F entering conditions), the SEER 21 unit should reduce cooling peak demand by 16.7%. Experiments were performed using both standard control and RH control (45% setpoint) for the SEER 21 unit. In the MH Lab experiments, the SEER 21 unit greatly exceeded expectations. Peak demand savings were calculated based on an outdoor temperature of 94°F, which is very close to the summer design temperatures for Miami, Orlando, and Atlanta.

- With <u>indoor ducts</u>, analysis found that the SEER 21 system produced 45.0% in cooling peak demand savings compared to the SEER 13 system when using standard control and 37.1% cooling peak demand savings compared to the SEER 13 system when using RH control.
- With <u>attic ducts</u>, analysis found that the SEER 21 system produced 22.7% in cooling peak demand savings compared to the SEER 13 system when using standard control and 19.6% cooling peak demand savings compared to the SEER 13 system when using RH control.

Seasonal heating savings. Based simply on the Heating Season Performance Factors (HSPF) of 8.0 and 9.6 for the SEER 13 and SEER 21 units, respectively, the SEER 21 unit would be expected to save 16.7% in seasonal heating energy. In the MH Lab experiments, the SEER 21 unit considerably outperformed its ratings.

- With indoor ducts, analysis found that the SEER 21 system produced on average about 40% in seasonal heating energy savings compared to the SEER 13 system in Miami, Orlando, and Atlanta.
- With attic ducts, analysis found that the SEER 21 system produced on average about 26.5% in seasonal heating energy savings compared to the SEER 13 system in Miami, Orlando, and Atlanta.

Heating peak demand savings. Based simply on manufacturer COP ratings (rating at 42°F delta-temperature and SEER 21 medium capacity), the SEER 21 unit should reduce heating peak demand by 4.7%. Based on the experimental data from the MH Lab, the SEER 21 unit greatly exceeded expectations. Peak demand savings were calculated based on an outdoor temperature of 30°F.

- With indoor ducts, analysis found that the SEER 21 system produced 23.8% in heating peak demand savings compared to the SEER 13 system.
- With attic ducts, analysis found that the SEER 21 system produced about 21.5% in heating peak demand savings compared to the SEER 13 system.

Impact of duct location. Experiments found substantial reductions in seasonal and peak demand energy consumption when switching from attic to indoor ducts. The MH Lab house has a medium-color asphalt shingle roof. On summer days, the peak attic temperature reaches about 125°F, or 35°F warmer than outdoors, and the daily average attic temperature is about 96°F, or 14°F warmer than outdoors. The following cooling and heating seasonal savings were obtained based on simulations using the experimentally derived best-fit equations and TMY3 data for Miami, Orlando, and Atlanta.

- Switching from attic to indoor duct system produces about 8% seasonal cooling energy savings for the SEER 21 unit and about 13% seasonal cooling energy savings for the SEER 13 unit.
- Switching from attic to indoor duct system produces about 25% seasonal heating energy savings for the SEER 21 unit and about 6% seasonal heating energy savings for the SEER 13 unit.

The impact of locating ductwork indoors is much greater at the peak summer hour (94°F out) and somewhat greater at the peak winter hour (30°F).

- Switching from attic to indoor duct system produces 38.8% peak cooling demand savings for the SEER 21 unit but only 14.0% peak cooling demand savings for the SEER 13 unit.
- Switching from attic to indoor duct system produces 14.9% peak heating demand savings for the SEER 21 unit and 12.3% peak heating demand savings for the SEER 13 unit.

1 Background

Nordyne has introduced a new line of variable capacity air conditioning and heat pump systems (using the "iQ Drive" system), which are marketed through a number of brand names including Frigidaire, Westinghouse, Maytag, and Nutone. They have achieved very high efficiency ratings. The straight cool units have energy efficiency ratings in the range of SEER 22 to 24.5. The heat pump units have efficiency in the range of SEER 21 to 23.

Unlike traditional cooling systems that cycle on and off, either on at full capacity or off, the iQ Drive system modulates capacity from 40% to 118% of nominal. The three-ton iQ Drive heat pump used in these experiments has nominal 35,000 Btu/h cooling capacity and nominal 34,000 Btu/h heating capacity. At lowest capacity, this heat pump produces 14,000 Btu/h (1.17 tons) of cooling. At highest capacity, this heat pump produces 41,300 Btu/h (3.44 tons) of cooling. In actual fact, then, capacity of this heat pump varies by a factor of three, from 34% to 100% of maximum capacity.

This system achieves very high energy efficiency when operating at a small fraction of its total capacity. Energy efficiency is about 30% higher when operating at 40% capacity compared to 80% capacity for the same outdoor temperature range. While operating in low-capacity mode, the evaporator and condenser coils are considerably oversized, allowing efficient heat exchange. Additionally, the compressor operates more efficiently when operating at lower speeds (as low as 15 Hz). Throughout most of the day, the unit does not turn off but rather shifts to a lower capacity. While a typical air conditioner operates about 30%-35% of the time on a typical summer day, the Nordyne iQ Drive units operate for about 65%-70% of the time on a typical summer day (this will, of course, vary depending upon the load to capacity ratio for individual homes). As a consequence, cold air remains in the ductwork a large majority of the time, and conductive heat losses would be expected to be greater than with a traditional fixed-capacity system. Furthermore, losses due to duct leakage may be greater for the iQ Drive system than a traditional on/off system. It is anticipated that experiments in future years will examine duct air leakage losses for the iQ Drive system.

The iQ Drive system has two operation modes; standard control and humidity control. In standard control mode, the air flow rate of the air handler remains relatively high when the compressor is operating at low capacity, and the sensible heat ratio (SHR) is therefore high. In the alternative RH control mode, an indoor relative humidity (RH) setpoint can be selected that prompts the AHU to operate with greatly reduced air flow, which lowers the equipment sensible heat ration (SHR) and yields lower indoor RH. Additional discussion of how the iQ Drive system operates is contained in the section titled "SPACE COOLING: How the Variable Capacity SEER 21 Heat Pump System Operates."

This report presents the results of Phase 1 of a proposed multiyear, multiphase research project. This project characterizes how a SEER 21 heat pump performs compared to a SEER 13 heat pump when operating with: airtight attic ducts; indoor ducts; RH control activated (and without); ducts that leak to attic and outdoors; various installed capacity-to-load ratios; and better insulated ducts.

Phase 1 experiments have specifically examined the impact of conductive losses of an attic duct system upon the energy efficiency of a variable capacity SEER 21 heat pump compared to a fixed capacity SEER 13 heat pump. It was anticipated that duct conductive losses would be greater for the variable capacity (SEER 21) system, because it was estimated that cooling system operation time might be about double that of the SEER 13 system. Since the iQ Drive system in standard mode operates with a relatively high cfm/ton, and that this air flow rate yields relatively warm supply air (at low capacity, where the machine operates most of the time), and somewhat elevated indoor RH, it was important that the iQ Drive system also be examined when operating in humidity control mode (which has very low cfm/ton and very cold supply air). Therefore, the conductive losses of the SEER 21 system are compared to those of a standard fixed-capacity SEER 13 heat pump, with the SEER 21 unit operating in standard control mode and in RH control mode (RH setpoint set to 45%). Future experiments will examine the impacts of duct leakage, equipment capacity to load ratio, and duct R-value.

In Phase 1 (2010 experiments), six cooling configurations have been examined: 1) SEER 13 unit with attic ducts, 2) SEER 13 unit with indoor ducts, 3) SEER 21 unit with attic ducts, 4) SEER 21 unit with indoor ducts, 5) SEER 21 with attic ducts and RH control set to 45%, and 6) SEER 21 with indoor ducts and RH control set to 45%.

While central Florida does not normally have a cold and lengthy heating season, considerable heating data was also obtained during the period January 2010 through March 2011 for the SEER 21 and SEER 13 units operating with the attic and indoor duct systems. This was achieved in part by selecting a relatively high heating thermostat setpoint (75^{o}F) and reducing the automated internal sensible and latent loads being delivered to the space.

1.1 Setting Up the Experiments

An experimental facility called the MH Lab, located on the FSEC campus, was selected to carry out these experiments. The MH Lab is a 1600 ft^2 double-wide manufactured home with a crawl space, a vented attic, three bedrooms, and two bathrooms. The house was manufactured in January 2002. Two AHUs for 3-ton SEER 13 and SEER 21 heat pumps were installed side-by-side inside the conditioned utility room of the house. The lab has two duct systems, one in the attic and one indoors. The heat pumps can be attached to either duct system.

Static pressure of the ductwork affects AHU fan air flows and energy consumption. Attempts were made to modify the air distribution system (ADS) to minimize and equalize static pressure in two duct systems. Supply plenums were constructed with the intent to minimize static pressure and make the pressure drop between the two duct systems as close to equal as possible. This was largely successful. Return air for both duct systems is located completely within the conditioned space adjacent to the AHUs. The supply ducts of the attic system have R-6 insulation and 1% duct leakage (all supply leaks, there are no return leaks to unconditioned spaces) to outdoors. The indoor ducts are located in a drop-ceiling space and are also insulated to R-6.

A data acquisition system was installed to record a variety of information regarding the heat pump operation, energy consumption of various items within the house, and indoor and outdoor conditions. Temperature and RH of air flowing into and out of the heat pump system are recorded only when the heat pump is operating.

- Temperatures are recorded at the entrance to the return (which is in the conditioned space and is less than 2 feet long), the discharge from the AHU, and at five supply registers (for each duct system). Temperatures are recorded entering the condenser coil (outdoor unit). Temperatures are also recorded at various indoor locations, in the attic, in the crawl space, and at various locations on the roof system.
- Relative humidity is recorded at the entrance to the return and the discharge from the AHU. RH is also recorded at various indoor locations, in the attic, in the crawl space, and outdoors.
- The air flow rate of the two systems is recorded at the entrance to the return. Since there were no return leaks during these Phase 1 experiments, this measurement represents total system air flow.
- Power meters were installed to record energy use for the house, the heat pump outdoor unit, the heat pump AHU, the refrigerator, the water heater, the oven, heat lamps that simulate internal loads, and the dishwasher.
- Condensate draining from the AHU is measured by a pair of tipping buckets that provide redundant measurement of moisture removed by the cooling coils.
- Weather conditions of air temperature, relative humidity, rainfall, wind speed/direction, and solar radiation (on the horizontal) are measured.

1.2 Internal Loads to Simulate Occupancy

The MH Lab is an unoccupied home. In occupied homes, the activities of occupants and appliances generate heat, which adds to the cooling load and reduces the heating load. This added heat is in the form of both sensible heat and latent heat. In order to carry out these experiments in the MH Lab, it was determined that cooling loads should be realistically representative of an occupied residence, because the presence of humans and human activities create a significant portion of the cooling load of the residence. This human-influenced load also has a particular latent versus sensible relationship, which affects the total load SHR and indoor RH.

Internal loads are automatically generated in the MH Lab to simulate occupancy of a three-person family. A detailed discussion of internally generated loads and occupant activities is presented in Appendix A, which contains schedules of occupant activities and internal loads. A shorter discussion of internal loads follows in this section. In most cases, the source for the occupancy or load schedule is “Building America Research Benchmark Definition” (BARBD), written by Robert Hendron of NREL and updated December 19, 2008. Throughout this document, the acronym BARBD refers to the December 2008 version of this document.

Internal loads can be generated by automatically operating various appliances on a schedule. In the MH Lab, we have automated the operation of the oven, dishwasher, and showers. Additionally, the electric water heater (located in the utility room) and the refrigerator operate (cycle) in a normal fashion except that the doors to the refrigerator and dishwasher remain closed.

Internal loads can also be simulated by means of alternative heat and water vapor sources. We use two heat sources to simulate all other sources of sensible heat—the kitchen oven and heat lamps. The oven cycles on 11 times throughout a day (the MH Lab is operated as if all days were week days) typically for 20 to 40 minutes at a time. Each oven "on" cycle is sufficiently short so that the oven does not reach its target temperature setting, and the oven heating element therefore operates continuously at full capacity during the "on" cycle. Two floor fans and a ceiling fan operate continuously to distribute the heat from the kitchen to other spaces within the house. The heat lamps are located in the living room, kitchen, and master bedroom, and together run continuously throughout the day, varying in energy output from 44W to 472W.

Latent heat is added to the space in part through operation of the master bedroom shower and by operation of the dishwasher. Together, these two appliances consume approximately 46 gallons per day. Only a small fraction of the water consumed by the shower and dishwasher enters the indoor air; most goes down the drains. Latent heat is also added to the space by means of water metered into an evaporation pan located in the oven, representing latent load that would come from house occupants (perspiration and respiration), cooking, and the refrigerator (from moisture in the refrigerator that would enter the space through door openings).

Based on Equation 16 from BARBD, the dishwasher would be operated 215 times per year, or 4.1 times per week. In order to reduce day-to-day variability in internal loads, the research team determined that it would be better for our experiments if the dishwasher were operated once each day. The electric heat drying cycle was not activated in the dishwasher.

2 How the Variable Capacity SEER 21 Heat Pump Operates

The iQ Drive system found in the SEER 21 heat pump allows three elements of the cooling system to vary: AHU fan speed, compressor speed, and condenser fan speed. AHU and compressor speed varies from 15 to 60 Hz. The condenser fan speed also varies, but it is not clear how it is controlled.

As discussed earlier, the SEER 21 heat pump has two cooling modes: standard control (no RH control setpoint) and RH control (user selectable RH setpoint). In standard mode, compressor capacity declines in response to reduction in cooling load. This decline in cooling load is detected based on room air temperature deviation from setpoint. As room temperature falls below the setpoint, the unit does not (at first) turn off, but rather the compressor slows until it reaches lowest capacity (40% of nominal). The AHU fan speed for this 3-ton system declines as well but maintains a flow rate equal to about 770 cfm (about 60% of full flow) when operating at minimum capacity. In this circumstance, the supply air temperature is fairly warm (typically about 12^{o}F cooler than the return air) and the system SHR is fairly high (~ 0.9 SHR). Because the AHU fan uses an electronically commutated motor (ECM), the energy consumption of the fan is much lower than a standard shaded-pole motor, particularly when operating at fractional speed.

In humidity control mode, compressor capacity declines in response to reduction in cooling load, but AHU fan speed declines even more on a percentage basis. While AHU air flow (at minimum capacity) is on the order of 770 cfm in standard mode, it declines to as low as 230 cfm in RH control mode. The transition to low air flow in the RH control mode (with cooling capacity at minimum, which is about 14,000 Btu/hr) occurs gradually over a period of 5 to 10 minutes. As the air flow rate declines, the supply air temperature also declines, falling steadily to 55^{o}F, 50^{o}F, 45^{o}F, and even down to 38^{o}F. At these lower air flow rates and lower supply air temperatures, SHR drops sharply. When the coil temperature reaches 38^{o}F, a low temperature limit is triggered (to prevent icing of the coil) and the fan air flow rate jumps suddenly to about 800 cfm, raising the supply air temperature to near 60^{o}F within a period of about 1 minute. After running at this higher fan speed for a short period of time, it then reverts to RH control mode with gradually slowing fan speed and lowering supply air temperatures. The entire cycle often takes about 15 to 20 minutes from start to finish and will repeat itself many times throughout the day as long as the indoor RH level (measured by the humidity sensor in the thermostat) is above the RH setpoint.

In heating mode, the heat pump varies capacity and AHU fan speed in much the same manner as the standard cooling mode. Instead of cycling off, compressor speed and capacity decline as the room air temperature rises relative to the thermostat setpoint. AHU fan speed also declines but not as precipitously as the compressor speed and capacity.

3 Cooling Energy Savings

Analysis has been performed to characterize the energy efficiency of the two heat pump systems, and the relative efficiency of the SEER 21 unit compared to the SEER 13 unit. Figure 1 shows data collected during the period of May 1 through November 30, 2010. Six different experimental configurations were examined: 1) SEER 13 with attic ducts; 2) SEER 13 with indoor ducts; 3) SEER 21 with attic ducts; 4) SEER 21 with indoor ducts; 5) SEER 21 (45%) with attic ducts; and 6) SEER 21 (45%) with indoor ducts. Note that “SEER 21 (45%)” refers to operation of the SEER 21 system in humidity control mode with RH control set to 45%. The SEER 21 (45%) configurations are an important variation because the standard control mode of the SEER 21 unit is optimized for energy savings and may not achieve the desired level of indoor humidity in some or even many circumstances.

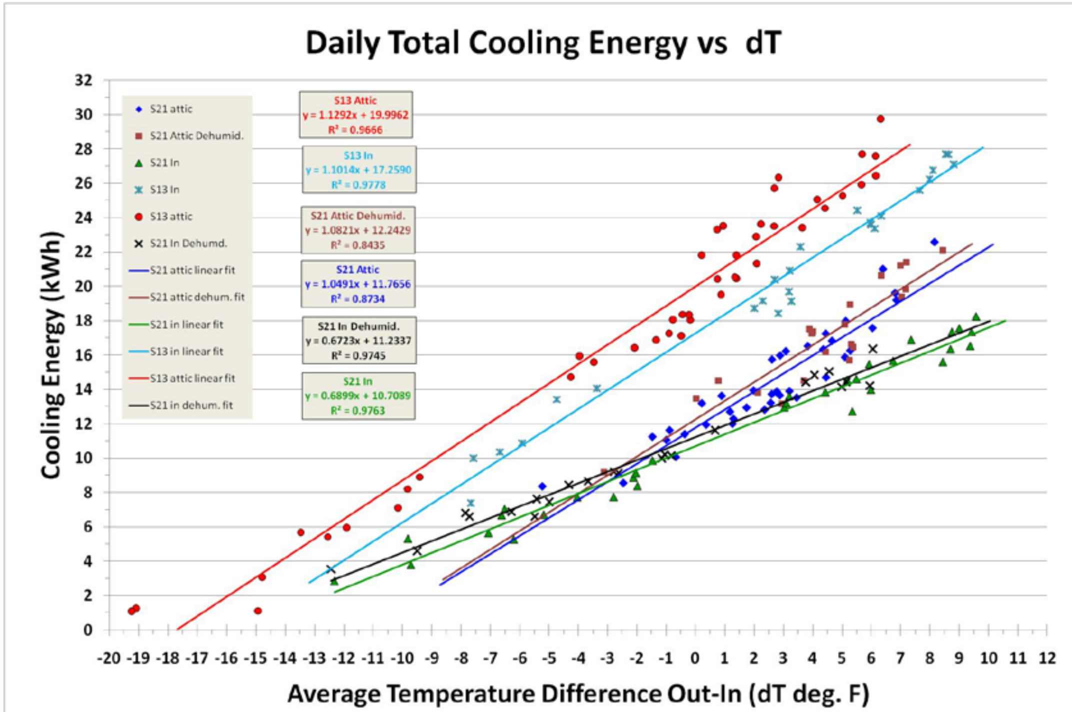

Figure 1. Cooling energy use as a function of delta-T (outdoor minus indoor temperature), including daily data points, best-fit lines, and best-fit equations.

Table 1 shows average daily indoor and outdoor temperatures, RH, and system runtime for each experimental configuration for all experiment days for the period from May 1 through November 30, 2010. This includes a substantial number of days that would not be considered typical hot and humid summer weather, especially in early May and throughout much of October and November.

Table 1. Average indoor temperature, indoor RH, and cooling system runtime for all experimental periods from May 1 through November 30, 2010, including lower outdoor dew point temperature weather.

	S13 attic	S21 attic	S21 (45) attic	S13 in	S21 in	S21 (45) in
Average outdoor temperature (^oF)	75.2	79.5	75.2	80.6	78.1	75.0
Average indoor temperature (^oF)	76.9	76.6	77.0	77.7	76.3	76.0
Delta-temperature (out-in; (^oF))	-1.7	2.9	-1.8	2.9	1.8	-1.0
Indoor RH	48.7	52.9	51.0	49.4	55.1	53.3
Cooling system runtime (%)	26.3	63.7	68.2	29.2	50.7	44.7

Table 2 shows average daily indoor and outdoor temperatures, RH, and system runtime for each experimental configuration for all experiment days when the outdoor dew point temperature was 70^oF or higher (in other words, for days that can be considered primarily hot and humid).

Table 2. Average outdoor and indoor temperature indoor RH, and cooling system runtime for periods with outdoor dew point temperature of 70°F or higher.

	S13 attic	S21 attic	S21 (45) attic	S13 in	S21 in	S21 (45) in
Average outdoor temperature (°F)	82.1	81.8	82.4	81.5	83.4	81.6
Average indoor temperature (°F)	77.4	76.6	77.0	78.1	76.8	76.6
Delta-temperature (°F)	4.7	5.2	5.4	3.4	6.6	5.0
Indoor RH	48.6	52.2	51.4	48.9	55.1	53.4
Cooling system runtime (%)	37.5	72.0	71.9	28.9	68.2	65.4

During hot and humid weather, the SEER 13 system consistently produces lower indoor RH than the SEER 21 system. The SEER 13 system produces 46% RH with either the attic or the indoor duct system. The SEER 21 system in normal control mode produces 50% RH with the attic duct system and 53% with the indoor duct system. The SEER 21 system in humidity control mode (set to 45%) produces 49% RH with the attic duct system and 51% with the indoor duct system.

System runtime is approximately twice as great for the SEER 21 system as the SEER 13 system. This occurs because the SEER 21 system spends the greatest majority of its time operating at or near minimum capacity; it often stays on for 10 hours at a time on hot summer days, and then cycles during the remaining 14 hours of the day. On a typical summer day, the SEER 21 system runs for about 16.5 hours while the SEER 13 system runs for about 8 hours per day (9 hours with the attic ducts and 7 hours with the indoor ducts).

3.1 Cooling Energy Regression Analysis

Daily cooling energy use (including standby energy use of the heat pumps) is plotted versus outdoor-indoor temperature differential. Least-squares regression analysis finds best-fit lines that are defined by the equations shown in Figure 1.

R^2 values are remarkably high, in the range of 0.97, for four of the experimental configurations, indicating that approximately 97% of the variability in daily energy use is predicted by delta-T alone. In two other experimental configurations (two SEER 21 experiments with attic ductwork, the R^2 values are about 0.85), still indicating high confidence in the results. While the thermostats were in all cases set to 76°F, room temperature averaged 76.9°F throughout the experiments (based on average of five locations in the Lab house). However, indoor temperature varied considerably (by as much as 1.7°F from one configuration to another) depending upon which system was operating (the SEER 13 and SEER 21 systems had their own separate thermostats) and upon which duct system was being used (the duct systems discharged different amounts of air into various rooms). Ceiling and floor fans were used to increase air mixing and to achieve uniform space temperature.

3.2 Cooling Energy Savings for Typical Summer Day

Cooling energy use has been normalized to delta-temperature (T_{out} minus T_{in}, where T_{in} is based on a five-room average) and to solar radiation. Best-fit least-squares regression lines are defined by equations in the form of Y = A + B(X), where Y is the daily cooling electrical energy use and X is the daily average temperature difference between indoors and outdoors, based on data collected from May 1 through December 1, 2010. Table 3 presents the intercepts and coefficients for all six experimental configurations and average daily energy use and savings at 82°F (typical summer day).

Table 3. Best-fit equation intercepts and coefficients in the form of Y = A + B(X), where Y is the daily cooling electrical energy use and X is the daily average temperature difference between indoors and outdoors.

	S13 attic	S21 attic	S21 (45) attic	S13 in	S21 in	S21 (45) in
(A) Wh/day	19996.2	11765.6	12242.9	17259	10708.9	11233.7
(B) Wh/day-°F	1129.2	1049.1	1082.1	1101.4	689.9	672.2
Wh/day @ 82°F (delta-T = 5oF)	25642	17011	17653	22766	14158	14595
Savings vs. SEER13 attic ducts	-	33.7%	31.2%	11.2%	44.8%	43.1%
Savings vs. SEER 13 indoor ducts	-	-	-	-	37.8%	35.9%
Savings indoor ducts vs. attic ducts	-	-	-	11.2%	16.8%	17.3%
Savings SEER 21 v SEER 21 (45%)	-	3.6%	-	-	3.0%	

Analysis finds that delta-temperature accounts for nearly all of the variability in daily energy use. Solar radiation, however, does account for a small fraction of the variability. Days with solar radiation (on the horizontal) of more than 5,880 Wh/m^2 typically had greater cooling energy use relative to the best-fit line. Outdoor temperature has been adjusted up or down based on total daily solar radiation measured on a horizontal surface. In this adjustment, variations in solar radiation above and below 5,880 watt-hours per square meter per day are used to add to or subtract from the daily average outdoor temperature. The adjustment was based on regression analysis of the difference of measured–predicted dT (delta dT) versus the measured average solar radiation during the cooling season (delta solar). The solar adjustment of outdoor temperature was obtained in the following manner: 1) calculate delta solar as measured-solar minus solar-base (5,880 Wh/m^2-day); 2) calculate dsol = delta solar/solar base; 3) calculate solar adjustment using -3.1605 x dsol + 0.1628 = dT adjustment; and 4) subtract dT adjustment from measured dT. For experiments using the indoor duct system, typical adjustments to the average daily outdoor temperature are in the range of $\pm$0.9°F with a maximum of 2.6°F. For the attic duct system, typical adjustments to the average daily outdoor temperature are in the range of $\pm$0.8°F with a maximum of 2.7°F.

The best-fit equations can be used to predict cooling system energy use as a function of (solar adjusted) delta-temperature. Using the best-fit equations and a typical summer day with an outdoor temperature of 82°F, the following energy savings are found. (Note: based on SEER ratings alone, one would expect 38.1% cooling energy use savings for the SEER 21 unit compared to the SEER 13 unit. Later in this report, yearly cooling energy savings are calculated using TMY3 data for three representative cities in the southeastern United States.)

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 35.9% compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 37.8% compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 3.0% compared to the SEER 21 unit with RH control active.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 31.2% compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 33.7% compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 3.6% compared to the SEER 21 unit with RH control active.

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 17.3% when employing RH control (45% setpoint). Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 20.9%.
- For the SEER 21 system (no RH control active), switching from the attic duct system to the indoor duct system saves 16.8%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 20.2%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 11.2%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 12.6%.
- It is reasonable that the energy penalty associated with using the attic duct system would be much greater for the SEER 21 system compared to the SEER 13 system, because the SEER 21 system runtime is nearly twice as great compared to the SEER 13 unit (72% of the time for the SEER 21 system versus 38% for the SEER 13 system during hot and humid weather). Therefore, conductive heat transfer from the attic to the duct interior operates for nearly twice the length of time for the SEER 21 unit.
- It is also reasonable that the energy penalty associated with using the attic duct system would be even greater when the SEER 21 system is in RH control mode (compared to without RH control) because the average supply air temperature is colder (compared to when the RH control is deactivated). The SEER 21 system runtime with RH control is slightly shorter than the SEER 21 system with standard control, but this may be due to the considerably hotter weather when the SEER system with standard control was operating.
- Note that most of the losses associated with the attic duct system are conductive losses, because there are no return leaks, air leakage of the supply ducts represents only 1.5% of the system air flow, and the AHUs and returns are in the conditioned space. Attic

temperatures during typical summer weather have a daily average of about 96°F and an average afternoon peak of about 125°F. It is assumed that duct losses from the indoor duct system are relatively small and that nearly all of the energy lost from the indoor ductwork finds its way back into the conditioned space.

Weather data collected at the MH Lab shows that for the period June 1 through September 30, 2010, the average outdoor temperature was 82.0°F. The coolest day for this 4-month period was 74.7°F while the hottest day was 86.1°F. The average indoor temperature throughout the cooling experiments was 76.9°F.

3.3 Measured Cooling Efficiency and Performance Correlations

Heat pumps become more energy efficient in cooling mode as outdoor conditions become cooler. Figure 2 shows that SEER 13 heat pump efficiency is about 66% higher when outdoors is 75°F compared to when outdoors is 95°F, based on MH Lab measured data (COP = 4.30 at 75°F and COP = 2.59 at 95°F; COP is coefficient of performance and is defined as energy produced by the unit divided by the electrical energy input to the unit).

The SEER 21 heat pump cooling efficiency also increases as it goes to part-load operation. Figure 3 plots SEER 21 cooling COP as a function of both outdoor temperature and capacity fraction, for the period of August 17-23, 2010. Each of the best-fit lines represents the efficiency of the SEER 21 heat pump for a bin of 15-minute periods representing an outdoor temperature range. Energy efficiency is about 60% higher for the 74-78°F outdoor temperature bin compared to the 93-98°F outdoor temperature bin. As shown in Figure 2, the SEER 21 system operates almost exclusively in the range of 40% to 80% capacity factor. Energy efficiency is about 30% higher when operating at 40% capacity compared to 80% capacity for the same outdoor temperature range.

Therefore, for both heat pumps, there would be an advantage to operating the cooling system more during cool hours of the day (e.g., sub-cooling the house at night and raising indoor temperature during the day or using the SEER 21 unit in a very high mass home such as with block walls and concrete slab floor). The SEER 21 heat pump also benefits from operating the system at part-load (e.g., oversizing the system to keep it operating at small fractional capacity most of the time). The SEER 21 unit achieves much of its energy efficiency advantage (compared to the SEER 13 unit) by operating at minimum capacity (about 40% capacity) for a large majority of the time.

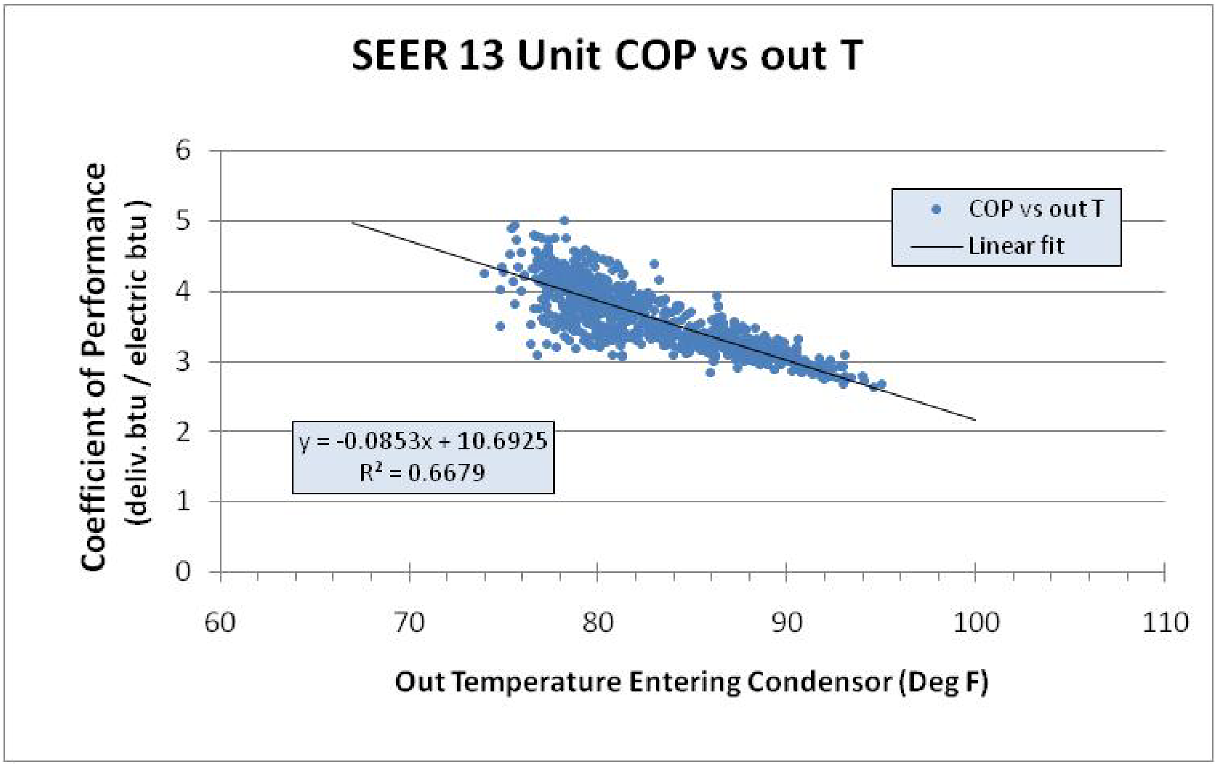

Figure 2. SEER 13 system measured cooling COP versus outdoor temperature.

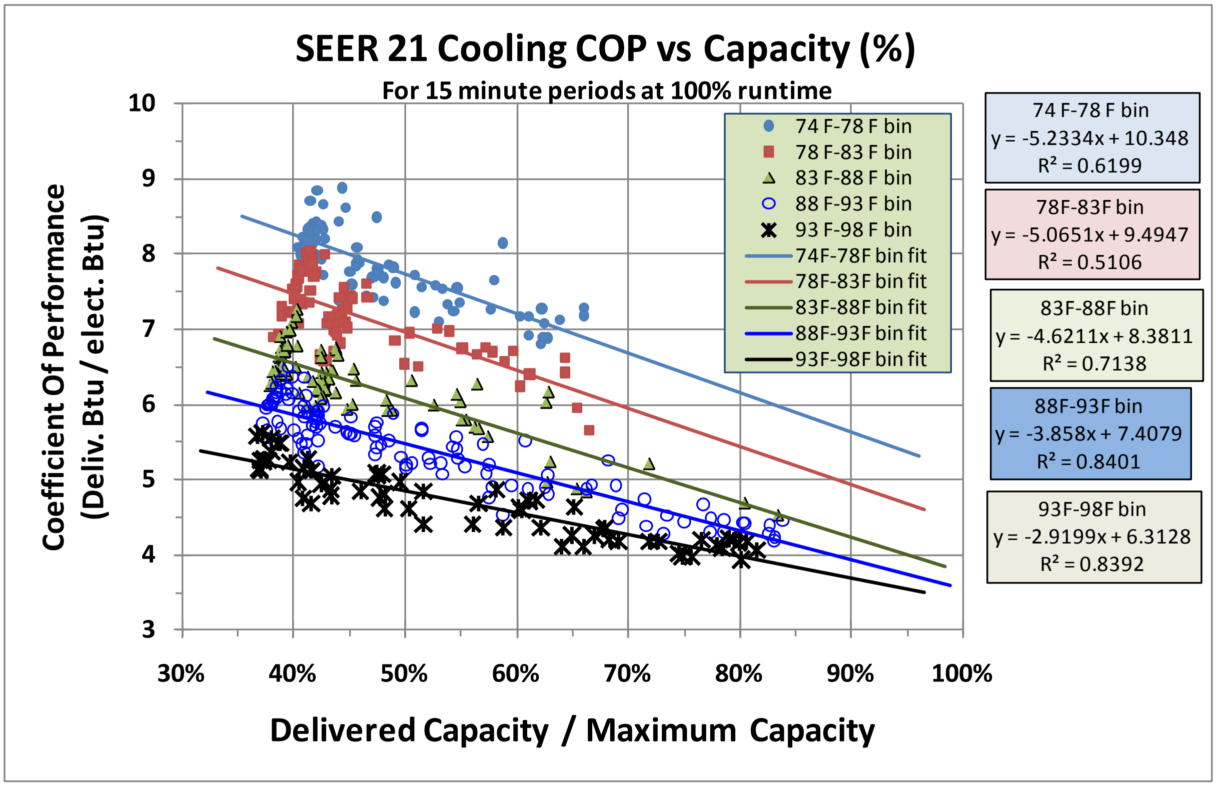

Figure 3. SEER 21 system measured cooling COP versus capacity fraction for various outdoor temperature bins.

3.4 AHU Fan Energy Savings

The SEER 21 heat pump uses an ECM for the AHU fan. The energy consumption of the fan is low compared to the shaded pole motor of the SEER 13 unit, especially at part-speed. SEER 21 AHU fan energy measurements were taken at various fan air flow rates (Figure 4).

When operating in standard system control (no RH setpoint employed), the SEER 21 AHU air flow rate is typically at about 770 cfm when operating at minimum capacity. Hence, while the cooling capacity is 40% of nominal full capacity, the AHU air flow rate is at about 61% of nominal full capacity. Fan power at 770 cfm is about 101 W. By contrast, the SEER 13 AHU fan consumes about 400W when it operates (when on, it always operates at full flow of about 1290 cfm). The SEER 21 AHU fan consumes 390W at 1,270 cfm, which is 2.5% less than the SEER 13 fan motor power. The SEER 13 AHU fan produces 3.2 cfm/watt, and the SEER 21 AHU fan provides 3.25 cfm/watt when operating at full nominal speed. When the SEER 21 system is operating at lowest capacity in standard control mode, the fan moves about 770 cfm using 101W, producing about 7.6 cfm/watt.

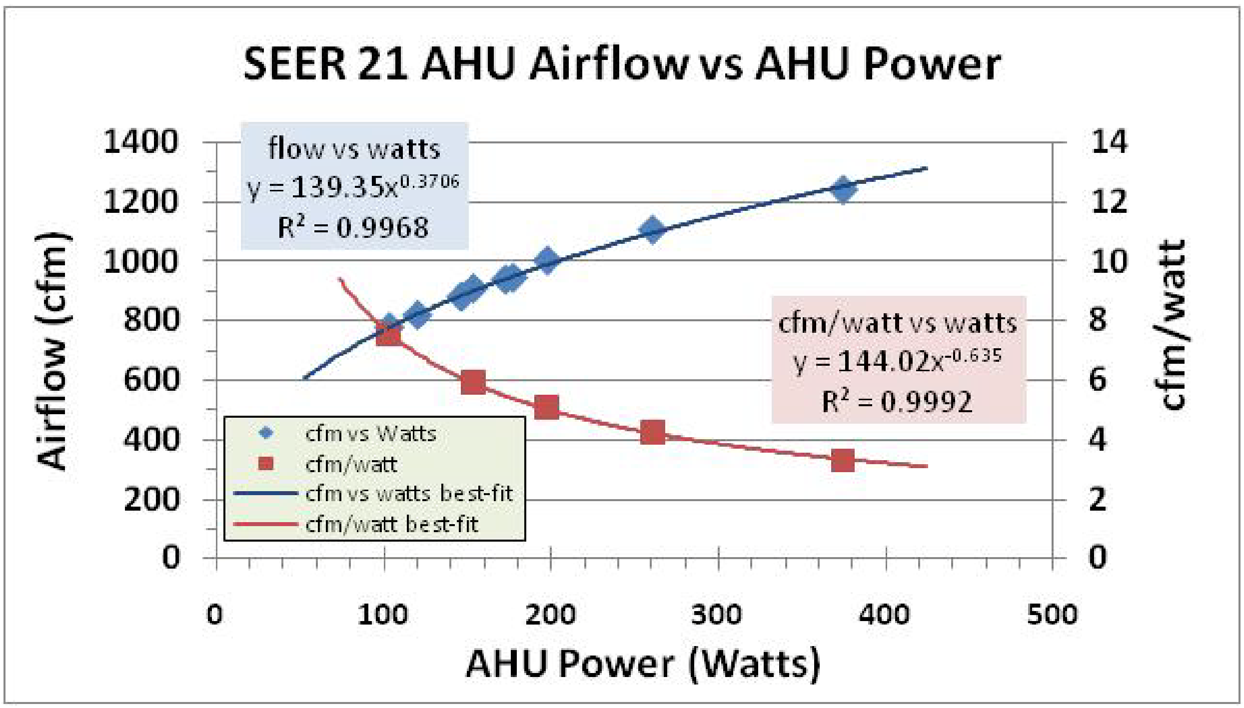

Figure 4. SEER 21 heat pump AHU fan power consumption measured in the lab.

Under RH control mode, the SEER 21 fan speed is slowed to reduce the supply air temperature and lower the equipment SHR (especially at low system cooling capacity), with flow rates as low as 230 cfm. At 230 cfm, the AHU power consumption is a remarkably low 29 W, including standby energy consumption. When the 25W of AHU standby energy consumption is subtracted, the AHU fan is found to consume 4W at 230 cfm, producing a robust 58 cfm/watt.

Clearly, there are large energy efficiency benefits of operating the heat pump at part load, including dramatically reduced fan energy use.

3.5 Standby Energy Use of the SEER 21 and SEER 13 Heat Pumps

The two heat pumps included in this study have considerable standby energy consumption. When the SEER 21 unit is not operating, it consumes about 80W; 25W for the AHU and 55W for the outdoor unit. The SEER 13 heat pump has standby losses of about 43W (46% less than that of the SEER 21 unit); 13W for the AHU and 30W for the outdoor unit. This standby energy consumption, for both heat pumps, occurs even if the thermostat is switched to OFF. The standby energy consumption (circuit boards, transformers, etc.) continues when the units are producing heating or cooling. If the SEER 21 unit is in standby mode for say, 60% of the hours of the year, then its standby losses (for the periods when the system is off) would be 420 kWh/year. If the SEER 13 unit is in standby mode for say 80% of the hours of the year, then its standby losses (for the periods when the system is off) would be 377 kWh/year. For either system, the standby electricity consumption cost would be in the range of $38 to $42 per year, assuming electricity cost of $0.10/kWh. It is important to note, however, that the seasonal and peak demand savings reported in this document include the stand-by energy consumption.

3.6 Annual Cooling Energy Savings for Three Cities

Cooling energy savings have been calculated (simulated) for the MH Lab house for three cities in the southeastern United States—Miami, Orlando, and Atlanta. Daily cooling energy consumption has been calculated using TMY3 data along with the best-fit equations for both the SEER 13 and SEER 21 heat pumps.

Annual cooling energy consumption has been calculated using the regression formulas that define the relationship between average daily delta-temperature (outdoors - indoors) and cooling energy use from the SEER 21 MH Lab experiments and TMY3 weather data for each of the three cities. Cooling energy use is calculated for each day of the year based on the average daily outdoor temperature. The calculated (simulated) daily cooling energy is summed for all days of the year (negative cooling energy values are treated as zero) for each of the following six experimental configurations: 1) SEER 13 with attic ducts, 2) SEER 13 with indoor ducts, 3) SEER 21 with attic ducts, 4) SEER 21 with indoor ducts, 5) SEER 21 (45%) with attic ducts, and 6) SEER 21 (45%) with indoor ducts. Note that the calculated cooling energy consumption is for the 1600 ft^2 MH Lab house when located in these three indicated cities. For larger houses and those with larger cooling loads, the energy savings would be greater, assuming that the SEER 21 unit is oversized by a factor of approximately two as was the case in the MH Lab house.

Tables 4-6 show the cooling energy consumption for the MH Lab house when located in Miami, Orlando, and Atlanta for the six cooling system/duct system configurations. Note that for this analysis, cooling energy is calculated only for days with an average daily temperature of 68°F (e.g., high 78°F and low 58°F) and above. For days cooler than this, it is assumed that people will open windows and vent the house. Following is a discussion of the cooling energy savings produced by the SEER 21 unit compared to the SEER 13 unit in Miami, Orlando, and Atlanta based on TMY3 data.

3.6.1 Miami

Table 4. Predicted annual cooling energy savings for the MH Lab house when located in Miami using the least-squares best-fit equations and TMY3 data.

	SEER 13	SEER 21	SEER 21(45%)	SEER 13	SEER 21	SEER 21(45%)
Duct system →	attic	attic	attic	indoors	indoors	indoors
Annual cooling energy (kWh)	6786	4215	4378	5916	3738	3896
Savings vs. SEER13 attic (kWh)	-	2571	2408	870	3048	2890
Savings vs. SEER13 attic	-	37.9%	35.5%	12.8%	44.9%	42.6%
Savings vs. SEER 13 indoors	-	-	-	-	36.8%	34.1%
Savings indoor ducts vs. attic ducts	-	-	-	12.8%	11.3%	11.0%
Savings SEER 21 vs. SEER 21 (45%)	-	3.7%	-	-	4.1%	-

The cooling energy savings analysis for Miami finds the following results based on TMY3 weather data and best-fit regression equations.

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 34.1% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 36.8% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 4.1% in seasonal cooling energy use compared to the SEER 21 unit with RH control active.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 35.5% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 37.9% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 3.7% in seasonal cooling energy use compared to the SEER 21 unit with RH control active (45% setpoint).

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 11.0% in seasonal cooling energy use when employing RH control (45% setpoint). Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 12.4%.
- For the SEER 21 system (no RH control active), switching from the attic duct system to the indoor duct system saves 11.3% in seasonal cooling energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 12.8%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 12.8% in seasonal cooling energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 14.7%.

3.6.2 Orlando

Table 5. Predicted annual cooling energy savings for the MH Lab house when located in Orlando using the least-squares best-fit equations and TMY3 data.

	SEER 13	SEER 21	SEER 21(45%)	SEER 13	SEER 21	SEER 21(45%)
Duct system →	attic	attic	attic	indoors	indoors	indoors
Annual cooling energy (kWh)	4811	3009	3121	4173	2758	2880
Savings vs. SEER13 attic (kWh)	-	1802	1690	638	2053	1931
Savings vs. SEER13 attic	-	37.5%	35.1%	13.3%	42.7%	40.1%
Savings vs. SEER 13 indoors	-	-	-	-	33.9%	31.0%
Savings indoor ducts vs. attic ducts	-	-	-	13.3%	8.3%	7.7%
Savings SEER 21 vs. SEER 21 (45%)	-	3.6%	-	-	4.2%	

The cooling energy savings analysis for Orlando finds the following results based on TMY3 weather data and best-fit regression equations.

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 31.0% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 33.9% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 4.2% in seasonal cooling energy use compared to the SEER 21 unit with RH control active.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 35.1% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 37.5% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 3.6% in seasonal cooling energy use compared to the SEER 21 unit with RH control active.

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 7.7% in seasonal cooling energy use when employing RH control (45% setpoint).

Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 8.4%.

- For the SEER 21 system (no RH control active), switching from the attic duct system to the indoor duct system saves 8.3% in seasonal cooling energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 9.1%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 13.3% in seasonal cooling energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 15.3%.

3.6.3 Atlanta

Table 6. Predicted annual cooling energy savings for the MH Lab house when located in Atlanta using the least-squares best-fit equations and TMY3 data.

	SEER 13	SEER 21	SEER 21(45%)	SEER 13	SEER 21	SEER 21(45%)
Duct system →	attic	attic	attic	indoors	indoors	indoors
Annual cooling energy (kWh)	3076	2051	2118	2672	1933	2014
Savings vs. SEER13 attic (kWh)	-	1025	958	404	1143	1062
Savings vs. SEER13 attic ducts	-	33.3%	31.1%	13.1%	37.2%	34.5%
Savings vs. SEER 13 indoor ducts	-	-	-	-	27.7%	24.6%
Savings indoor ducts vs. attic ducts	-	-	-	13.1%	5.8%	4.9%
Savings SEER 21 vs. SEER 21 (45%)	-	3.2%	-	-	4.0%	

The cooling energy savings analysis for Atlanta finds the following results based on TMY3 weather data for Atlanta and best-fit regression equations.

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 24.6% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 27.7% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 4.0% in seasonal cooling energy use compared to the SEER 21 unit with RH control active.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) saves 31.1% in seasonal cooling energy use compared to the SEER 13 unit.

- The SEER 21 system with RH control deactivated saves 33.3% in seasonal cooling energy use compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated saves 3.2% in seasonal cooling energy use compared to the SEER 21 unit with RH control active.

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 4.9% in seasonal cooling energy use when employing RH control (45% setpoint). Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 5.2%.
- For the SEER 21 system (no RH control active), switching from the attic duct system to the indoor duct system saves 5.8% in seasonal cooling energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 6.1%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 13.1% in seasonal cooling energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling energy use by 15.1%.

3.7 Calculated Annual Cooling Energy Savings Compared to SEER Ratings

Based on SEER ratings alone, one would expect 38.1% cooling energy use savings for the SEER 21 unit compared to the SEER 13 unit. Following is a summary of the cooling energy savings produced by the SEER 21 unit compared to the SEER 13 unit derived from annual TMY3 analysis, for Miami, Orlando, Atlanta, and the typical 82^{o}F summer day.

- When operating in standard control mode (no RH setpoint), SEER 21 cooling energy savings were found to be 36.8%, 33.9%, 27.7%, and 37.8% for Miami, Orlando, Atlanta, and the typical 82^{o}F summer day, respectively, <u>with indoor ductwork.</u>
- When operating in standard control mode (no RH setpoint), SEER 21 cooling energy savings were found to be 37.9%, 37.5%, 33.3%, and 33.7% for Miami, Orlando, Atlanta, and the typical 82^{o}F summer day, respectively, <u>with attic ductwork.</u>
- When operating in the RH control mode (RH setpoint = 45%), SEER 21 cooling energy savings were found to be 34.1%, 31.0%, 24.6%, and 35.9% for Miami, Orlando, Atlanta, and the typical 82^{o}F summer day, respectively, <u>with indoor ductwork</u>.
- When operating in RH control mode (RH setpoint = 45%), SEER 21 cooling energy savings were found to be 35.5%, 35.1%, 31.1%, and 31.2% for Miami, Orlando, Atlanta, and the typical 82^{o}F summer day, respectively, <u>with attic ductwork</u>.

The following conclusions can be drawn.

- With indoor ductwork, the SEER 21 unit (<u>using standard control</u>) produces cooling energy savings on the order of 36% compared to the SEER 13 unit (with the exception of Atlanta) when using <u>indoor</u> ductwork and 36.5% compared to the SEER 13 unit (with the exception of Atlanta) when using the <u>attic</u> ductwork. In either case, the relative performance falls short of the anticipated 38.1% (based on SEER rating) by a small margin (about 5%).

- With indoor ductwork, the SEER 21 unit (with 45% RH control) produces cooling energy savings on the order of 33.5% compared to the SEER 13 unit (with the exception of Atlanta) when using indoor ductwork and 34% compared to the SEER 13 unit (with the exception of Atlanta) when using the attic ductwork. In either case, the relative performance falls short of the anticipated 38.1% (based on SEER rating) by a larger margin (about 11.5%).

4 Cooling Peak Demand Reduction

Analysis has been performed to identify peak cooling demand savings that can be achieved by the SEER 21 unit compared to the SEER 13 unit for the hottest hours of the hottest days. A regression method has been employed to determine peak demand savings. Heat pump energy use from the hours of 2:00 to 7:00 PM have been selected from a group of six to nine hotter than average 2010 summer days for each experimental configuration. The cooling energy consumption for each hour has been plotted versus the outdoor-indoor temperature differential for that hour. Figure 5 shows the peak-hour regression analysis for all six configurations. Figure 6 shows the peak-hour regression analysis for two of the six configurations using indoor ducts. Using the best-fit regression equations that have been derived, peak hour electrical demand for each heat pump with each duct system can be determined for a typical 94°F design outdoor temperature.

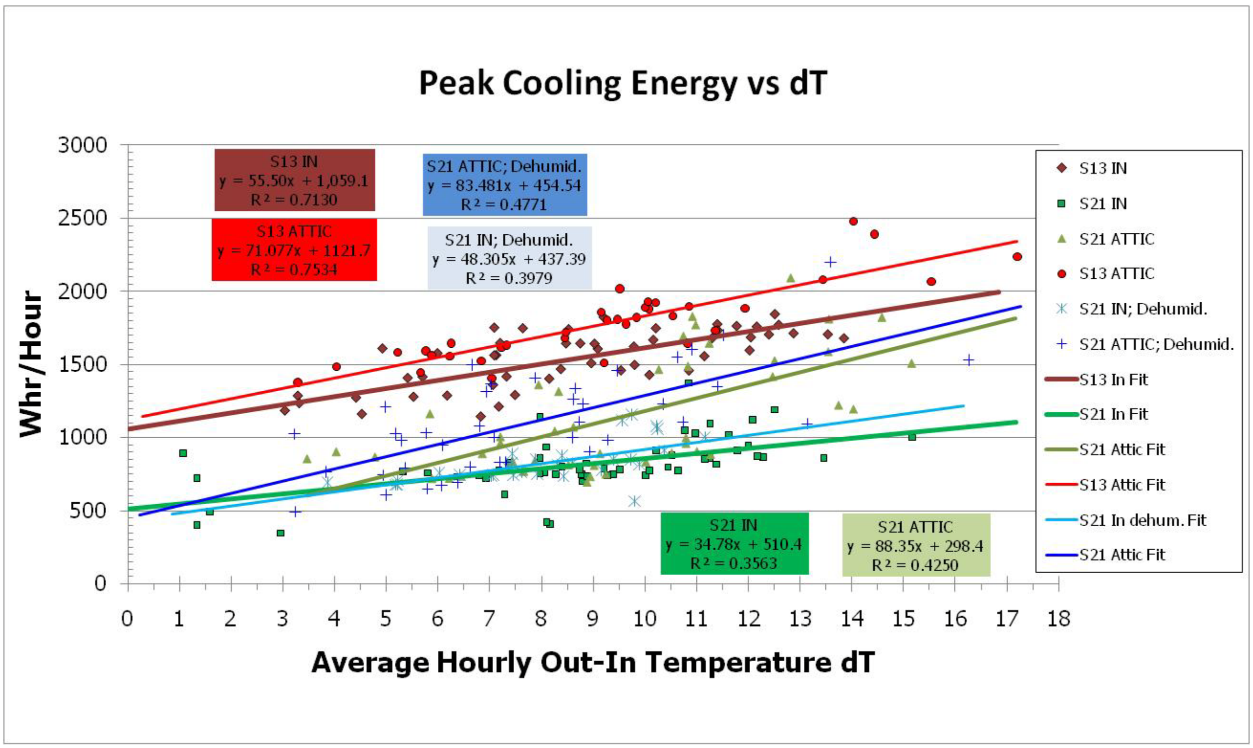

Figure 5. Least-squares best-fit regression analysis for the hours of 2:00 to 7:00 PM from hot summer days for six different experimental configurations.

The reader will note that the R^2 values for the SEER 13 unit with attic ducts and also with indoor ducts are relatively high, in the range of 0.71 to 0.75. By contrast, R^2 values for the SEER 21 unit with both attic and indoor ducts are much lower, in the range of 0.36 to 0.48. The reason for this relates to the cycling behavior of the SEER 21 thermostat. It tends to keep the cooling operating for an extended period before the system cycles off, and then it tends to remain off for an extended period before the system cycles back on (in other words, when the system does cycle, the value for Nmax is large). Furthermore, when the system first cycles on, it tends to operate at higher capacity and therefore consumes considerably greater energy and operates at lower efficiency during the earlier portion of each cooling cycle. Each of these factors contributes to the scatter and lower R^2 values.

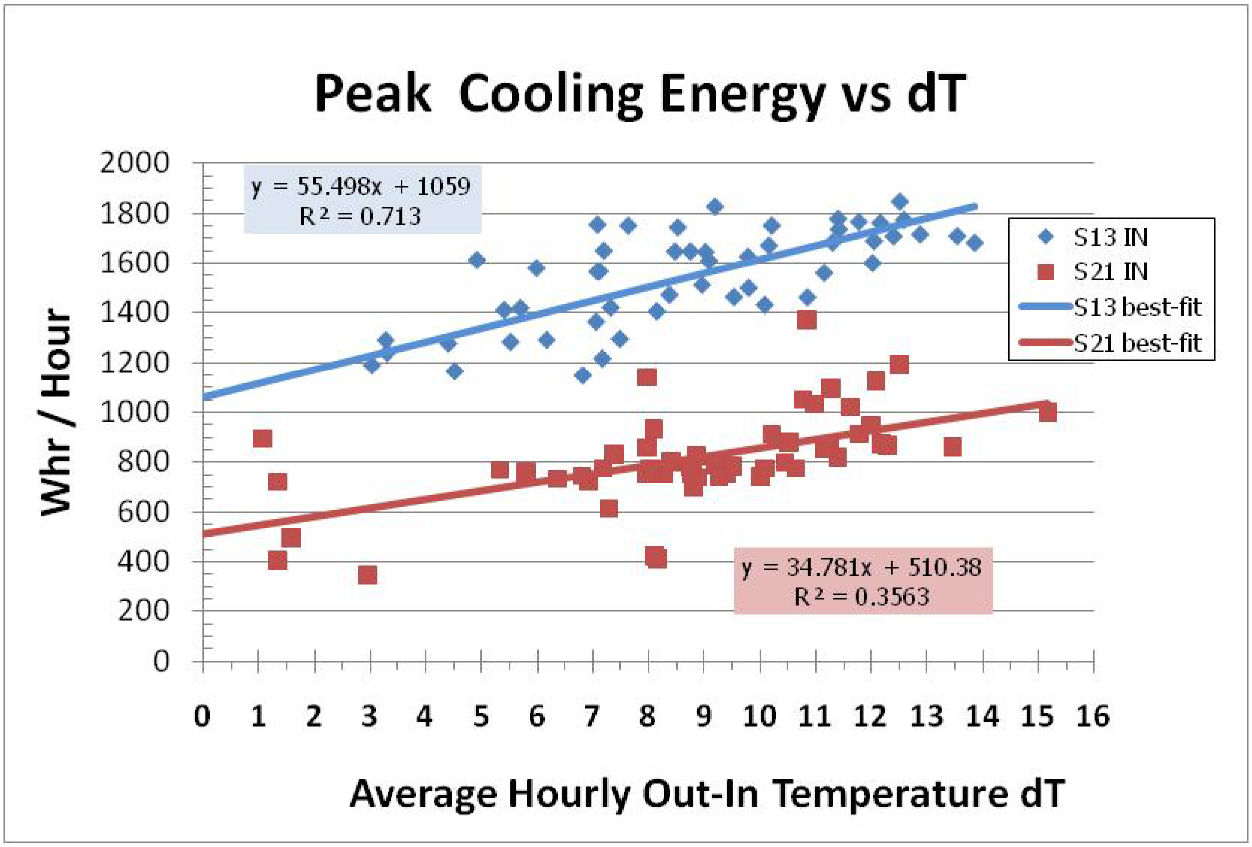

Figure 6. Least-squares best-fit regression analysis for the hours of 2:00 to 7:00 PM from hot summer days for the SEER 13 and SEER 21 units, each with indoor ducts.

A second method of determining peak demand has also been implemented, namely creating a 24-hour composite cooling energy consumption profile from the hottest days. This second method can be used to confirm the accuracy of the regression analysis method. In this second method, 24-hour composites were produced for groups of days that had nearly identical outdoor conditions (temperature and solar radiation) but only for two configurations; SEER 13 with indoor ducts and SEER 21 with indoor ducts. The composite for the SEER 13 system was derived using a group of 11 days that had an average outdoor temperature of 83.3°F and average 3:00 to 5:00 PM temperature of 86.4°F. The composite for the SEER 21 system was derived using a group of 11 days that had an average outdoor temperature of 82.3°F and average 3:00 to

5:00 PM temperature of 86.1°F. It was not possible to produce composite-day comparisons for the other four test configurations because there was an insufficient number of comparable hot days for those configurations. The results of the 24-hour composite method are presented in Figure 7.

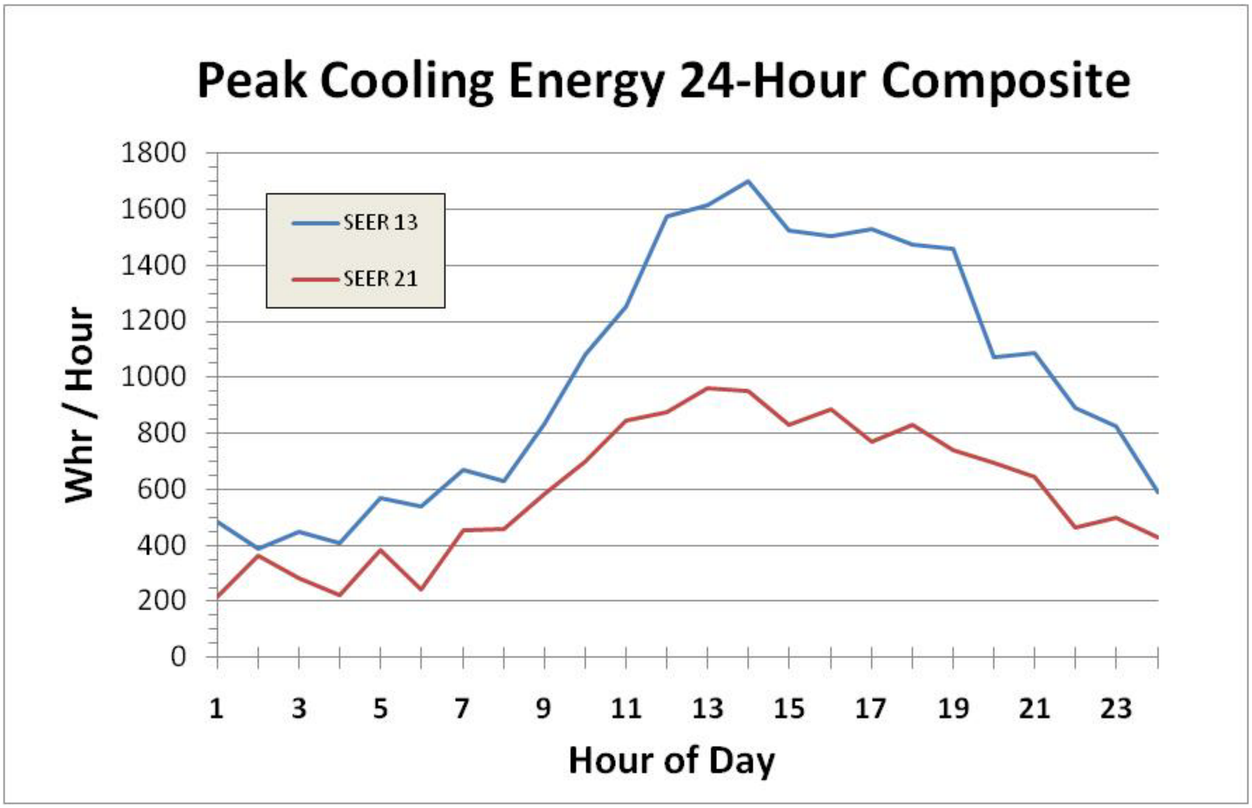

Figure 7. Peak demand profile for two groups of hot summer days representing SEER 13 and SEER 21, each using indoor ducts.

Comparison indicates that there is very good agreement between the two methods. Based on the linear regression analysis, the peak demand savings of SEER 21 with indoor ducts compared to SEER 13 with indoor ducts was 47.4% for the 4:00 to 5:00 PM period. Based on the 24-hour composite demand profiles for the SEER 13 in and SEER 21 in configurations, the peak demand reduction was 45.5%, as illustrated in Figure 8 that shows that the two methods provide essentially identical results at the 4:00 to 5:00 PM peak and throughout the hottest hours of the day.

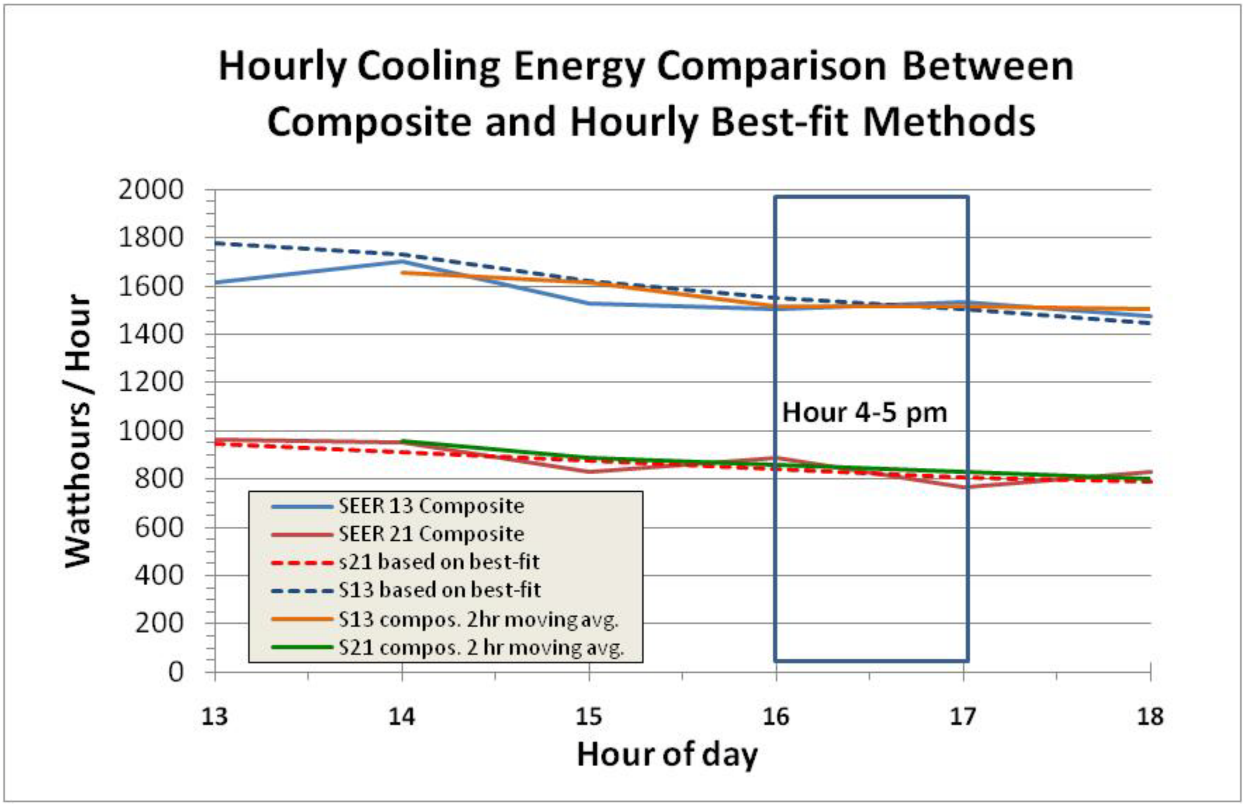

Figure 8. Comparison of regression and composite methods for SEER 13 and SEER 21 with indoor ducts.

Based on the regression analysis method, the 47.4% demand savings of the SEER 21 unit (with standard control mode) compared to the SEER 13 unit is equal to 725 W, with each system using the indoor duct system. The magnitude of the peak demand savings is somewhat unexpected since the EER ratings of the SEER 13 and SEER 21 units (11.8 and 13.0, respectively) suggest only a 9.2% peak demand reduction if the two heat pumps were, in fact, operating at full capacity at the peak hour. A key factor that allows the SEER 21 unit to consume 47.4% less electricity than the SEER 13 unit on these very hot summer afternoons is the oversizing of the SEER 21 unit, which allows this system to operate at very nearly minimum capacity even during peak hours. The peak cooling load for the MH Lab is about 1.5 tons (excluding duct losses). The 3-ton SEER 21 heat pump provides about 1.2 tons when operating at minimum capacity. Therefore, the SEER 21 unit can remain at or near minimum capacity and maximum efficiency even on the hottest summer afternoons.

4.1 Discussion of Peak Demand Reduction Based on Regression Analysis

The regression analysis normalizes cooling energy use to delta-T (T_{out} minus T_{in}, where T_{in} is based on an average from five locations in the house). Best-fit least-squares regression lines are defined by equations in the form of Y = A + B(X), where Y is the hourly cooling electrical energy use and X is delta-T. Table 7 presents the equations for all six experimental configurations.

The best-fit equations can be used to predict cooling system energy use as a function of delta-T for a specific outdoor temperature for a given hourly period. Using the best-fit equations, indoor temperature of 77°F, and a peak summer afternoon with an outdoor temperature of 94°F (very nearly the design dry bulb temperature for Miami, Orlando, and Atlanta), the following energy savings are calculated (Table 7). Recall that based on EER ratings alone—11.8 for the SEER 13 unit and 13.0 for the SEER 21 unit—one would expect a 9.2% cooling peak demand reduction for the SEER 21 unit compared to the SEER 13 unit, assuming that both units were operating at full capacity at this peak hour.

Table 7. Peak demand best-fit equation and coefficient in the form of Y = A + B(X), for each of the six experimental configurations, where Y is the daily cooling electrical energy use and X is delta-T (X = 17°F for this example).

	S13 attic	S21 attic	S21 (45) attic	S13 in	S21 in	S21 (45) in
(A) Wh/hour	1121.7	298.4	454.54	1059.1	510.4	437.39
(B) Wh/hour-°F	71.077	88.35	83.481	55.50	34.78	48.305
(Y) Wh/hr @ 94°F (delta-T = 17oF)	2330	1800	1874	2003	1102	1259
Savings vs. SEER13 attic ducts	-	22.7%	19.6%	14.0%	52.7%	46.0%
Savings vs. SEER 13 indoor ducts	-	-	-	-	45.0%	37.1%
Savings indoor ducts vs. attic ducts	-	-	-	14.0%	38.8%	32.8%
Savings SEER 21 vs. SEER 21 (45%)	-	3.9%	-	-	12.5%	

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) produces 37.1% peak demand reduction compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated produces 45.0% peak demand reduction compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated produces 12.5% peak demand reduction compared to the SEER 21 unit with RH control active.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system with RH control active (45% setpoint) produces 19.6% peak demand reduction compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated produces 22.7% peak demand reduction compared to the SEER 13 unit.
- The SEER 21 system with RH control deactivated produces 3.9% peak demand reduction compared to the SEER 21 unit with RH control active.

DEMAND SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system (when employing RH control at 45% setpoint), switching from the attic duct system to the indoor duct system reduces peak demand by 32.8%.

Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling peak demand by 48.8%.
- For the SEER 21 system (no RH control active), switching from the attic duct system to the indoor duct system reduces peak demand by 38.8%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling peak demand by 63.3%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system reduces peak demand by 14.0%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases cooling peak demand by 16.3%.
- One can clearly see that ductwork located in a hot attic dramatically impacts the energy efficiency and energy consumption of the SEER 21 system during peak cooling hours.
- Note that most of the losses associated with the attic duct system, in this case, are conductive losses, because there are no return leaks and only 1.0% air leakage of the supply ducts. It is assumed that duct losses from the indoor duct system are relatively small and that nearly all of the energy lost from the indoor ducts (by conduction and air leakage) finds its way back into the conditioned space. This assumption is reasonable given that the interior system was completed entirely below an existing finished ceiling, and installation was overseen by research staff.

It is important to emphasize the peak demand impact of attic ductwork on the SEER 21 system. For the SEER 13 unit, the increase in peak electrical demand during the hottest hours produced by switching from the indoor to attic ducts was a substantial 16.4%. This results almost entirely from conductive heat gain from the supply ductwork to the hot attic, since the supply ductwork is essentially airtight.

By contrast, the magnitude of the increase in peak demand when switching from indoor to attic ducts for the SEER 21 unit is remarkably large; 48.8% for the SEER 21 unit with 45% RH control and 63.4% for the SEER 21 unit without RH control activated. These large increases in peak demand result from two factors. First, the SEER 21 AHU is running 100% of the time during peak hours compared to only about 50% for the SEER 13 AHU, so conductive heat gains are nearly twice as large. Second, the additional load produced by the conductive gains through the supply duct walls push the SEER 21 unit into higher capacity operation where the system energy efficiency is considerably reduced. Nevertheless, the peak demand is still significantly less for the SEER 21 system compared to the SEER 13 system.

These results argue strongly for locating ductwork inside the conditioned space, or otherwise placing them in a space that is cooler than a 125°F attic. Though not yet tested, it is expected that white metal roofs, tile roofs, and other systems that will produce a much cooler attic will also enhance the ability of the SEER 21 system to shed peak cooling demand.

These results also argue for improved duct insulation. Future experiments have been proposed to increase the duct R-values from their current R-6 to R-10+.

An important question arises from these results: what are the factors that allow the SEER 21 system to wildly outperform its EER rating when tested in a real house, producing 47% peak demand reduction (with indoor ducts) while the EER ratings indicated an expected 9.2% reduction?

4.2 Oversizing of the SEER 21 System is a Key Element of the SEER 21 System Outperformance

The answer appears to lie with the heat pump capacity relative to peak cooling load. The SEER 13 and SEER 21 heat pumps have rated capacity of 35,400 and 35,000 Btu/h, respectively. The MH Lab design cooling load, when using the indoor duct system, is about 18,000 Btu/h. Therefore, even on hot summer afternoons the SEER 21 unit (with indoor ducts) is only operating at about 50% of full capacity. As a result, the SEER 21 unit can operate at or just above its minimum capacity (14,000 Btu/h) during the hours of peak demand. In the future, it would be useful to run additional experimental configurations with SEER 21 systems of various capacities to identify the seasonal and peak demand impacts of various equipment capacity-to-building-load factors.

4.3 Indoor Ductwork is a Key Element of the SEER 21 System Performance

With indoor ducts, the SEER 21 unit reduces peak demand by 47%. By contrast, the SEER 21 unit reduces peak demand by only 23% compared to the SEER 13 unit when using attic ducts. (Note that the roof of the MH Lab house is medium-colored tan asphalt shingle, so the attic becomes very hot on hot summer afternoons; ~ 125°F.) Therefore, heat gain from the hot attic (by conduction) into the supply ducts substantially diminishes the net energy efficiency of the SEER 21 system because cold supply air is in the ductwork much longer. This fact points to the importance of the thermal environment of the supply ductwork. Obviously, locating the ducts inside the house eliminates almost all of those efficiency losses. Lowering the temperature of the attic is another alternative to avoid a substantial portion of these conductive losses. This can be achieved by means of a tile roof, a white metal roof, certain types of vented colored metal roof, and by means of a radiant barrier. It can be said, therefore, that use of indoor ductwork produces an optimal circumstance for the operation of variable capacity cooling systems. It would be useful to run additional experiments with the tan asphalt shingle roof covered by a white tarpaulin (or similar approach) to identify the seasonal and peak demand reduction benefits of a cooler attic space.

5 Heating Energy Savings

When operating in heating mode, the SEER 21 heat pump system operates in much the same manner as when operating in standard cooling mode. The capacity of the compressor unit is varied as a function of delta-T of room temperature compared to setpoint. Instead of cycling on and off at full capacity, the compressor varies from 40% to 118% of nominal capacity or 34% to 100% of total capacity. When the setpoint is satisfied, the system does not shut off, but rather adjusts the compressor capacity downward to match heating capacity to heating load. As the compressor capacity declines, the AHU fan speed also declines but not proportionally. When operating at the lowest capacity (about 13,600 Btu/hr or 40% of the system's 34,000 Btu/hr nominal full capacity), the AHU fan flow remains fairly high at about 800 cfm.

While there were six experimental configurations for the cooling season, there were only four experimental configurations for the heating season because no RH control option exists while in heating mode. The four experimental configurations were as follows: 1) SEER 13 with attic duct system, 2) SEER 13 with indoor duct system, 3) SEER 21 with attic duct system, and 4) SEER 21 with indoor duct system.

Thermostats were set at 75°F for the heating season. This setpoint is higher than a typical winter heating setpoint (72°F is more representative of a typical Florida heating setpoint). This elevated setpoint temperature was chosen in order to create greater heating loads and longer heat pump runtimes. While the two thermostats were set to 75°F, actual indoor temperature was warmer and averaged 76.2°F on days when heating was required. This ranged from 75.9°F with the SEER 21/indoor ducts configuration to 76.6°F with SEER 13/attic duct configuration (Table 8). Internal loads associated with house occupancy were also reduced (compared to the cooling season internal loads) to increase the net heating load and increase heat pump operation. The cooling season sensible internal load of 27.7 kWh/day was reduced to 21.1 kWh/day for the heating experiments. It is important to note that the electric strip heating elements were disabled in both heat pumps so that no electric resistance heating could occur during these experiments.

Table 8. Average indoor temperature, indoor RH, and heating system runtime for all experimental periods from February 11-16, 2010

	S13 attic	S21 attic	S13 in	S21 in
Average outdoor temperature (°F)	56.5	55.6	55.4	51.6
Average indoor temperature (°F)	76.6	76.3	76.5	75.4
Delta-temperature (out-in; (°F))	-20.1	-20.7	-21.1	-23.8
Indoor RH (%)	43.6	41.8	36.9	35.8
Heating system runtime (%)	20.9	24.7	20.9	27.1

5.1 Heating Energy Regression Analysis

To perform the heating energy evaluation, daily total heating energy has been plotted against the average daily temperature difference between outdoors and indoors, in similar fashion to that done for the cooling analysis. Data collected during the 2010-2011 heating season is shown in Figure 9. Based on the Heating Seasonal Performance Factors (HSPF)—9.6 and 8.0 for the SEER 21 unit and the SEER 13 unit, respectively—the SEER 21 unit is expected to save 16.7% in seasonal heating energy use compared to the SEER 13 unit. As shown, the SEER 21 significantly outperformed its HSPF performance rating relative to the SEER 13 unit. It is important to note that the heat pumps used in the MH Lab have no electric resistance heating, so all of the heating provided to the space comes from heat pump operation.

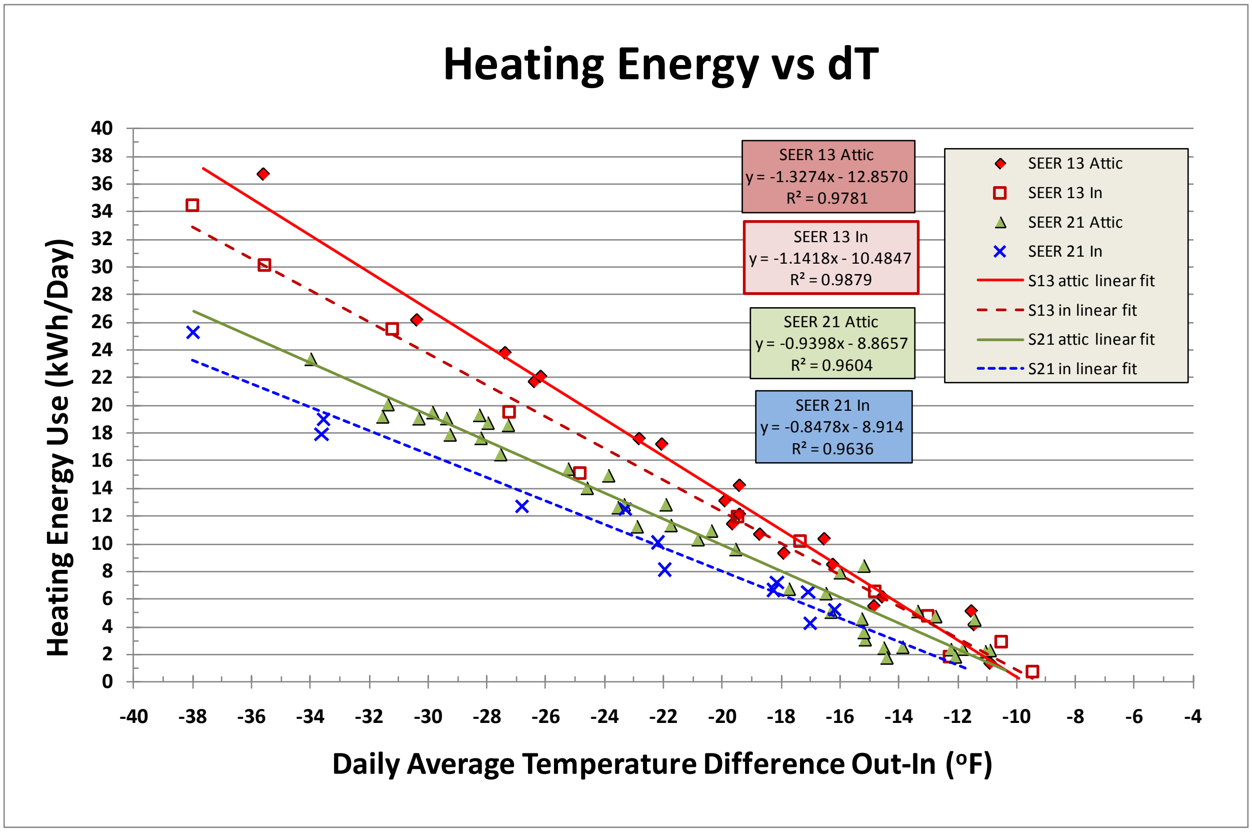

Figure 9. Heat pump heating electrical energy consumption versus delta-T for the SEER 13 and 21 systems when using indoor and attic duct systems.

5.2 Heating Energy Savings for a Typical Winter Day

Based on a delta-T of 22°F (indoors minus outdoors) and the regression equations, the SEER 21 unit saves substantially more than predicted for a typical heating day in central Florida (Table 9). This temperature differential of 22°F delta-T was chosen for this comparison because it is a fairly typical load-weighted delta-T for central Florida heating days (e.g., high of 60°F, low of 40°F, and 50°F daily average, while indoor temperature is assumed to be 72°F). Since the SEER 21 unit operates at fractional capacity most of the time and therefore runs considerably longer than the SEER 13 unit, it is logical that duct heat losses (when using the attic duct system) would degrade the SEER 21 system heating performance more than they would for the SEER 13 unit.

Table 9. Heating energy savings calculated from best-fit equation Y = A + B(X), where Y is the daily heating energy use and X is the daily average temperature difference between outdoors and indoors, -22°F dT for this example.

	S13 attic	S21 attic	S13 in	S21 in
(A) kWh/day	-12.8570	-8.8657	-10.4847	-8.9140
(B) kWh/day-°F	-1.3274	-0.9398	-1.1418	-0.8478
(Y) Wh/day @ 50°F (delta-T = 22°F)	16.35	11.81	14.63	9.74
Savings vs. SEER13 attic ducts	-	27.8%	10.5%	40.4%
Savings vs. SEER 13 indoor ducts	-	-	-	33.4%
Savings indoor ducts vs. attic ducts	-	-	10.5%	17.5%

WHEN HEATING USING THE INDOOR DUCT SYSTEM

- The SEER 21 system saves 33.4% compared to the SEER 13 unit.

WHEN HEATING USING THE ATTIC DUCT SYSTEM

- The SEER 21 system saves 27.8 % compared to the SEER 13 unit.

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 17.5%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 21.3%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 10.5%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 11.7%.
- It is reasonable that the energy penalty associated with using the attic duct system would be much greater for the SEER 21 system compared to the SEER 13 system, because the SEER 21 system runtime is about 24% greater compared to the SEER 13 unit. Therefore, conductive heat transfer from the attic to the duct interior is greater for the SEER 21 unit.
- Note that most of the losses associated with the attic duct system are conductive losses, because there are no return leaks. Air leakage of the supply ducts represents only 1.0% of the system air flow, and the AHUs and returns are in the conditioned space. It is assumed that duct losses from the indoor duct system are relatively small and that nearly all of the energy lost from the indoor ductwork finds its way back into the conditioned space.

Heating energy savings produced by the SEER 21 unit, compared to the SEER 13 unit, is essentially twice as great as predicted by the HSPF when using indoor ducts. Measured SEER 21 heating savings were 33.5% versus HSPF-predicted savings of 16.7% when using indoor ducts. Even when using the attic duct system, the actual SEER 21 heating savings were 27.8%, thereby exceeding its relative HSPF performance by 66%. The apparent reason for this outperformance is that the SEER 21 heat pump is greatly oversized and thus operating at small fractional capacity nearly all of the time, where the SEER 21 heat pump operates at substantially higher efficiency.

5.3 Annual Heating Energy Savings for Three Cities

Heating energy savings have been calculated for the MH Lab house when located in three cities in the southeastern United States—Miami, Orlando, and Atlanta. Daily heating energy consumption has been calculated (simulated) using TMY3 data along with the best-fit equations for both the SEER 13 and SEER 21 heat pumps.

Annual heating energy consumption has been calculated using the regression formulas that define the relationship between average daily outdoor temperature and heating energy use (based on least-square best-fit relationship) from the SEER 21 MH Lab experiments and TMY3 weather data for each of the three cities. Heating energy use is calculated for each day of the year based on the average daily outdoor-indoor temperature differential. The calculated (simulated) daily heating energy is summed for all days of the year (negative heating energy values are treated as zero) for each of the four experimental configurations. Those six experimental configurations are as follows: 1) SEER 13 with attic ducts, 2) SEER 13 with indoor ducts, 3) SEER 21 with attic ducts, and 4) SEER 21 with indoor ducts. Note that the calculated heating energy consumption is for the 1600 ft^2 MH Lab house when located in these indicated cities. For houses with larger heating loads, the energy savings would be greater, assuming that the SEER 21 unit is oversized by a factor of approximately two as was the case in the MH Lab house.

Tables 10-12 show the heating energy consumption for the MH Lab house when located in Miami, Orlando, and Atlanta for the four heating system/duct system configurations based on TMY3 calculations. Following is a discussion of the heating energy savings produced by the SEER 21 unit compared to the SEER 13 unit in Miami, Orlando, and Atlanta based on TMY3 data.
Note that while the MH Lab heating was operated with a 75°F setpoint (that produced an average indoor temperature of 76.2°F), the TMY3 simulations were run with a space temperature of 72°F. The reason for the discrepancy is that project staff selected a higher heating setpoint for the experiments in order to maximize heating operation so that the maximum amount of heating system data would be obtained. When performing the TMY3-based simulations, a space temperature of 72°F was selected since this is more typical of actual occupant behavior.

Based on the rated HSPF of 9.6 and 8.0 for the SEER 21 and SEER 13 heat pumps, respectively, one would expect the SEER 21 unit to save 16.7% in seasonal energy use compared to the SEER 13 unit. Based on annual simulations, actual savings have been found to be considerably greater (Tables 10-12).

5.3.1 Miami

Table 10. Predicted annual heating energy savings for the MH Lab house when located in Miami using the least-squares best-fit equations and TMY3 data.

	SEER 13	SEER 21	SEER 13	SEER 21
Duct system →	attic	attic	indoors	indoors
Annual heating energy (kWh)	95	72	94	48
Savings vs. SEER13 attic (kWh)	-	23	1	47
Savings vs. SEER13 attic ducts	-	24.2%	1.1%	49.5%
Savings vs. SEER 13 indoor ducts	-	-	-	48.9%
Savings indoor ducts vs. attic ducts	-	-	1.1%	33.3%

The heating energy savings analysis for Miami shows the following results based on TMY3 weather data and best-fit regression equations. When interpreting these numbers, keep in mind that hours of heating in Miami are very limited, so the percent differences should be considered in this light.

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system saves 48.9% in seasonal heating energy use compared to the SEER 13 unit.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system saves 24.2% in seasonal heating energy use compared to the SEER 13 unit.

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 33.3% in seasonal heating energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 50.0%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 1.1% in seasonal heating energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 1.1%.

5.3.2 Orlando

Table 11. Predicted annual heating energy savings for the MH Lab house when located in Orlando using the least-squares best-fit equations and TMY3 data.

	SEER 13	SEER 21	SEER 13	SEER 21
Duct system →	attic	attic	indoors	indoors
Annual heating energy (kWh)	489	360	456	273
Savings vs. SEER13 attic (kWh)	-	129	33	216
Savings vs. SEER13 attic ducts	-	26.4%	6.7%	44.2%
Savings vs. SEER 13 indoor ducts	-	-	-	40.1%
Savings indoor ducts vs. attic ducts	-	-	6.7%	24.2%

The heating energy savings analysis for Orlando shows the following results based on TMY3 weather data and best-fit regression equations.

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system saves 40.1% in seasonal heating energy use compared to the SEER 13 unit.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system saves 26.4% in seasonal heating energy use compared to the SEER 13 unit.

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 24.2% in seasonal heating energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 31.9%.

- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 6.7% in seasonal heating energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 7.2%.

5.3.3 Atlanta

Table 12. Predicted annual heating energy savings for the MH Lab house when located in Atlanta using the least-squares best-fit equations and TMY3 data.

	SEER 13	SEER 21	SEER 13	SEER 21
Duct system →	attic	attic	indoors	indoors
Annual heating energy (kWh)	3112	2244	2775	1870
Savings vs. SEER13 attic (kWh)	-	868	337	1242
Savings vs. SEER13 attic ducts	-	27.9%	10.8%	39.9%
Savings vs. SEER 13 indoor ducts	-	-	-	32.6%
Savings indoor ducts vs. attic ducts	-	-	10.8%	16.7%

The heating energy savings analysis for Atlanta finds the following results based on TMY3 weather data and best-fit regression equations.

WHEN USING THE INDOOR DUCT SYSTEM

- The SEER 21 system saves 32.6% in seasonal heating energy use compared to the SEER 13 unit.

WHEN USING THE ATTIC DUCT SYSTEM

- The SEER 21 system saves 27.9% in seasonal heating energy use compared to the SEER 13 unit.

ENERGY SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system saves 16.7% in seasonal heating energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 20.0%.
- For the SEER 13 system, switching from the attic duct system to the indoor duct system saves 10.8% in seasonal heating energy use. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating energy use by 12.1%.

5.4 Calculated Annual Heating Energy Savings Compared to HSPF Ratings

Based on HSPF ratings alone, one would expect a 16.7% heating energy use savings for the SEER 21 unit (HSPF = 9.60) compared to the SEER 13 unit (HSPF = 8.00). Following is a summary of the heating energy savings produced by the SEER 21 unit compared to the SEER 13 unit, as derived from the annual TMY3 analysis for Miami, Orlando, Atlanta, and the typical 50^{o}F winter day.

- SEER 21 heating energy savings were found to be 48.9%, 40.1%, 32.6%, and 33.4% for Miami, Orlando, Atlanta, and the typical 50^{o}F winter day, respectively, with indoor ductwork.
- SEER 21 heating energy savings were found to be 24.2%, 26.4%, 27.9%, and 27.8% for Miami, Orlando, Atlanta, and the typical 50^{o}F winter day, respectively, with attic ductwork.

The following conclusions can be drawn.

- With indoor ductwork, the SEER 21 unit produces heating energy savings on the order of 40% compared to the SEER 13 unit (with the exception of Atlanta) and 26.5% compared to the SEER 13 unit (including Atlanta) when using the attic ductwork. In either case, the relative heating performance greatly exceeds the anticipated 16.7% savings (based on HSPF ratings) by a large margin (about 140% margin with indoor ducts and 60% margin with attic ducts).

6 Heating Peak Demand Reduction

Analysis has been performed to identify peak heating demand savings for the coldest hours of the coldest days for the SEER 21 unit compared to the SEER 13 unit. A regression method has been employed to determine peak demand savings in a manner similar to that for cooling. Heating energy use from the hours of 2:00 to 8:00 AM has been selected from a group of six to eight colder than average winter days for each experimental configuration. The heating energy consumption for each hour has been plotted versus the outdoor-minus-indoor temperature differential for that hour. Figure 10 shows the peak-hour regression analysis for all four configurations. Using the best-fit regression equations that have been derived, peak hour electrical demand for each heat pump with each duct system can be determined for specific delta-temperature inputs. It is important to note that the heat pumps used in the MH Lab have no electric resistance heating, so all of the heating provided to the space comes from heat pump operation.

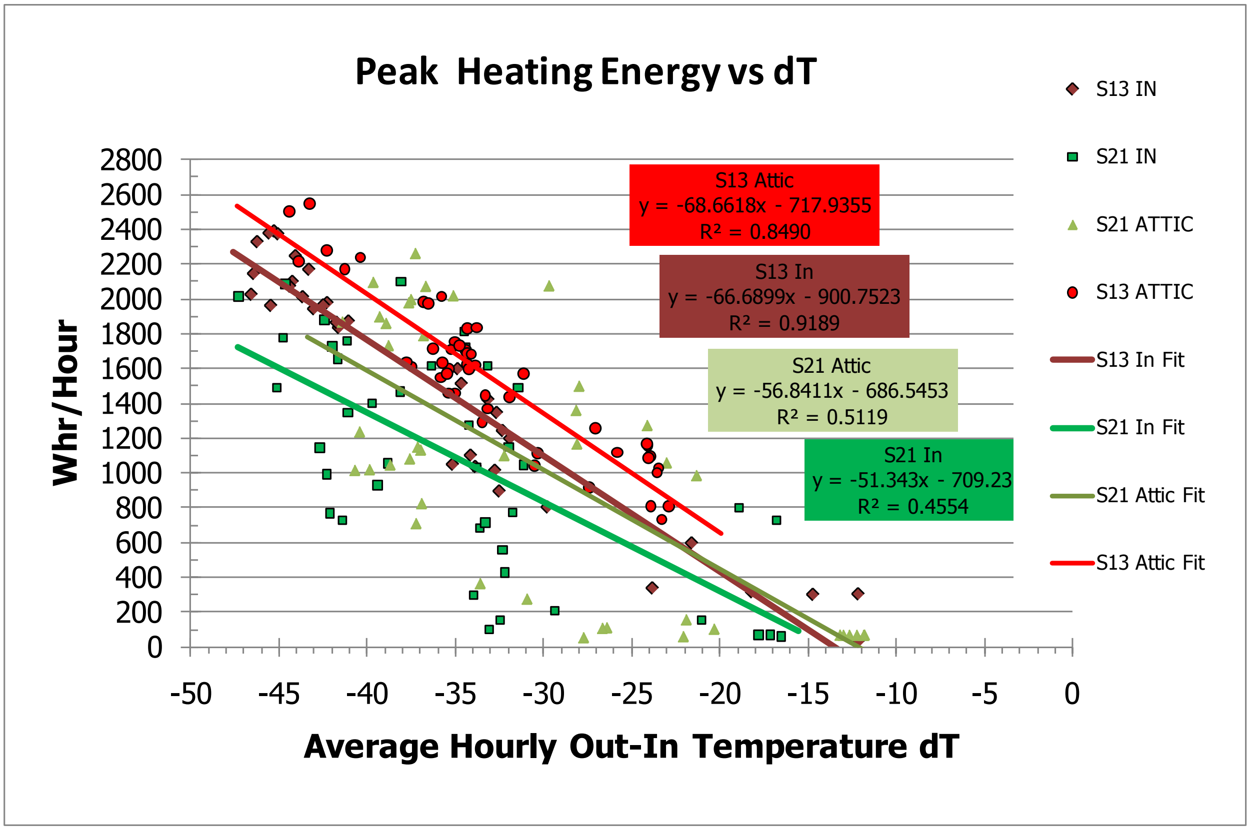

Figure 10. Least-squares best-fit regression analysis for the hours of 2 to 8 AM from cold winter days for four experimental configurations.

The reader will note that the R^2 values for the SEER 13 unit with attic ducts and also with indoor ducts are relatively high, in the range of 0.85 to 0.92. By contrast, R^2 values for the SEER 21 unit with both attic and indoor ducts are much lower, in the range of 0.46 to 0.51. The reason for this relates to the cycling behavior of the SEER 21 thermostat. It tends to keep the heat operating for an extended period before the system cycles off, and then it tends to remain off for an extended period before the system cycles back on (in other words, when the system does cycle, the value for Nmax is large). Furthermore, when the system first cycles on, it tends to operate at higher capacity and therefore consumes considerably greater energy and operates at lower efficiency during the earlier portion of each heating cycle. Each of these factors contributes to the scatter and lower r^2 values.

6.1 Discussion of Heating Peak Demand Reduction

The regression analysis normalizes heating energy use to delta-T (T_{out} minus T_{in}, where T_{in} is based on an average from five locations in the house). Best-fit least-squares regression lines are defined by equations in the form of Y = A + B(X), where Y is the hourly heating electrical energy use and X is delta-T. Table 13 presents the equations for all four experimental configurations and peak heating electrical demand when assuming an indoor temperature of 72°F and an outdoor temperature of 30°F (42°F delta-T, which would be representative of substantial portions of Florida). As a point of reference, the 99.6% heating dry bulb values from ASHRAE

Fundamentals 2009 Chapter 14 ("Appendix: Design Conditions for Selected Locations") are 47.7°F for Miami, 37.7°F for Orlando, and 20.7°F for Atlanta.

Peak demand simulation/calculation has not been performed for lower outdoor temperatures (which would be more representative of northern Florida and Atlanta) because the energy consumption rate of this SEER 21 3-ton heat pump is not as well represented by a straight line regression beyond the range of about -42 to -45°F delta-T. As delta-T approaches the range of -50 °F to -55°F, the SEER 21 heat pump will approach its full capacity and maximum electrical demand (about 3000 W), so the two curves for the SEER 21 system will logically curve upward and to the left (Figure 10). This -50 °F to -55°F delta-T range falls outside the environmental conditions that occurred during our experiments. Therefore, the reader should be advised to be cautious regarding extrapolating beyond -45°F. The reason for this concern is that the linear regression equations are likely to overestimate efficiency at 50+ dT for this 3-ton system since efficiency tails off rather rapidly as 100% of nominal capacity is approached. If a 4-ton or larger SEER 21systems were installed, then the higher efficiency region would extend further to the left (toward colder outdoor temperatures). The peak demand versus delta-T equations and peak demand savings for 42°F are shown in Table 13.

Table 13. Peak heating demand savings calculated from best-fit equation Y = A + B(X), where Y is the daily heating energy use and X is the daily average temperature difference between indoors and outdoors, 42°F dT for this example.

	SEER 13 attic	SEER 21 attic	SEER 13 in	SEER 21 in
(A) Wh/hour	-717.94	-686.55	-900.75	-709.23
(B) Wh/hour-°F	-68.66	-56.84	-66.69	-51.34
(Y) Wh/hour @ 30°F (X = 42°F dT)	2166	1700	1900	1447
Demand reduction vs. SEER 13 attic ducts	-	21.5%	12.3%	33.2%
Demand reduction vs. SEER 13 indoor ducts	-	-	-	23.8%
Demand reduction indoor vs. attic ducts	-	-	12.3%	14.9%

WHEN HEATING USING THE INDOOR DUCT SYSTEM

- The SEER 21 system reduces peak demand by 23.8% compared to the SEER 13 unit.

WHEN HEATING USING THE ATTIC DUCT SYSTEM

- The SEER 21 system produces 21.5% peak demand reduction compared to the SEER 13 unit.

DEMAND SAVINGS FROM SWITCHING FROM ATTIC TO INDOOR DUCT SYSTEM

- For the SEER 21 system, switching from the attic duct system to the indoor duct system reduces peak demand by 14.9%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating peak demand by 17.5%.

- For the SEER 13 system, switching from the attic duct system to the indoor duct system reduces peak demand by 12.3%. Conversely, it can also be stated that switching from the indoor duct system to the attic duct system increases heating peak demand by 14.0%.

The SEER 21 system reduces peak demand, at 30°F outdoor temperature, by 23.8% when using the indoor ducts and 21.5% when using the attic ducts. Based on manufacturer expanded performance data, COPs for the SEER 13 and SEER 21 heat pumps are 3.01 and 3.15, respectively, when operating at 42°F delta-temperature and assuming that the SEER 21 is operating at "intermediate" capacity. "Intermediate" capacity was selected because the heat pump is considerably oversized relative to the peak heating load. The indicated COPs of 3.01 and 3.15 suggest that the SEER 21 should only produce peak demand reduction of 4.7% at 30°F ambient temperature. The fact that the measured data from the MH Lab shows 21.5% to 23.8% demand reduction indicates a rather remarkable level of outperformance. An explanation for this positive performance gap is not readily apparent.

7 Conclusions

7.1 SEER 21 versus SEER 13 Heat Pump Results

In nearly all respects, the SEER 21 heat pump exceeds performance expectations relative to a SEER 13 heat pump. Seasonal cooling performance falls short of expectations by a small margin, but the other results for peak cooling performance, seasonal heating performance, and peak heating performance found that the SEER 21 unit outperforms its ratings and in some cases by a large margin. (The seasonal and peak demand savings presented in this section occur when both heat pumps are using the attic duct system, unless otherwise stated.)

7.2 Cooling Performance of the SEER 21 Heat Pump

In terms of seasonal cooling performance, the SEER 21 performance fell slightly short of expectations. While the SEER ratings of the two heat pumps (SEER 21 and SEER 13) would indicate expected cooling energy savings of 38.1% for the SEER 21 unit, actual seasonal savings were approximately 36% based on regression analysis and TMY3 calculations. When the SEER 21 unit was operated in the RH control mode (45% setpoint), actual seasonal savings were approximately 33.5% based on regression analysis and TMY3 calculations.

In terms of peak cooling performance, the SEER 21 performance greatly exceeded its ratings when examined at 94°F outdoor temperature. Based on EER ratings (13.0 and 11.8) and assuming that each system was operating at full capacity, the SEER 21 unit would produce an expected peak demand reduction of 9.2%. In actual practice, results from the MH Lab found peak cooling demand reduction of 22.7%, an approximate 2.5-fold level of outperformance. When the heat pumps were using indoor ducts, the MH Lab found peak cooling demand reduction of 45.0%, an approximate five-fold level of outperformance. The key factor appears to be equipment oversizing. While the MH Lab house has a design cooling load of 18,000 Btu/hr, the installed 3-ton units are actually oversized by 100%. Because the SEER 21 unit is greatly oversized, it can operate at or near minimum capacity during the hottest hours of hot summer days, and the SEER 21 unit operates much more efficiently when operating a minimum or near minimum capacity.

7.3 Heating Performance of the SEER 21 Heat Pump

In terms of seasonal heating performance, the SEER 21 performance greatly exceeded performance expectations. While the HSPF ratings of the two heat pumps (9.6 and 8.0) would indicate expected heating energy savings of 16.7% for the SEER 21 unit, actual seasonal savings was approximately 26.5% based on regression analysis and TMY3 calculations. When the heat pumps were using indoor ducts, the seasonal heating savings were an even more robust 40%.

In terms of peak heating performance, the SEER 21 performance greatly exceeded its ratings when examined at 30°F outdoor temperature. Based on manufacturer-expanded performance data, COPs for the SEER 13 and SEER 21 heat pumps are 3.01 and 3.15, respectively, when operating at 42°F delta-temperature and assuming that the SEER 21 unit is operating at "intermediate" capacity. The indicated COPs of 3.01 and 3.15 suggest that the SEER 21 unit should only produce peak demand reduction of 4.7% at 30°F ambient temperature. In actual practice, results from the MH Lab found peak demand reduction of 21.5%, an approximate five-fold level of outperformance. When the heat pumps were using indoor ducts, the MH Lab found peak demand reduction of 23.8%, also an approximate five-fold level of outperformance. An explanation for this positive performance gap is not readily apparent.

7.4 Savings from Indoor Ducts

Conductive duct losses from ductwork to the attic impact the performance of the heat pumps in both cooling and heating operation. Conductive losses of the attic ductwork create a larger energy penalty for the SEER 21 heat pump compared to the SEER 13 heat pump because the SEER 21 system operates at a low capacity nearly twice as many hours per day as the SEER 13 unit. (Note that most of the losses associated with the MH Lab attic duct system are conductive losses; because there are no return leaks, air leakage of the supply ducts represents only 1% of the system air flow, and the AHUs and returns are in the conditioned space.) Attic temperatures during typical summer weather have a daily average of about 96°F (about 14°F above ambient) and an average afternoon peak of about 125°F (about 31°F above ambient). When using the MH Lab's essentially leak-free attic ductwork, the SEER 21 and SEER 13 heat pump systems experience the following impacts when going from the attic duct system to the indoor duct system.

- On a typical summer day, cooling energy decreases by 16.8% for the SEER 21 unit and 11.2% for the SEER 13 unit. (The cooling energy decrease is 50% greater for the SEER 21 unit versus the SEER 13 unit.)
- On a peak summer afternoon (94°F), peak cooling energy decreases by 38.8% for the SEER 21 unit and 14.0% for the SEER 13 unit. (The cooling peak demand decrease is 177% greater for the SEER 21 unit versus the SEER 13 unit.)
- On a typical central Florida winter day, heating energy decreases by 16.7% for the SEER 21 unit and 10.8% for the SEER 13 unit. (The heating energy decrease is 55% greater for the SEER 21 unit versus the SEER 13 unit.)
- On a peak central Florida winter morning (30°F), peak heating energy decreases by 14.9% for the SEER 21 unit and 12.3% for the SEER 13 unit. (The heating peak demand decrease is 21% greater for the SEER 21 unit versus the SEER 13 unit.)

Because the SEER 21 unit operates for a much larger number of hours per day than the SEER 13 unit, conductive losses are considerably greater for the SEER 21 system. For the SEER 13 unit, conductive duct losses represent about 11% of total heating and cooling energy use on a typical day, and about 13% at the peak heating and cooling hour. For the SEER 21 unit, conductive losses are greater for the SEER 21 unit compared to the SEER 13 unit for each of the heating and cooling circumstances. There are, however, large variations. For heating and cooling typical day energy use, the SEER 21 unit experiences about 50% greater conductive losses than the SEER 13 unit. On the peak cooling day, the conductive losses are 177% greater for the SEER 21 unit compared to the SEER 13 unit. On the peak heating day, the conductive losses are only 21% greater for the SEER 21 unit compared to the SEER 13 unit.

Therefore, it can be concluded that there are significant benefits of locating the ductwork indoors, especially for the SEER 21 unit and especially during the peak cooling hours.

While the effects of duct conductive losses have been characterized, the effects of duct air leakage have not yet been studied. It is expected that the impacts of duct leakage will be greater, and perhaps much greater, upon the SEER 21 unit compared to the SEER 13 unit. It is anticipated that duct leakage impacts will be studied in the MH Lab during the next phase of experiments during 2012.

This first phase SEER 21 testing provides significant evidence that oversizing variable capacity heat pumps produces substantial improvement in seasonal and peak energy consumption. Additional research is required, however, before the effects of equipment sizing can be fully assessed. For 2013, it is proposed that the MH Lab 3-ton heat pumps be replaced by 2-ton and perhaps 4-ton heat pumps to further quantify the benefits of oversizing. Alternatively, the SEER 13 unit could be downsized to 1.5 tons (in order to offer both systems the best opportunity for optimum efficiency) and then compared to both 2-ton and 4-ton SEER 21 units.

If it turns out that considerable oversizing is as beneficial as has been portrayed in this report, then this may require alterations to widely accepted sizing guidelines, utility incentive criteria, and building code language. As this research unfolds, it may become clear that oversizing should be encouraged as best practice for variable-capacity and perhaps two-stage AC and heat pump systems.

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Acknowledgements

The encouragement and support of Dr. Subrato Chandra, the Project Leader for the U.S. DOE's Building America program at the Florida Solar Energy Center, is appreciated. The support and encouragement of FPL program manager, Mr. Craig Muccio, is gratefully acknowledged. This support does not constitute FPL endorsement of the views expressed in this report.

The authors would like to express thanks to FSEC staff: Rich Raustad for excellent help with datalogger programming; David Hoak in assisting in the instrumentation, experiment controls, and day-to-day management of the MH Lab and the SEER 21 experiments; Neil Moyer for his hard work in developing the pre-existing robust instrumentation package in the MH Lab and assistance in readying the MH Lab for these SEER 21 experiments; Patrick Gillis for assistance with lab and experiment modifications; and Don Shirey for project design assistance.

Appendix A

Schedule of Occupancy and Occupancy-Generated Loads for the MH Lab for Cooling Season SEER 21 Experiments

Experiments have been performed in the MH Lab to examine the energy efficiency, peak demand, and system performance of a 21 SEER 3-ton heat pump from Nutone that uses the Nordyne iQ variable speed technology compared to a standard 13 SEER Nutone heat pump. Two duct systems, one indoors and one in the attic, were used for these experiments. Various levels of duct leakage, equipment sizing, and duct insulation are also proposed and will be implemented in future experiments.

In order to carry out these experiments in the MH Lab, cooling loads need to be realistically representative of an occupied residence, because the presence of humans and human activities create a significant portion of the cooling load of the residence. This human-influenced load also has a particular latent versus sensible relationship that affects the load SHR and indoor RH. Following are proposed schedules of human activities and internal loads. In most cases, the source for the occupancy or load schedule is "Building America Research Benchmark Definition" (BARBD), Updated December 19, 2008, written by Robert Hendron of NREL. Throughout this document, BARBD refers to the December 2008 version of this document and the source within BARBD for the proposed schedule (table, figure, or equation) is provided for each item.

BARBD states the following on page 2: "All building envelope components (including walls, windows, foundation, roof, and floors) for the Benchmark shall be consistent with the HERS Reference Home as defined by the National Association of State Energy Officials (NASEO) and the Residential Energy Services Network (RESNET) in the 'National Home Energy Rating Technical Guidelines,' dated September 19, 1999 (RESNET 2002)." Given that the MH Lab is an existing manufactured home with an already-set shape and size, and with existing insulation, windows, crawl space, and attic, these elements of the lab building will remain as they are.

The MH Lab is a 1600 ft^2 manufactured house on crawl space with three bedrooms and two bathrooms.

Occupants (sensible and latent heat from people)
Strategy: See Figure 14. "Detailed hourly load profiles in different parts of the house on weekdays and weekends."
Number of people: 3 (source is Equation 17 from BARBD)
Source: BARBD

- Figure 23 from BARBD is used for number of people in the house for each hour of the day.
- Table 19 from BARBD is used for sensible and latent load from people; from 10:00 PM to 6:00 AM the internal load is 210 Btu/hr-person sensible and 140 Btu/hr-person latent, and from 6:00 AM to 10:00 PM will be 230 Btu/hr-person sensible and 190 Btu/hr-person latent.
- The occupancy and load numbers have been combined into Table A-1.

Table A-1. Schedule for simulated sensible and latent heat produced by the people occupying this house.

Time period	Hours	Number of people	Sensible heat load (Btu/hr)	Cumulative sensible heat (Btu)	Latent heat (Btu/hr)	Cumulative latent heat (Btu) [lb water]
10 PM to 7 AM	10	3	630	6300	420	4200 (4.00)
8 AM	1	2.7	621	621	513	513 (0.49)
9 AM	1	1.2	276	276	228	228 (0.22)
10 AM to 4 PM	7	0.75	173		143	1001 (0.95)
5 PM	1	0.9	207		171	171 (0.16)
6 PM	1	1.65	380		314	314 (0.30)
7 to 9 PM	3	2.7	621		513	1539 (1.47)
						7966 (7.59)

Some loads are simulated or controlled using the actual device. The dishwasher is operated once a day. Showers are automated to come on in the master bathroom three times per day with water temperature thermostatically controlled at 105°F. A refrigerator/freezer unit operates in normal mode, except the doors to the refrigerator and freezer sections remain closed. Additional load is added by the oven to account for the load associated with those door openings. More discussion of the refrigerator is included the “Refrigerator and Freezer” section later in this appendix.

Other loads (from people perspiring and respiring, from cooking, etc.) are generated by the oven, heat lamps, and water metered into an evaporation pan in the oven. The heat required to convert liquid water to water vapor is considered in the total sensible heat introduced into the lab building by the oven and heat lamps. The energy required to convert that liquid water to water vapor is calculated and added to the operation time of the oven.

To simulate daily latent load generated from occupant activities, 9.74 pounds of water is converted to water vapor each day, excluding the latent load produced by the dishwasher and showering, which is produced by actual operation of those devices. The amount of heat input required to convert 9.74 pounds of liquid water at 75°F to water vapor is calculated to be 11,514 Btu. This includes 1334 Btu (9.74 lb x 137°F x 1 Btu/lb-°F = 1334 Btu) of sensible heat required to warm the liquid water from 75°F to 212°F plus 10,227 Btu required to convert the water to vapor (9.74 lb x 1050 Btu/lb = 10,227 Btu). The oven provides the 11,514 Btu of sensible heat to affect this temperature and phase change. The oven combined with intermittent operation of heat lamps (located in the living room and master bedroom) is also used to simulate most of the sensible heat associated with occupants and with their activities, but excluding showers, dishwasher, and most of the refrigerator sensible heat.

Exterior door openings

A literature search could find no data on infiltration produced by exterior door opening (from people going in and out of the house), either on the number of door openings per day, the time of day schedule, the length of each door open and close event, or the infiltration that resulted. FSEC staff created a daily schedule with a total of 20 door openings (Table A-2).

Table A-2. Schedule for simulation of opening of exterior doors.

Time period (ending at)	Number of door openings	Cubic feet	Exhaust fan operation time
1 AM	0	0	
2 AM	0	0	
3 AM	0	0	
4 AM	0	0	
5 AM	0	0	
6 AM	0	0	
7 AM	2	110	8 min. 30 sec.
8 AM	3	165	12 min. 42 sec.
9 AM	1	55	4 min. 12 sec.
10 AM	0	0	
11 AM	0	0	
12 PM	1	55	4 min. 12 sec.
1 PM	1	55	4 min. 12 sec.
2 PM	0	0	
3 PM	0	0	
4 PM	0	0	
5 PM	1	55	4 min. 12 sec.
6 PM	4	220	16 min. 54 sec.
7 PM	3	165	12 min. 42 sec.
8 PM	2	110	8 minutes 30 seconds
9 PM	1	55	4 min. 12 sec.
10 PM	1	55	4 min. 12 sec.
11 PM	0	0	
12 AM	0	0	
DAILY TOTAL	20	1100	

Tracer gas decay tests were performed to determine the air infiltration that occurs from each door opening/closing event. Tracer gas decay tests were performed on the MH Lab with exterior doors closed and then repeated with exterior doors opened once every 5 minutes. The test was repeated a third time with exterior doors opened once every 2.5 minutes. Each door opening event lasted 7 seconds. The differential in house infiltration rate going from no door openings to 12 door openings per hour to 24 door openings per hour was used to determine that each door opening allows 55 cubic feet of air into the house. This infiltration rate may be an underestimation because winds were light and delta-temperature (outdoors minus indoors) was small during these tests.

Infiltration due to opening of exterior doors was implemented by operating the hallway bathroom exhaust fan for specific periods of time. Measurements found that the exhaust fan moves 13 cfm. The automation system runs the hallway bathroom exhaust fan for the periods defined in Table A-2 to simulate exterior door openings.

A psychrometric analysis shows the load impact from door opening on a typical summer day is small. Assuming outdoor conditions of 85^{o}F dry bulb and 75^{o}F dew point temperature and indoor conditions of 76^{o}F dry bulb and 55^{o}F dew point temperature, delta enthalpy is 12.36 Btu/lb (indoor enthalpy is 28.72 Btu/lb and outdoor enthalpy is 41.08 Btu/lb). Total load contributed by door openings on a typical summer day is then 1020 Btu (1100 cubic feet x 0.075 x 12.36 Btu/lb

= 1019.7 Btu/day; 82% of the load is latent and 18% is sensible). As indicated, our estimate of 55 cubic feet of infiltration per door opening may be smaller than typical because wind and delta-T was small during our tests. It is quite likely that actual air infiltration under more typical conditions will be greater than this.

Dishwasher operation

Based on Equation 16 from BARBD, the dishwasher would be operated 215 times per year, or 4.1 times per week. In order to reduce day-to-day variability in internal loads, it was determined that the dishwasher should be operated once each day. Since this produces more internal load than typical, other sources of simulated load were adjusted (reduced) to account for the additional dishwasher cycles.

Duct leakage

The SEER 21 experiments started with no duct leakage. Based on testing, the attic duct system has supply leakage of about 1% of system air flow. On the return side, there is a small return plenum and no return ductwork, all within the utility room, so there is no return duct leakage. This amount of duct leakage is our baseline "no duct leakage" configuration.

Based on Table 6 of the BARBD, standard duct leakage (total, meaning combined leakage to indoors and to outdoors) is 10% of system air flow (9% of supply air flow and 1% of return air flow; note that in the 2004 BARBD duct leakage was listed as 6.5% of supply air flow and 3.5% of return air flow). By contrast, duct leakage measurements carried out at FSEC during the past decade indicated that supply and return leakage is very nearly equal, with typical leakage to outside on the order of 12% (6% supply and 6% return) in the average home.

For the specific experiments that will be carried out in the MH Lab in future Phases, duct leakage (as well as duct location) will be a primary variable to be examined. We propose to perform experiments using the attic duct system with 6% supply leakage, 6% return leakage, and 6% supply leakage plus 6% return leakage. Each of the duct leakage amounts listed in this paragraph will be leakage to outdoors or unconditioned buffer zones (such as attics or crawl spaces; we will not consider leakage from the ductwork to and from the indoor space).

Window characteristics

BARBD defines window characteristics for the lab house, including total window area. It also states that window area will be distributed with the same proportion on each wall. Window U-values and solar heat gain coefficient (SHGC) values are specified in BARBD Table A-3. Since the MH Lab is an existing manufactured home, and the windows are typical double-pane clear, the experiments will stay with the existing window size, distribution, and performance characteristics.

Table A-3. (BARBD Table 3) Vertical Fenestration U-values (UF) and SHGC

HDD65 from Nearest Location Based on TMY3 Data*	UF Air to Air, Includes Framing and Sash (Btu/hr-ft^2-°F)	SHGC, Includes Framing and Sash
≥ 7,000	0.36	0.32
6,000–6,999	0.39	0.32
5,000–5,999	0.46	0.58
4,000–4,999	0.53	0.58
3,000–3,999	0.58	0.58
2,000–2,999	0.62	0.65
1,000–1,999	0.79	0.65
≤ 999	1.00	0.79

Window opening

Windows remained closed all of the time.

Window shading

In actual operation, bedroom blinds would normally be closed at night and most likely opened in the daytime. For these experiments, the blinds have remained fixed in a partially closed position throughout the experiments.

Lights

Using Equation 9 from BARBD, lighting energy for the MH Lab would be 1388 kWh/yr (3802 Wh/day). This 3802 Wh/day is distributed throughout the 24 hours of the day according to Figure 14 from BARBD (Figure A-1). Lights were turned off throughout the experiments and sensible loads associated with normal light operation have been simulated by heat generated by the kitchen oven. The schedule heat generated by lights to be implemented by the oven is shown in Table A-4.

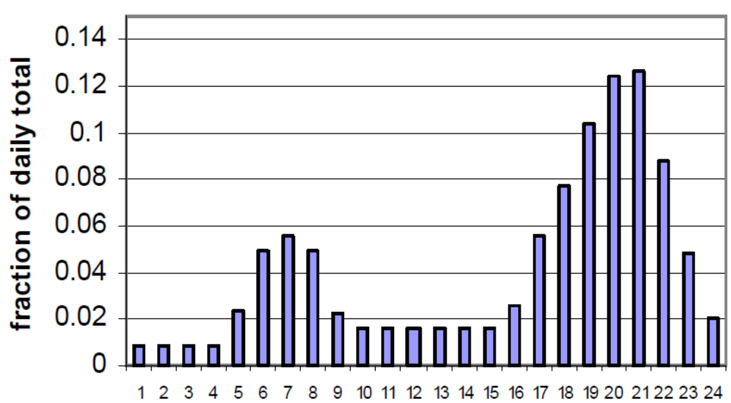

Figure A-1. Lighting schedule proposed in BARBD (BARBD Figure 14)

Table A-4. Lighting schedule for experiments.

Time period (end)	Fraction of daily total/hr	Lighting energy (Wh/hr)
1 AM to 4 AM	0.007	33
5 AM	0.022	105
6 AM	0.05	238
7 AM	0.055	261
8 AM	0.05	238
9 AM	0.022	105
10 AM – 3 PM	0.015	71
4 PM	0.025	119
5 PM	0.056	266
6 PM	0.076	361
7 PM	0.104	494
8 PM	0.124	589
9 PM	0.126	599
10 PM	0.087	414
11 PM	0.048	228
12 AM	0.02	95

Refrigerator and freezer

There is a refrigerator/freezer in the kitchen of the MH Lab. It is operated at standard refrigerator/freezer temperatures (approximately 38^{o}F and 0^{o}F, respectively), and will therefore operate, consume energy, and give off heat from compressor operation.

There are two aspects of normal refrigerator/freezer operation that are not reflective of normal operation in an actual occupied home; 1) the placement of warm food items into the unit and 2) the opening and closing of refrigerator/freezer doors. Based on a study reported in "Investigation of Energy Consumption and Energy Savings of Refrigerator-Freezer During Open and Closed Door Condition" by Hasanuzzaman M., Saidur R., Masjuki H.H., the energy use of a refrigerator/freezer is 40% higher when in normal use compared to a closed-door test. The total sensible load generated by the oven was adjusted to account for this, adding 560 Wh/day to the total sensible load according to the following schedule (Table A-5), which was created by the research team based on typical refrigerator use.

Table A-5. Added refrigerator energy to account for typical opening of refrigerator doors.

Time period (ending at)	Added refrigerator energy (W)
1 AM	0
2 AM	0
3 AM	0
4 AM	0
5 AM	0
6 AM	0
7 AM	56
8 AM	84
9 AM	28
10 AM	0
11 AM	0
12 PM	28
1 PM	28
2 PM	0
3 PM	0
4 PM	0
5 PM	28
6 PM	112
7 PM	84
8 PM	56
9 PM	28
10 PM	28
11 PM	0
12 AM	0
TOTAL	560

Washer/dryer

For the MH Lab, these appliances were assumed to be in an attached garage so there were no internal loads generated from the operation of the washer and dryer. In actual fact, there is no attached garage and no washer and dryer.

Stove/oven

According to Table 15 in BARBD, the electric range/oven in the MH Lab should use 605 kWh/yr with a 60% sensible/40% latent split. Total oven load would be 1.65 kWh/day. The 60% sensible would be 0.99 kWh/day and the latent would be 2.15 lb/day of H_2O. The sensible and latent heat generated by the oven has been produced by the automated scheduled oven operation and by metered delivery of water into an evaporation pan in the oven (Table A-6).

Miscellaneous Electric Loads (MELs)

BARBD Table 17 lists MELs. The following electricity uses are simulated in the house derived from BARBD Table 17 (yearly kWh in parentheses); ceiling fans (155), HVAC controls (20), GFI (24), door bell (30), first color TV (213), second color TV (75), first VCR (62), second VCR (22), DVD player (24), video gaming (13), home office including computer and FAX (191), bathroom appliances (44), other MELs (377), and kitchen but not including oven/range or refrigerator (788). The sensible heat generated by these MELs was produced in the MH Lab by operation of the oven.

Table A-6. Schedule of oven energy use to simulate MELs over a 24-hour period

Time period (period ending at)	Fraction of daily total/hr	Cooking energy (W)
10 PM to 5 AM	0.00	0
6 AM to 9 AM	0.10	165
10 AM to 12 PM	0.00	0
12 PM to 1 PM	0.10	165
2 PM to 5 PM	0.00	0
5 PM to 7 PM	0.25	412.5
8 PM to 9 PM	0.10	165

Hot water

Based on BARBD Table 7, the 50-gallon electric domestic hot water (DHW) heater, which is located in the MH Lab utility room close to the two AHUs, is set to 120^{o}F. Our primary interest in DHW use relates to the standby losses (heat gain) to the space from the tank and pipes, and to sensible and latent heat gain to the space because of DHW use in the house. In other words, it is not particularly the energy consumption of the DWH system itself that is of interest. Showering, taking baths, sink use, dishwasher, and clothes washer are the five primary uses of hot water in a house.

- According to BARBD Table 10, showering should consume 18.01 gal/day of 105^{o}F water. The shower in the master bedroom was placed on an automated schedule. A mixing valve was installed to provide 105^{o}F water whenever it operated. The recommended schedule for operation of the shower is shown in Figure A-2.

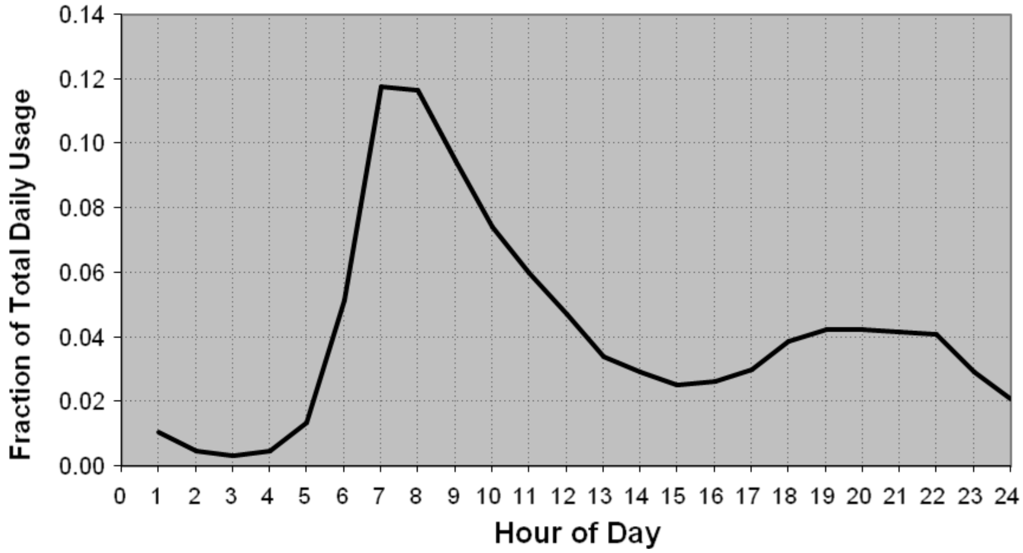

Figure A-2. BARBD proposed shower use schedule.

- According to BARBD Table 10, taking a bath should consume 3.51 gal/day of 105°F water. BARBD indicates that the sensible gain to the space should be 371 Btu/day. Interestingly, BARBD indicates that latent heat gain from a bath is "negligible compared to showers and sinks," so it indicates that latent load from the bath should be zero. Based on this, bathing was simulated by simply adding 371 Btu of sensible heat to the space each day by means of the oven. The recommended schedule for taking a bath is shown in Figure A-3.

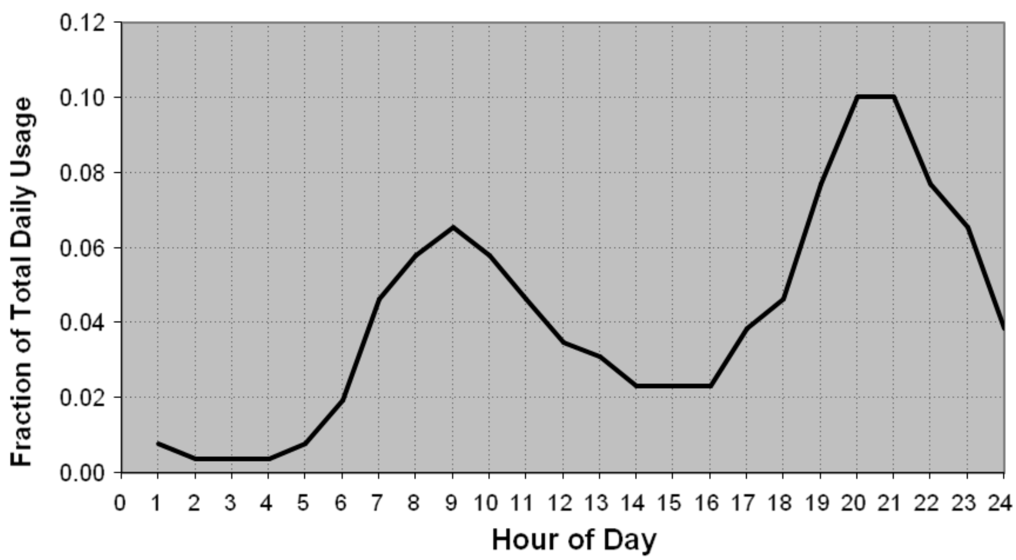

Figure A-3. BARBD proposed bath use schedule.

According to BARBD Table 10, water use in sinks should consume 24.98 gal/day of 105°F water. The sensible contribution would be 619 Btu/day. The latent contribution would be 281

Btu/day (0.29 pints/day). Since hot water use was not implemented at sinks, the indicated sensible and latent loads were simulated though the oven/evaporation pan setup. The recommended schedule for sink hot water use is shown in Figure A-4.

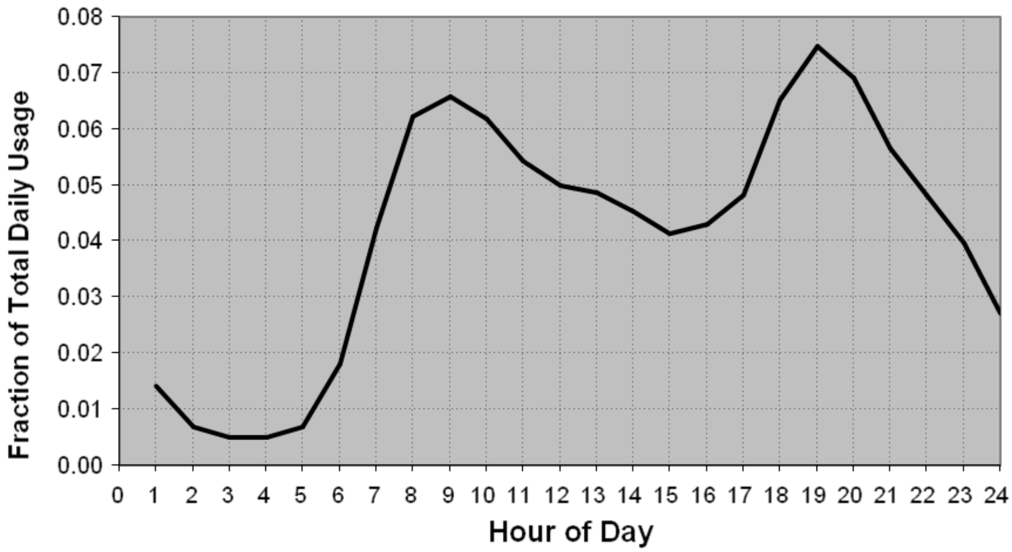

Figure A-4. BARBD proposed sink use schedule.

- Since the dishwasher in the house runs through one cycle each day, there is no need to simulate the sensible and latent heat contribution to the space from the dishwasher. It is true that since the dishwasher door is not being opened at the end of each cycle (to remove clean dishes), some of the typical moisture entry to the space will not occur. The original intent was to activate the dishwasher heating cycle so that most or all of the moisture remaining on the dishes would be driven off into the room. However, this did not happen so some moisture remains in the dishwasher from one cycle to the next.
- Since the clothes washer is not in the house, the hot water draw for the clothes washer has been disregarded. If there were a clothes washer located in an attached garage, and if the clothes washer was operated on a regular schedule, it would have essentially no impact upon the internal loads of the house.

According to Table 12 in BARBD, the clothes washer would normally use 15 gallons per day. Because the clothes washer is assumed (for purposes of our experiments) to be in an attached garage, but there is no attached garage, therefore this 15 gallons per day (of 120^{o}F water) has been removed from our total draw pattern.

Appendix B

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This combination qualifies for a Federal Energy Efficiency Tax Credit when placed in service between Feb 17, 2009 and Dec 31, 2010.

Certificate of Product Ratings

AHRI Certified Reference Number: 3423952 Date: 2/24/2010

Product: Split System: Heat Pump with Remote Outdoor Unit-Air-Source
Outdoor Unit Model Number: FT4BI-036K
Indoor Unit Model Number: B4VM-E36K-B
Manufacturer: NUTONE
Trade/Brand name: NUTONE FT4BI SERIES

Manufacturer responsible for the rating of this system combination is NUTONE

Rated as follows in accordance with AHRI Standard 210/240-2006 for Unitary Air-Conditioning and Air-Source Heat Pump Equipment and subject to verification of rating accuracy by AHRI-sponsored, independent, third party testing:

Cooling Capacity (Btuh):	35000
EER Rating (Cooling):	13.00
SEER Rating (Cooling):	21.00
Heating Capacity(Btuh) @ 47 F:	34000
Region IV HSPF Rating (Heating):	9.60
Heating Capacity(Btuh) @ 17 F:	22000

A * following a rating indicates a voluntary rerate of previously published data, unless accompanied with a WAS which indicates an involuntary rerate.

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AHRI Air-Conditioning, Heating, and Refrigeration Institute

2009 Air-Conditioning, Heating, and Refrigeration Institute

CERTIFICATE NO.: 129115003413984049

Figure B-1. AHRI certificate of product rating for 21 SEER Nutone heat pump.

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Certificate of Product Ratings

AHRI Certified Reference Number: 3753870 Date: 3/22/2010

Product: Split System: Heat Pump with Remote Outdoor Unit-Air-Source
Outdoor Unit Model Number: FT4BD-036K
Indoor Unit Model Number: GB5BM-036K-B
Manufacturer: NUTONE
Trade/Brand name: NUTONE FT4BD SERIES

Manufacturer responsible for the rating of this system combination is NUTONE

Rated as follows in accordance with AHRI Standard 210/240-2006 for Unitary Air-Conditioning and Air-Source Heat Pump Equipment and subject to verification of rating accuracy by AHRI-sponsored, independent, third party testing:

Cooling Capacity (Btuh):	35400
EER Rating (Cooling):	11.80
SEER Rating (Cooling):	13.00
Heating Capacity(Btuh) @ 47 F:	36000
Region IV HSPF Rating (Heating):	8.00
Heating Capacity(Btuh) @ 17 F:	23000

A * following a rating indicates a voluntary rerate of previously published data, unless accompanied with a WAS which indicates an involuntary rerate.

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AHRI Air-Conditioning, Heating, and Refrigeration Institute

CERTIFICATE NO.: 129137607885115198

Figure B-2. AHRI certificate of product rating for 13 SEER Nutone heat pump.

EERE Information Center
1-877-EERE-INF (1-877-337-3463)
www.eere.energy.gov/informationcenter

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