

15.C.3c            Journal or Conference Paper: Whole House Research Performance Results  
Due: November 10, 2007

The Subcontractor shall prepare at least three technical paper for submission to an appropriate major technical conference or journal, describing the team's overall results from whole-house systems engineering research studies. The paper shall discuss the most promising advanced building system approaches to achieve 40-50% savings in residential space conditioning, hot water, and lighting loads relative to the Benchmark. The paper shall clearly identify the appropriate climate, building type, and building systems addressed by the recommendations. The paper shall summarize the building science knowledge and quality control tools that are required to successfully implement building design recommendations. The paper shall include examples of successful system solutions, examples of common mistakes to be avoided, and basic information about the potential impacts of making changes in the example solutions. The paper may be distributed through the DOE Building America Program Internet web site and hard copy format. The papers shall be delivered directly to the NREL Technical Monitor for peer review at least two weeks before the conference or journal submission deadline.

# DRAFT

## Introducing the market to high-performance green building on Hilton Head Island

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### Introduction

Primarily as a resort location, Hilton Head Island has a somewhat different residential housing market than other more traditional areas. The market is made up of both year-round occupancy and seasonal occupancy, and the size and cost of new homes range from the very large and expensive to those of more normal size but still higher cost. Most houses are simply “built to code.” High-performance and “green” housing practices have not begun to penetrate the market.

As part of the U.S. Department of Energy’s Building America Program, a partnership was developed with a builder who had learned from experience that just building to code left a lot to be desired from an overall performance perspective. He came to believe that real value lies in implementing building science principals within a systems engineering approach to high-performance housing.

The whole-house performance approach described here builds a framework of understanding that starts with principals that lead to evaluation of options that leads to a coherent plan that leads to quality execution of producing high-performance homes. High-performance homes are comfortable, healthy, safe, durable, energy efficient, and respecting of the environment. A high-performance home will also reduce a builder’s risk of warranty/service call-back and customer complaint, leaving more room for profitability.

### Systems principals, options evaluation, and as-built characteristics

A logical construction sequence approach is used here to describe the systems principals and to evaluate reasonable construction options. As one progresses through the construction sequence you can see the value of looking both forward and behind to see the linkages in the systems engineering approach.

### Sitework

Historically, Hilton Head Island receives about 50 inches of rain per year. The site is a four-acre parcel with nearly two acres of freshwater wetlands that will remain undeveloped. In addition to site drainage requirement required by code, pervious

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pavement was used throughout the project for the driveway and parking spaces near the detached garages, and for all sidewalks (Ruiz 2007). Low maintenance grasses and shrubby were purposefully designed into the landscape. The site plan is shown in Figure ???.

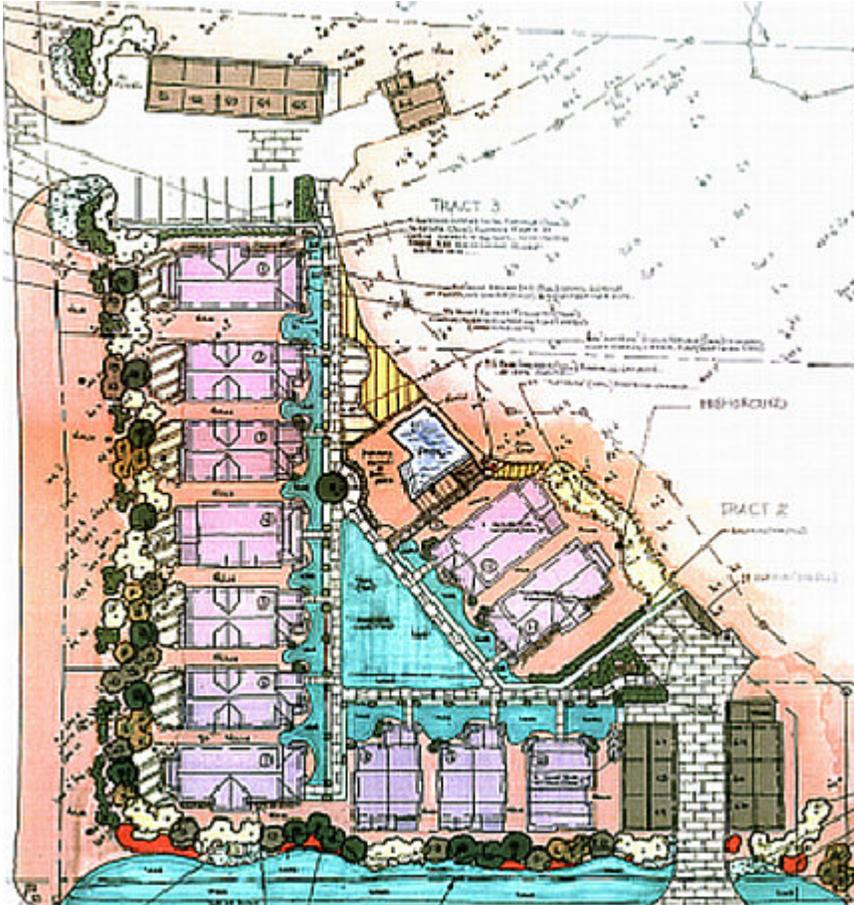


Figure ??? Project site plan

### ***Foundation***

A slab-on-grade foundation is the most cost effective and trouble-free foundation in most parts of the U.S. where the frost depth is above about three feet. Sealed crawlspaces with insulated walls and a small amount of conditioned supply air could have been used if the grade sloped, or if the first floor needed to be elevated, but that was not the case. A 4-inch monolithic slab with turned-down edges was poured over a 6-mil polyethylene vapor barrier over compacted sand/stone. Soil under the foundation was treated for termites. Slab-edge insulation was not used due to the long-term risk of termite infestation through or behind the insulation.

### ***Exterior Walls***

Detailing of exterior walls can be the most complex of the building enclosure elements. The negative effects of water intrusion, air infiltration, thermal conduction, water vapor

diffusion, and solar radiation must all be considered along with the realities of many wall penetrations, architectural detailing, wind and weight loading requirements, security requirements, component attachment, interior and exterior finishing aesthetics, etc.

Having a high priority for comfort at low cost in hot-humid climates requires, in order of priority for walls:

- glazing with low solar heat gain;
- air sealing;
- opaque areas with moderately high thermal insulation; and
- glazing with thermal resistance at least high enough to avoid wintertime condensation.

Having a high priority for durability in hot-humid climates requires:

- a continuous water drainage layer behind the cladding, integrated with window, door, roof, and other penetration flashings, to protect water sensitive materials located deeper in the assembly;
- a capillary suction break between foundation materials in soil contact and walls above;
- water vapor diffusion resistance between water absorptive claddings and wall sheathing to retard moisture movement driven by solar heat; and
- interior finish materials that do not retard water vapor movement to allow drying to the inside air.

To accomplish all of these goals, and having started with an initial builder criteria of conventional wood stud framing, the wall system chosen was as follows:

- 2x6 16" o.c. wood studs filled with open cell spray foam insulation in the cavity
- Foam gasket and capillary break between the pressure treated bottom plate and the foundation;
- Gypsum wallboard and latex paint interior finish;
- OSB sheathing covered by corrugated house wrap to increase drainage, covered by 1/4" XPS foam sheathing to retard solar driven water vapor, covered by fiber cement siding and paint;
- Windows with NFRC rated solar heat gain coefficient of 0.33 and U-value of 0.32; and
- Butyl flashing membranes integrated with the house wrap drainage layer for all windows, doors, roof-to-wall flashings (including kick-out flashings, see Figure ???), and wall penetrations for plumbing and wiring.



## Figure ??? Kick-out flashing at roof-wall intersection

### Roof

Primarily as a strategy to lower costs, traditional attics leave a lot of potentially useful sheltered space unused. Prefabricated trusses have reduced construction cost and construction time in trade for more sprawling plans to make up for the loss of living space. In many high-performance homes, cathedralized attics make better use of that space than traditional attics by moving the insulation directly under the roof plane to enclose all air distribution system components within the thermal and air pressure boundary of the building enclosure. Illustrated in Figure ???, that construction method is specifically allowed by the International Residential Code (section R806.4), and the Florida Building Code.

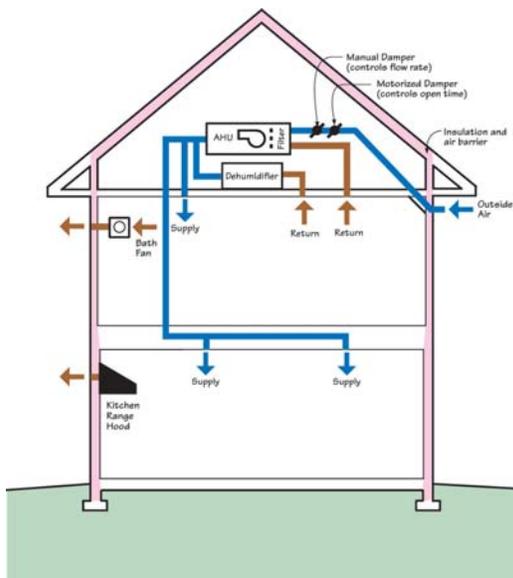


Figure ??? Cathedralized attic enclosing the central space conditioning air distribution system within thermal and air pressure boundary of the building enclosure

Going further than cathedralized attics, cathedral ceilings generally make the most use of sheltered space by finishing the underside of the roof framing to convert all of what would have been attic space to conditioned living space. A 1" to 2" soffit-to-ridge vent space may or may not be left under the roof sheathing, but in either case, application of open cell or closed cell spray foam insulation is the best way to insulate and air seal the roof/ceiling assembly.

All of the houses in this project had either cathedralized attics or cathedral ceilings, and all were insulated to R-30 with open cell spray foam. Gypsum board and latex paint provided the interior finish. Wood sheathing, roofing paper underlayment, copper flashings, and 40 year fiberglass/asphalt shingles provided the water and structural protection.

### Central Forced Air Heating and Cooling

Proper comfort conditioning, filtration, and distribution of indoor air are critical to the success of high-performance homes. These systems should be designed and properly sized, but in order for that to be successful, the builder's commitment to the following items must be in place:

- Building enclosure leakage not more than 0.25 cfm50 per ft<sup>2</sup> of enclosure surface area
- Duct leakage to outside not more than 5% of the high speed flow rate, and total duct leakage not more than 10% of the high speed flow rate
- Provision for return air transfer from rooms with doors to assure less than 3 Pascal pressure difference between rooms and the common area
- High-performance glazing with U-value and SHGC in the range of 0.35
- Uniform and properly installed insulation

By a commitment to quality control practices backed up by testing, the builder should provide assurance of these things to the HVAC contractor in order to expect the contractor to have confidence that right-sizing the equipment will reduce his risk of comfort complaints.

Right-sizing the equipment starts with using software adhering to ACCA Manual J version 8 to calculate system loads and room air flow requirements for cooling and heating systems. There are many inputs to such software, and different ways to somewhat subjectively inflate the system size. Good information is given in the Manual J text, but here are some of the most important factors to get right for the high-performance homes discussed here:

- All ducts and air handlers should be input as located within the conditioned space (while the actual location may be directly or indirectly conditioned, the important factor is that the entire air distribution system is within the thermal and air pressure boundary of the enclosure). The resulting duct heat gain/loss load reported by the program should be zero.
- Infiltration should be set at 0.1 ach for both winter and summer. Mechanical ventilation should be set at 65 cfm.
- The glazing U-value and SHGC should be set at the values shown on the NRFC rating label attached to the glazing (U=0.32, SHGC=0.33). A "custom window" should be created to do this. For most glazing, the interior shading should be set for drapes-medium, 50% drawn, no insect or external shade screens, ground reflectance equal to 0.20.
- Outdoor design conditions should not exceed the ASHRAE 0.4% design for cooling, which for Savannah, GA is 95.4 F dry bulb and 77.1 F wet bulb. Indoor conditions should be set at 75 F dry bulb and 63 F wet bulb (50% RH).
- For production built communities, the building design load for each plan should be calculated for the orientation that creates the highest system load, but the individual room duct sizing should be done based on the average flow of all four cardinal orientations. For rooms with more than 18% glass to floor area ratio, the duct size can be increased to the maximum of all four orientations.
- Equipment selection should be based on indoor and outdoor sections that are matched in capacity and listed in the ARI directory. The equipment will be selected based on the manufacturers extended performance ratings to meet the design sensible load at the actual (not nominal) outdoor and indoor design conditions. Use

the ACCA Manual S provision that allows one-half of the unused latent capacity to count as sensible capacity. If the total load (sensible+latent) exceeds the total capacity of the system by more than 900 Btu/h then go to the next bigger size, otherwise, stay at the smaller size. A thermal expansion valve refrigerant metering device should be used and the refrigerant charge checked using the sub-cooling method.

The air distribution system needs to be designed as well, to make sure that the right amount of air gets to where it is supposed to go to meet the space conditioning loads and provide comfort. Use of supply registers that allow adjustment of the airflow rate and airflow direction is also important for final balancing and room air circulation. In high-performance homes, the duct systems can be more compact because the air flow requirements are lower, and there is no need to have extended duct runs to “wash” outside walls and windows with cool or warm air. A more compact duct system makes it easier to locate the ducts inside conditioned space (in floor systems, soffits/chases/fur-downs, and inside walls). Here are some additional important practical principles to apply:

- Supply air run-outs should be sized for the room airflow requirement at 500 ft/min. Supply air trunks or plenums should be sized for not more than 750 ft/min. Return air ducts should be sized at not more than 350 ft/min, return grilles should be sized for no more than 300 ft/min.
- Total external static pressure (defined as the pressure differential between the return side and the supply side of the air handler cabinet) should not exceed the manufacturer’s specification, usually 125 Pa (0.5 inch water column).
- Ducts feeding supply registers in bedrooms should not be larger than 6” diameter (100 cfm maximum) to avoid blowing too much air too fast on sedentary people. Reasonable care should be taken to avoid blowing air directly on beds. Most master bedrooms will require at least two supply registers rather than one large supply register.
- Provision for return air transfer from closable rooms is required (jump ducts or transfer grilles). Pressurization or depressurization of rooms or the common area should not exceed 3 Pa.

These design guidelines were followed for each of the five house plans used in the project. An example system and duct sizing output for one of the plans is shown in Figure ???. All of the houses were fitted with either 1.5-ton or 2-ton (nominal) air source heat pumps with variable speed indoor fan and thermal expansion valve. Published efficiencies were 15.1 SEER and 8.05 HSPF as shown in Figure ???.

Front of house facing:	N	NE	E	SE	S	SW	W	NW	max	avg	
<b>RHVAC program output</b>											
Heating Load (kBtu/h)	22.2										
Sensible Cooling Load (kBtu/h)	18.8		17.2		18.1		17.6		18.8	17.9	<b>BSC Spec</b>
Latent Cooling Load (kBtu/h)	3.2		3.2		3.2		3.2				
Total Cooling Load (kBtu/h)	22.0		20.4		21.3		20.7		22.0	21.1	2.0 ton
<b>Room Air Flow (cfm)</b>											
Living	129		92		125		97		129	111	111
Dining	82		51		79		56		82	67	67
Kitchen	72		65		70		65		72	68	68
Bed 1	107		109		98		114		114	107	107
Bath 1	14		9		14		8		14	11	11
Bed 1 closet	8		8		8		8		8	8	8
Bed 2	95		114		97		116		116	106	106
Bath 2	39		25		38		27		39	32	32
Bed 2 closet	13		12		12		12		13	12	12
Bed 3	100		114		92		116		116	106	106
Bath 3	55		54		54		54		55	54	54
Bed 3 closet	7		7		7		7		7	7	7
Hall	62		50		60		49		62	55	55
Laundry	29		28		28		28		29	28	28
Totals:	812		738		782		757			772	800
<b>Supply Duct Diameter (in)</b>											
Living	2-5		1-6		2-5		1-6				2-5
Dining	1-6		1-5		1-6		1-5				1-6
Kitchen	1-6		1-5		1-6		1-5				1-6
Bed 1	2-5		2-5		2-5		2-5				2-5
Bath 1	1-4		1-4		1-4		1-4				1-4
Bed 1 closet	1-4		1-4		1-4		1-4				1-4
Bed 2	1-6		2-5		1-6		2-5				2-5
Bath 2	1-4		1-4		1-4		1-4				1-5
Bed 2 closet	1-4		1-4		1-4		1-4				1-4
Bed 3	2-5		2-5		1-6		2-5				2-5
Bath 3	1-5		1-5		1-5		1-5				1-5
Bed 3 closet	1-4		1-4		1-4		1-4				1-4
Hall	1-5		1-5		1-5		1-5				1-5
Laundry	1-4		1-4		1-4		1-4				1-4

Figure ??? System and duct sizing output for the Maggie plan

ARI Ref #	Model Status	Manufacturer	Trade/Brand Name	Outdoor Unit Model Number	Indoor Unit Model Number	Furnace Model Number	Cooling			High Heating 47°F		Low Heating 17°F
							Capacity (Btu/h)	EER	SEER	Capacity (Btu/h)	HSPF	Capacity (Btu/h)
1236865	Discontinued	THE TRANE COMPANY	XL15i Weathertron	2TWX5024A1	2TEE3D31A1		25,000	12.50	14.50	22,600	8.00	14,100
1236867	Discontinued	THE TRANE COMPANY	XL15i Weathertron	2TWX5024A1	2TEE3D37A1		24,800	12.60	15.00	21,600	8.50	13,200
1236869	Discontinued	THE TRANE COMPANY	XL15i Weathertron	2TWX5024A1	2TEE3D40A1		26,200	13.00	15.50	22,400	8.50	13,600
1106214	Discontinued	THE TRANE COMPANY	XL15i Weathertron	2TWX5024A1	2TEE3F31A1		25,000	13.00	15.10	22,600	8.05	14,100
1106216	Discontinued	THE TRANE COMPANY	XL15i Weathertron	2TWX5024A1	2TEE3F37A1		25,000	12.70	15.00	21,600	8.60	13,200

Figure ??? ARI Directory listing for the matched equipment

### Supplemental Whole-house Dehumidification

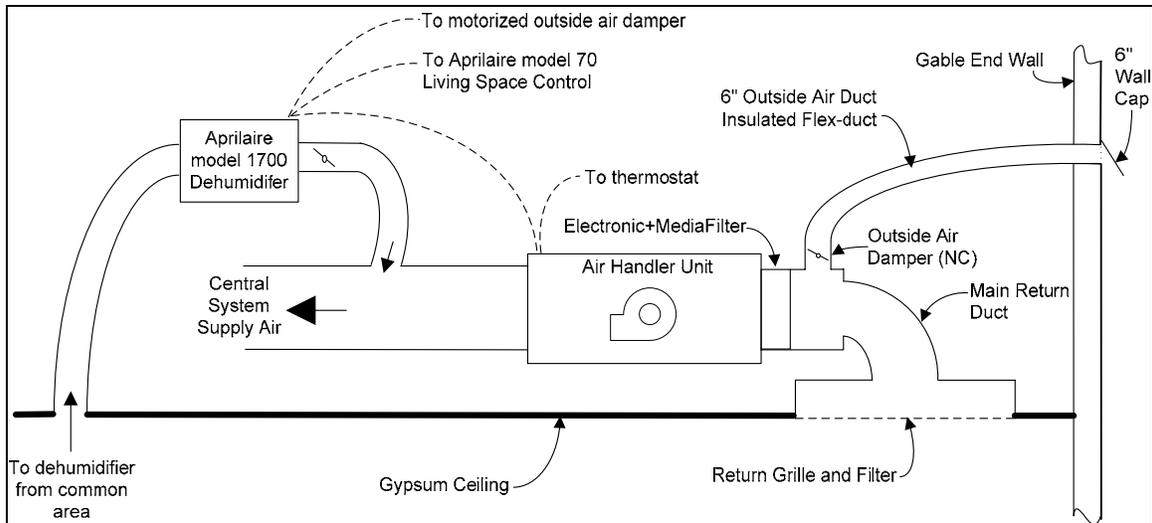
High efficiency houses in warm-humid climates have low sensible heat gain. Low sensible heat gain is good for reducing cooling costs, but contributes to part load moisture control challenges. Especially during Spring and Fall seasons, there are a significant number of hours where little or no sensible cooling is needed but moisture removal is still needed due to internal moisture generation and ventilation. This situation can also occur during summer nights and rainy/overcast periods. Conventional cooling equipment is equipped mostly for reducing air temperature (sensible cooling), with only about 20 to 30 percent of its capacity designed for removing moisture (latent cooling). This results in periods of high indoor relative humidity.

Enhanced humidity control settings for the central cooling system are often applied as follows:

- Reduced evaporator coil air flow: The blower speed controls should be set to be reduced for the early minutes of a cooling cycle to let the evaporator coil get colder and begin to remove moisture from the air faster. In general, for humid climates, 200 to 300 cfm/ton can be used in the early minutes of operation, and 300 to 350 cfm/ton can be used for full cooling operation.
- Reduced cooling setpoint: A strategy employed by some thermostats to try to increase moisture removal is to cause the cooling setpoint to be depressed below the requested temperature setpoint if indoor humidity is above the requested humidity setpoint. This strategy for enhanced humidity control is marginally effective at best, it is inefficient, and it often leads to occupant comfort complaints. Also, anytime the indoor drybulb temperature is below the outdoor dew point temperature, the building enclosure is more at risk of moisture related problems. For all these reasons, the depressed setpoint strategy should not be used.

A better solution for year-round indoor humidity control in warm-humid climates has been to add separate dehumidification equipment to supplement the normal cooling system during periods when moisture removal alone is needed. This dehumidification capacity can also result in occupants being more comfortable at a higher cooling setpoint, which can save energy. Supplemental whole-house dehumidification will provide year-round humidity control, assuring against mold odors, especially during swing seasons and unoccupied periods.

The houses in this project (except one due to space constraints) were fitted with a whole-house dehumidifier integrated with the central system according to the schematic in Figure ????. The dehumidifier was ducted with an intake from a common area location in the house and a discharge into the central system main supply air duct (requiring a normally-closed damper to prevent backflow when the dehumidifier was not active). Control for the dehumidifier was by a sensor in the living space that measured and displayed the indoor humidity level and activated and deactivated the dehumidifier according to the user selected setting. More detail on the operation of the dehumidification and ventilation systems integrated with the central system will be given in the next section covering ventilation.



**Figure ??? Schematic of whole-house dehumidifier and supply ventilation integrated with central space conditioning system**

### ***Ventilation and Indoor Air Quality (Rudd 2006)***

The first step toward improving indoor air quality is to keep sources of pollution out the house to begin with. In this project, the only combustion appliance was the tankless hot water heater which was sealed-combustion, direct vent. No-VOC paints were used throughout. All garages are detached. The houses were well sealed against air infiltration so that most air exchange, and the air pressure relationship, between the indoors and outdoors would be mechanically and purposefully controlled.

The next step is to provide for local exhaust ventilation where moisture, odor, and indoor air contaminants are produced and exist at high concentrations. These locations typically include bathrooms, kitchens, and laundries. In this project, a minimum 50 cfm exhaust fan, controlled by a standard on/off switch, was installed in each bathroom and laundry room. A minimum 100 cfm cook-top exhaust fan, controlled by a standard on/off switch, was installed in the kitchen. The fans were ducted to exhaust directly to outdoors, and all duct joints were sealed. Occupants were or will be informed that the exhaust fans when the rooms are in use.

Whole-house dilution ventilation is then needed to reduce the concentration of diffuse pollutants throughout the conditioned living space. Especially in warm-humid climates, distributed supply ventilation works better than exhaust ventilation because:

- a known amount of filtered outside air will be drawn from a known fresh air location, then tempered with a large percentage of indoor air, and possibly cooled and dehumidified or heated before it is distributed; and
- the conditioned space is slightly pressurized, causing conditioned air to exit the building enclosure through whatever outlet pathways are available (often exhaust points in tight homes) rather than drawing humid air inward through the building enclosure where it may cause moisture problems and/or be contaminated.

In this project, a 6 inch diameter insulated outside air duct and normally-closed motorized damper were fitted to the return side of the air handler unit generally

according to the schematic in Figure ????. The system supplies about 50 cfm of outside air for a minimum and maximum of 33% of the time. This fan cycle rate will not provide the ASHRAE 62.2 (62.2) airflow amount, although the system could meet the 62.2 airflow amount if the fan was operated continuously. Operating the central fan continuously is NOT recommended, especially in warm-humid climates, because of re-evaporation of moisture from the wet cooling coiling (Henderson and Shirey 2006) and excessive fan energy consumption which ends up as heat that the cooling system must remove. As was done in this project, the best practice is to install one 62.2 compliant exhaust fan in every house, which is the ventilation system of record for rating purposes. The existence of that fan exhaust fan, and an on/off switch, meets the 62.2 requirements by itself. Central fan cycling operation is then outside of the rating in the same way that the Fan On button on the thermostat is outside of the rating. In reality, about half the fan cycling operation for supply ventilation does double-duty because it is needed for thermal comfort mixing anyway.

The ventilation controls for this particular system are integrated with the whole-house dehumidifier controls. Here are the principals of operation:

- a) The dehumidifier must be have power in order for any ventilation and central fan cycling and outside air damper cycling to occur. The dehumidifier will operate to reduce indoor humidity independently of ventilation and central fan cycling.
- b) The central fan will operate for at least 10 minutes per half hour (including any operation due to thermostat demand).
- c) The outside air damper will be open for 10 minutes per half hour while the central fan is operating. The outside air damper will not be open for more than 10 minutes per half hour regardless of any additional fan runtime due to thermostat demand. The outside air fraction is about 10% or less, so, being mixed with 90% or more inside air, there is no need to dehumidify it first. The moisture will be removed with normal cooling demand, or by the dehumidifier if cooling demand does not control it.
- d) The dehumidifier will run only as needed based on the measured humidity in the living space and the humidity setpoint. As humidity rises in the living space for any reason, ventilation or otherwise, the dehumidifier will be energized and bring the humidity back down.

Air filtration was handled in all the homes using a combination electronic plus wide media air filtration product. Filtration efficiency was 98% to 99% for large particles (1 micron and larger) and 94% for small particles down to 0.35 microns.

## ***Lighting***

Daylighting of the home interior is an important component of energy conservation and of the enjoyment occupants experience in the space. More glass area than needed is energy wasteful. Even for the components in these high-performance homes in Hilton Head, SC, a unit area of glazing requires about 3 times more space conditioning energy than the same area of insulated opaque wall. However, too little glass does not contribute to good overall environmental design either. The windows in this project were well placed for daylight and view while preserving privacy.

Compact fluorescent lighting uses about one quarter the power of incandescent lighting for the same lighting intensity. In predominantly cooling climates, this reduces energy

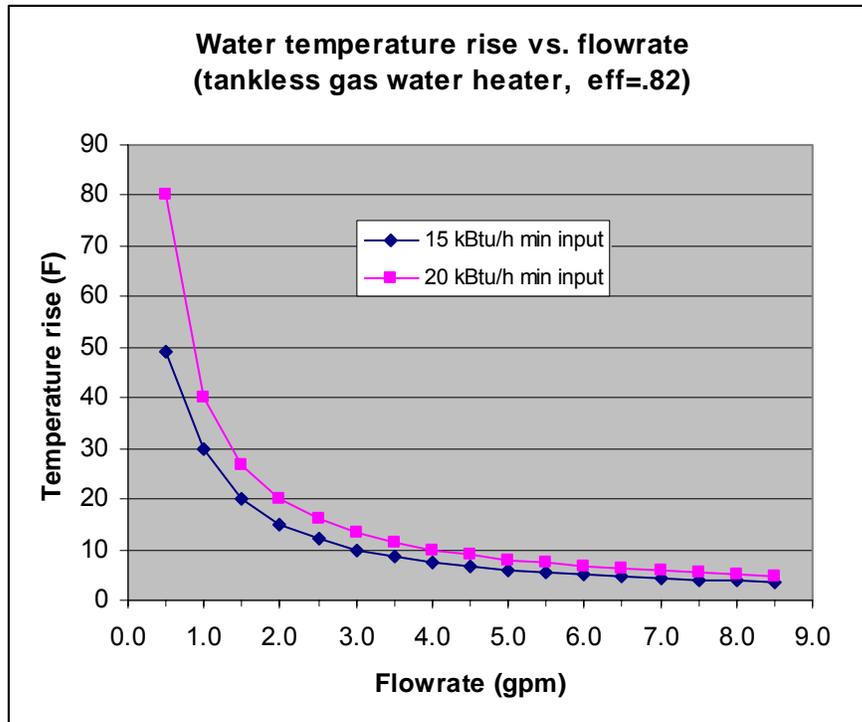
consumption in two ways, the energy used for lighting and the energy to remove the heat generated by the lighting. Compact fluorescent lighting was used throughout each home in this project. The lighting was planned and designed to work well both functionally and aesthetically.

### ***Hot Water Heating***

Hot water heating in each home was by a gas, sealed-combustion, direct vent tankless heater with an Energy Factor of 0.85. That compares to standard gas hot water heaters having an EF=0.56. In one house, solar hot water heating was added to achieve even higher energy savings.

The combination of tankless hot water heating and solar hot water heating creates some challenges that are being researched in this project. Running pre heated water into a tankless water heater will not damage the unit, but it can cause wide temperature fluctuations at the domestic taps. All gas-fired tankless hot water heaters have a minimum firing rate—usually not less than 15 kBtu/h. If the entering water temperature is too close to the outlet temperature setpoint, then the unit may not fire or fire intermittently causing wide temperature fluctuations at the domestic taps. One major manufacturer recommends that the water going into the unit be no warmer than 75 °F to avoid this problem.

Referring to Figure ???, at the minimum hot water draw rate of 0.5 gpm, the minimum firing rate will produce a 50 °F temperature rise. That means that if the water heater outlet setpoint is 125 °F, and the inlet water temperature is greater than 75 °F, then the water heater will shut off, delivering water to the tap as low as 75 °F. If the flow rate increases, or if the inlet water temperature falls, then the heater will fire again and start delivering 125 °F water to the tap. Referring again to Figure ???, depending on the water flow rate (between the minimum and maximum allowed by the unit) this type of temperature fluctuation can occur with solar preheated water anywhere between 75 °F (at 0.5 gpm) and 121 °F (at 8.5 gpm). It is very likely that the solar preheated water will quite often fall within that range.



**Figure ??? Water temperature rise versus flow rate for a typical gas tankless hot water heater**

Tankless water heaters have the potential to cause annoying temperature fluctuations at the taps for other reasons as well. If the water draw is below the common 0.5 to 0.7 gpm minimum flow rate, such as when drizzling water to rinse dishes or shave, the unit will not fire, delivering main temperature water to the tap. When water use is of the rapid on/off type, hot and cold water will be intermittently delivered to the tap due to water heating delay times as the unit cycles on and off. It can commonly take 10 seconds after the beginning of a hot water draw for a tankless heater to prove proper draft and fire the gas burner. One major manufacturer now keeps the vent blower running for about one minute after the end of each hot water draw in order to reduce the re-firing time to a few seconds. So, delivery of cold water between the on/off hot water demand times can typically last from a few seconds to 10 seconds.

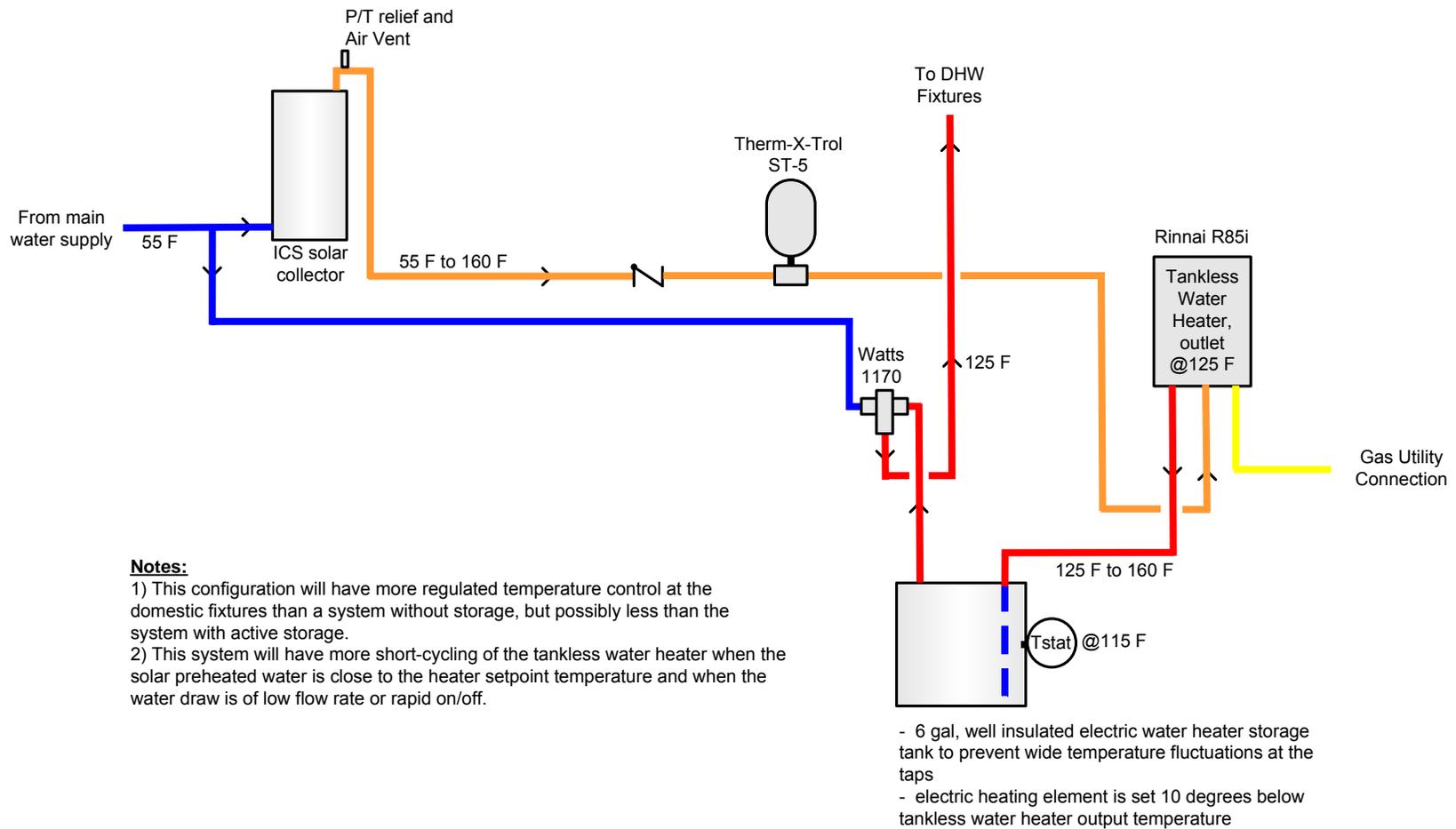
Due to the expected inefficiencies and occupant annoyances (Grubb 2006, Gleason 2007) related to these operational characteristics, field research is being conducted to evaluate whether the systems shown on Figures ??? and ??? will resolve these issues, with a focus on the integration of solar hot water heating with tankless hot water heaters.

The system of Figure ??? adds a small, well-insulated storage tank that is backed up with electric heat to a setpoint approximately 10 °F below the tankless hot water heater outlet setpoint. In that way, the temperature fluctuation delivery problem will be resolved for conditions when:

1. the hot water demand is below the minimum flow rate to fire the gas heater; and
2. the inlet water is warm enough that the water heating capacity needed is below the minimum firing capacity of the gas heater. The frequency and duration of this condition will impact how often the electric heating element will need to come on.

The electric heating element will also be needed to offset long-term heat loss from the small storage tank (for example overnight) when there is no hot water demand to infuse the tank with new hot water. If the electric back up was not there, it could take several minutes for hot water to reach the tap as the water that had cooled off in the tank must be replenished with new warm water. The mixing valve is required in case the solar pre-heated water is too hot for delivery to the domestic taps.

The system of Figure ??? goes further by eliminating the short-cycling inefficiency of the gas heater. It also eliminates the need for any electric heating element. The system adds a pumped circulation loop off the side of the small, well-insulated storage tank to the tankless water heater, much like an indirect water heater. Whenever the thermostat switch on the storage tank closes, the circulator will be energized, moving water through the gas heater. Tankless hot water heaters have a relatively high flow resistance; the pump needed to force water through the unit will draw about 90 W. Therefore, while this system will provide the best operation in terms of supplying regulated temperature water to the taps, and it does not require an electric heating element, there will be circulator and storage tank losses that need to be better understood. The system of Figure ??? also has the advantage of being easily adapted to combination space and domestic hot water heating applications



**Figure ??? Tankless Hot Water Heater Application with Solar Preheat and Passive Storage Tank**

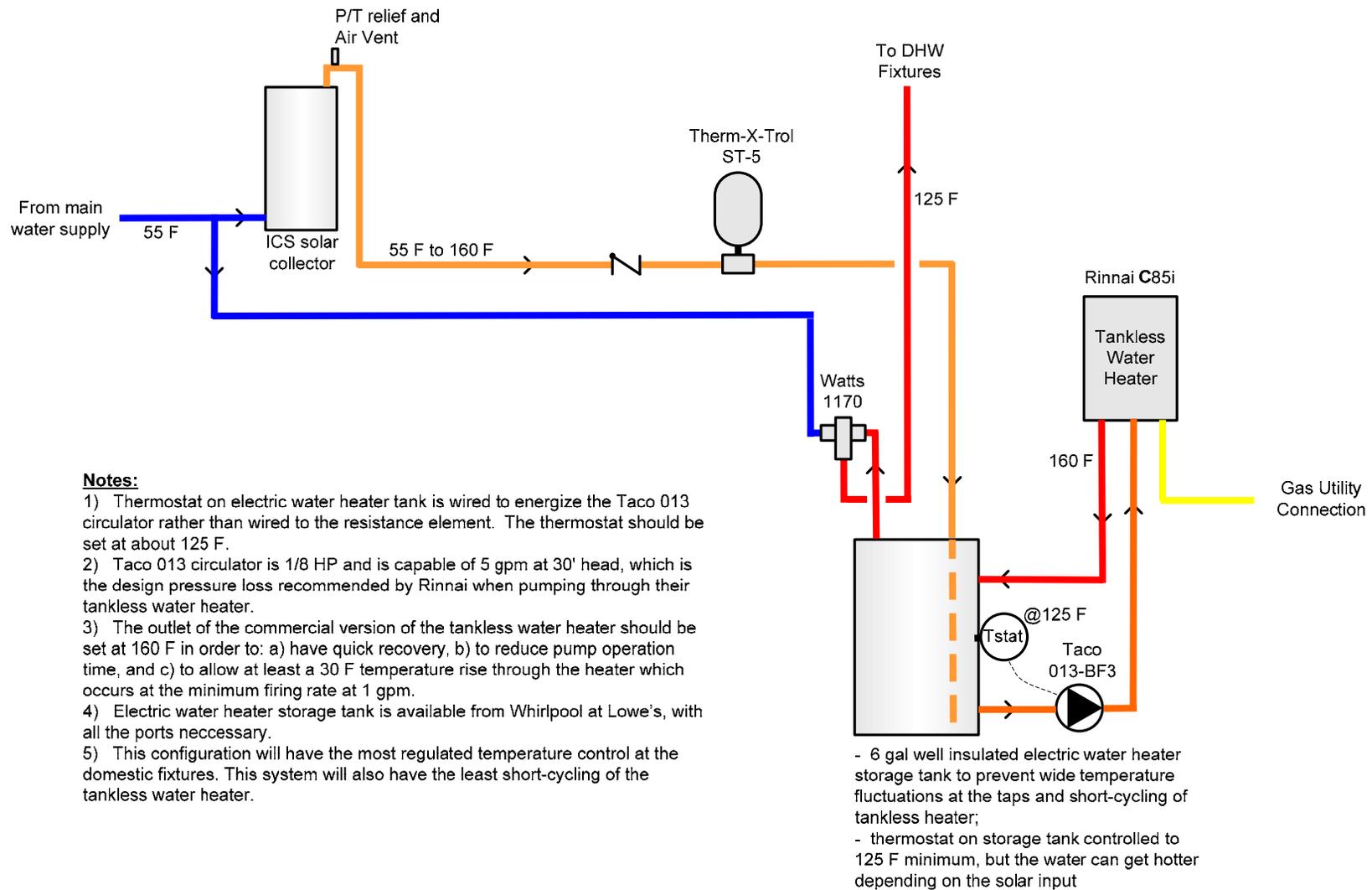


Figure ??? Tankless hot water heater application with solar preheat and active storage

## ***Appliances***

The dishwasher and refrigerator were Energy Star.

## ***Sustainable Materials***

The homes were finished with bamboo and ceramic tile floors, and recycled carpets.

## **Energy Performance Evaluations**

## **Successful field implementation, quality control, and third-party verification**

## **Marketing strategies**

## **Conclusion**

## **Acknowledgements**

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