U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Variable Capacity Comfort Systems and Smart Ventilation Systems in High-Performance Homes

Panelists

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Moderator

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October 3, 2017

Building AMERICA®
U.S. Department of Energy

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Agenda

- ✓ **Welcome and Introductory Remarks**
- ✓ **Overview of Building America (buildingamerica.gov)**
  - Linh Truong – National Renewable Energy Laboratory
- ✓ **Speakers**
  - Eric Martin, Chuck Withers, Danny Parker, and Karen Fenaughty– Florida Solar Energy Center
- ✓ **Questions and Answers**
- ✓ **Closing Remarks**

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- Research Institute, University of Central Florida
- Established in 1976 to certify solar water heaters
- ~65 researchers + ~30 support staff
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- Involved with Building America since mid 90's
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Today's Webinar Topics

RH Control of Variable Capacity Heat Pumps

- Systems vary compressor speed, refrigerant flow rate, and air flow enabling output ranging from 10-120% of nominal rated capacity.
- Ability to match capacity to load.
- Extended runtime (typical day: 65-70% vs. 30-35%) and ability to vary Sensible Heat Ratio creates POTENTIAL for better RH control.

Today's Webinar Topics

Smart Mechanical Ventilation Systems

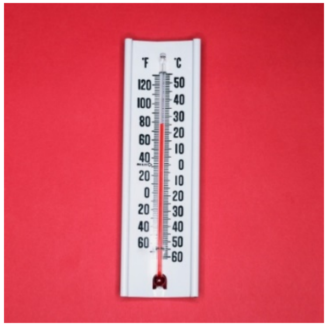
- Systems optimize energy consumption and comfort while maintaining IAQ by varying fan operation.
- Systems ventilate more during periods that provide energy, comfort, and/or IAQ advantages and less during periods that provide a disadvantage.
- System operation controlled in response to differing control variables, such as outdoor temperature, outdoor moisture, occupancy, etc.

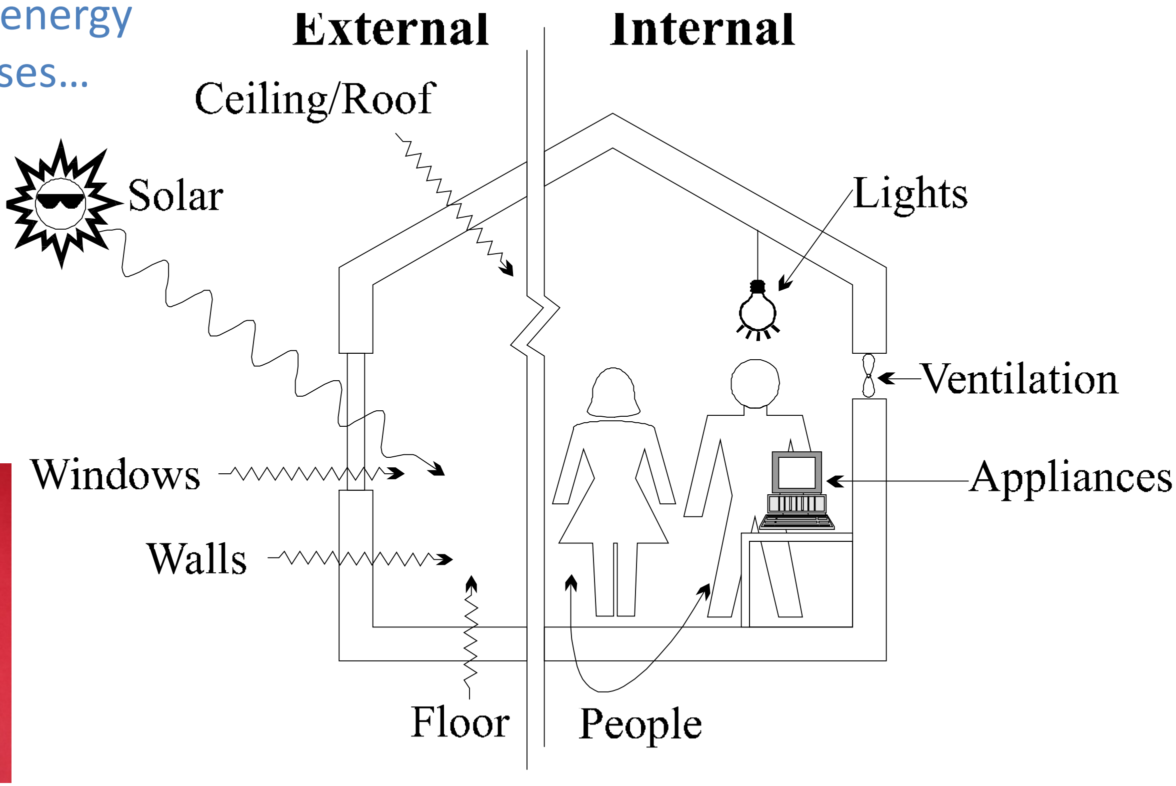
Low Load Home Problem Statement

Energy efficient home construction and remodeling leads to reduced sensible load, but latent loads remain unchanged. As a result, conventional space cooling equipment runs less, and may no longer manage moisture and comfort adequately, primarily during shoulder season transitions and late evening/early morning hours.

As whole house energy Efficiency increases…

Sensible Loads Are Reduced





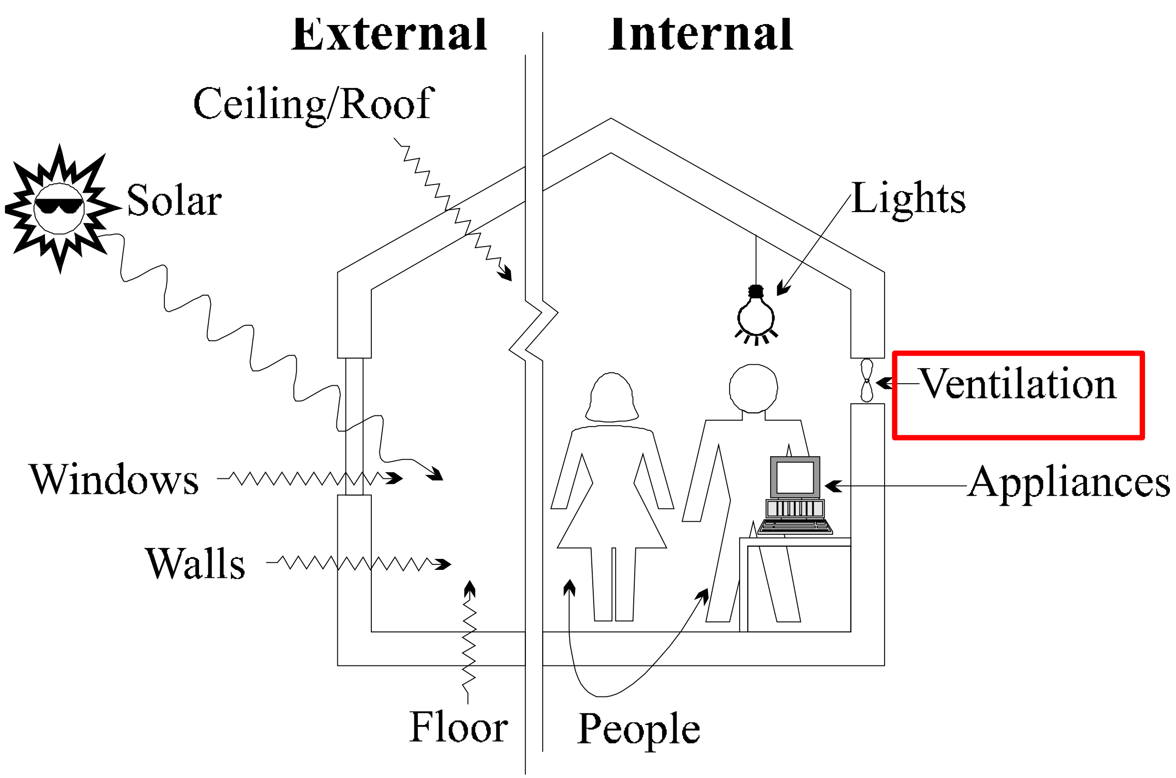
Latent Loads Hold Steady

Right Sizing and Low Load

- Isn't right-sizing suppose to take care of RH control?
- Correctly sized fixed capacity cooling systems generally provide good RH control in typical residences.
- In "low-load homes", fixed capacity systems may be less effective because:
  - Smaller peak loads – right sized conventional equipment not available (<1.5 tons).
  - Very low off-peak loads – fixed capacity way oversized.
  - Less run time = less mixing and less opportunity for moisture removal.

Contributing Factor: Mechanical Ventilation

Mechanical ventilation is a critical component of a comprehensive strategy for good IAQ. However, continuous delivery of outdoor air has potential to impact energy use and comfort, and presents a barrier to installation and operation of compliant systems.



Target Comfort Metric: Hours > 60% RH

"It was generally agreed that annual hours above 60% RH is the single most appropriate humidity control performance metric to use to compare system performance and required supplemental dehumidification energy. That metric does give generally the same result as looking at 4-hour and 8-hour events above 60% RH."

- 60% RH limit provides the best practice for providing comfort and durability
  - Internal moisture generation rate
  - Construction moisture drying
  - Occupant comfort perception and susceptibility to illness

Rudd, A. (2013). Building America *Expert Meeting: Recommended Approaches to Humidity Control in High Performance Homes.* Somerville, MA: Building Science Corporation. http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/expt_mtg_humidity_control.pdf.

Fundamental Concepts

- Typically air conditioning system controls respond to sensible heat load
  - Thermostat set-point generates calls for cooling
  - Resulting latent (moisture) removal depends on:
    - Machine capacity
    - Runtime
    - Coil temperature
    - Air flow rate
- Typically, an air conditioner devotes 25% of its capacity to removing moisture, 75% for sensible heat
  - Sensible heat ratio (SHR) = 0.75
  - What if the load is 60% sensible and 40% latent?

Supplemental RH Control Solutions

System	Cost	Pros	Cons
Overcooling	$0	Low first cost. User control.	Results in cold clammy comfort. No help in swing season. Energy inefficient.
Lowering fan speed	$0-$75	Improves dehumidification.	Some loss in cooling efficiency. No help in swing season.
Heat pipes	$3000	Long life, low maintenance .	Requires space. No help in swing season.
Enthalpy recovery ventilation	$700-$1400	Can reduce load from ventilation. Balanced house pressure possible.	Extra energy to run the two fans needed. No help in swing season.
Two-speed air conditioner	$1800*	Low speed can result in lower energy use.	Higher first cost. Still some hours swing season it will not operate.
Dedicated outdoor air system	$3200-$7000	Excellent ventilation RH control and effectiveness potential.	High first cost.
Stand-alone dehumidifier	$150-$2000	Works with or without AC.	Energy -inefficient. Adds heat. Some RH dead bands can be excessive. Noise may be issue.
Integrated ducted dehumidifier	$1000-2000	Works with or without AC. Good RH control. Air is distributed better than stand-alone.	Energy inefficient. Adds heat, some RH dead bands have been found excessive
Sub-cooling / Full-condensing reheat	$1600-$1750	Good RH control. More efficient than dehumidifiers.	Overcools and then heats, using energy for both. High first cost.

Vieira, R. and D. Beal. (2017). *Residential Performance Code Methodology for Crediting Dehumidification and Smart Ventilation.* https://securedb.fsec.ucf.edu/pub/pub_show_detail?v_pub_id=4795

Common Solution: Supplemental Dehumidification

- Supplemental dehumidification is required in high performance homes in humid climates, irrespective of mechanical ventilation rates.
- Homes using supplemental dehumidification strategies are able to reduce, but not eliminate hours of indoor relative humidity above 60% (on average from around 30% of annual hours to 15% of hours >60%; dehumidifier capacity and set points interact such that all high humidity hours are not eliminated).
- One study estimated that supplemental dehumidifiers in high performance homes operate 10% of the year and require 170 kWh per year with a 60% RH set point, 5 times that with a 50% set point.

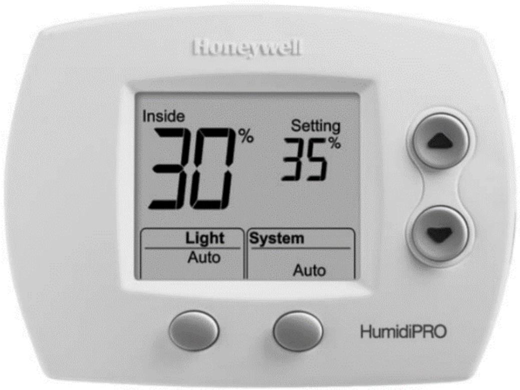
Less, B. and I. Walker, Nov. 2016, Smart Ventilation Control of Indoor Humidity in High Performance Homes in Humid U.S. Climates, Ernest Orlando Lawrence Berkeley National Laboratory. LBNL-1006980, https://eta.lbl.gov/sites/all/files/publications/1006980.pdf

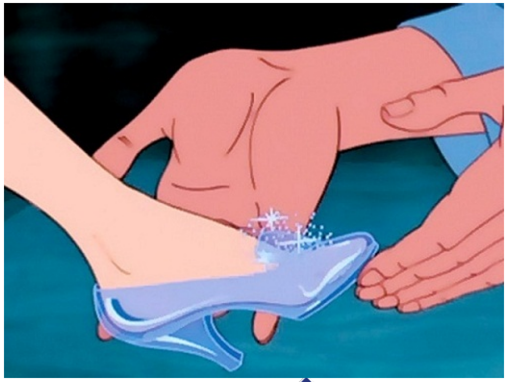
- Another study estimated supplemental dehumidifier energy of 9-12 kWh/d (3833 kWh per year) with humidistat in direct influence of humid outdoor air.

Rudd, A., Lstiburek, J., Eng, P., and Ueno, K. 2005. Residential Dehumidification Systems Research for Hot-Humid Climates (Subcontract Report). Golden, CO: National Renewable Energy Laboratory, NREL/SR-550-36643. www.nrel.gov/docs/fy05osti/36643.pdf.

Seeking an Integrated Solution

- Theoretically AC systems can be optimized for latent heat removal (lower SHR)
  - Longer runtimes
  - Lower airflow
  - Colder coil
  - Lower total capacity
  - Avoid overcooling
- As variable capacity AC systems respond to varying sensible load, what is resulting latent performance?





Past Variable Capacity Research at FSEC

- 2013: Test of a solar powered, supplemental mini-split heat pump in lab home showed good RH control under high load in high mass building.
- 2010 – 2015: Variable capacity heat pump testing in lab home
  - With centrally ducted SEER 22 unit we observed:
    - Substantially long runtimes
    - Patterns of periodically lowering cfm/ton, corresponding with lower supply air temperatures, but…
    - Resulting average indoor RH similar to fixed capacity system
    - Supplemental dehumidification required during overnight/early morning hours
  - With ductless SEER 22 mini-split heat pump we observed:
    - Ability to vary sensible heat ratio, but…
    - Unit would never operate close to lowest stated capacity
    - Cycling behavior during low load

2015-2017 Field Research

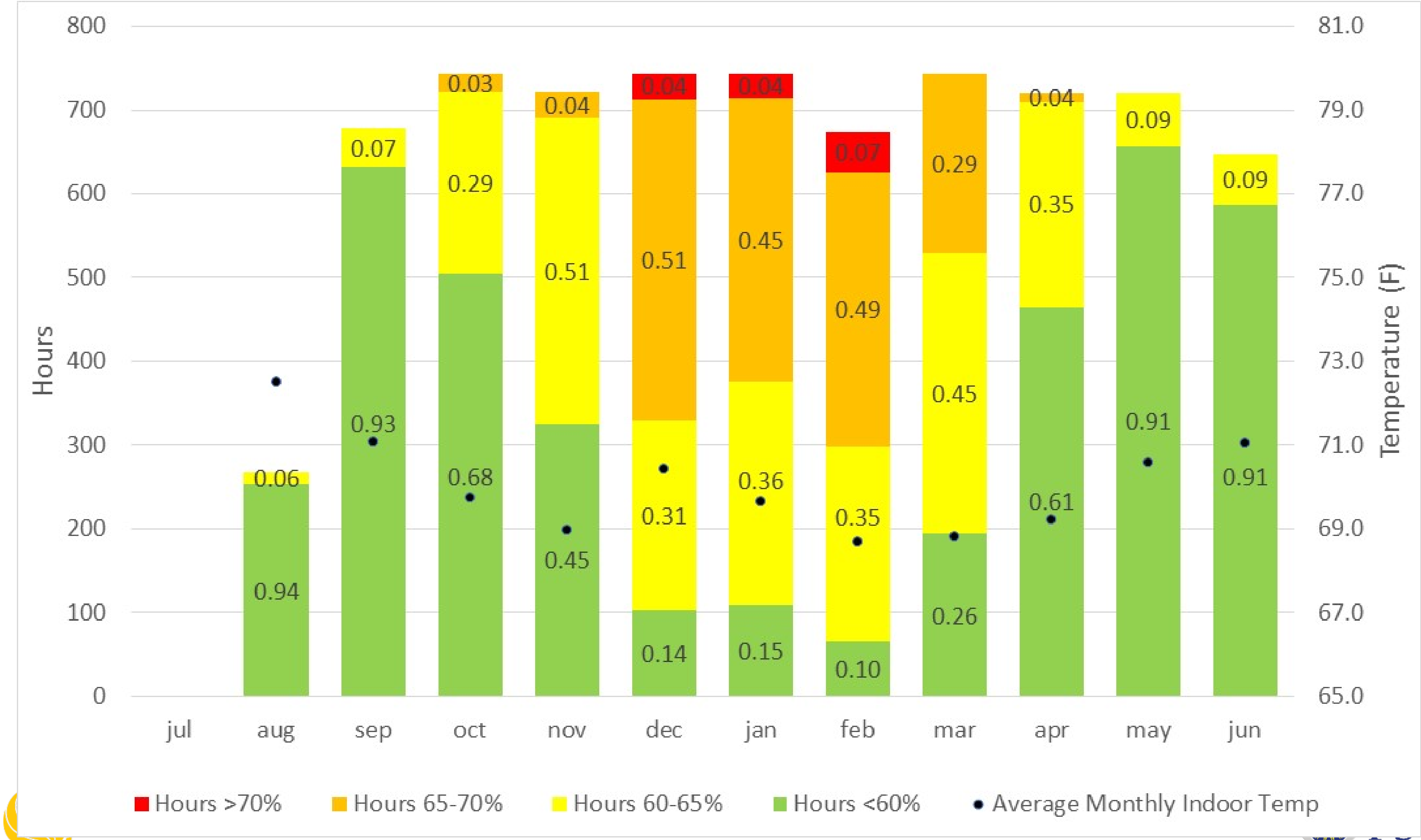
SE Volusia Habitat for Humanity (Florida – HERS 48)

- Duplex (1,075 ft^2 per unit)
- Cooling Peak = 11,323 Btu/h
- Ductless Multi-split (19 kBtu/h) with 2 fan coil units in main body (9 kBtu/h each) SEER 22
  - 2 transfer fans circulate air to BRs
  - ERV for mechanical ventilation (82% of 62.2-2010 33 cfm)

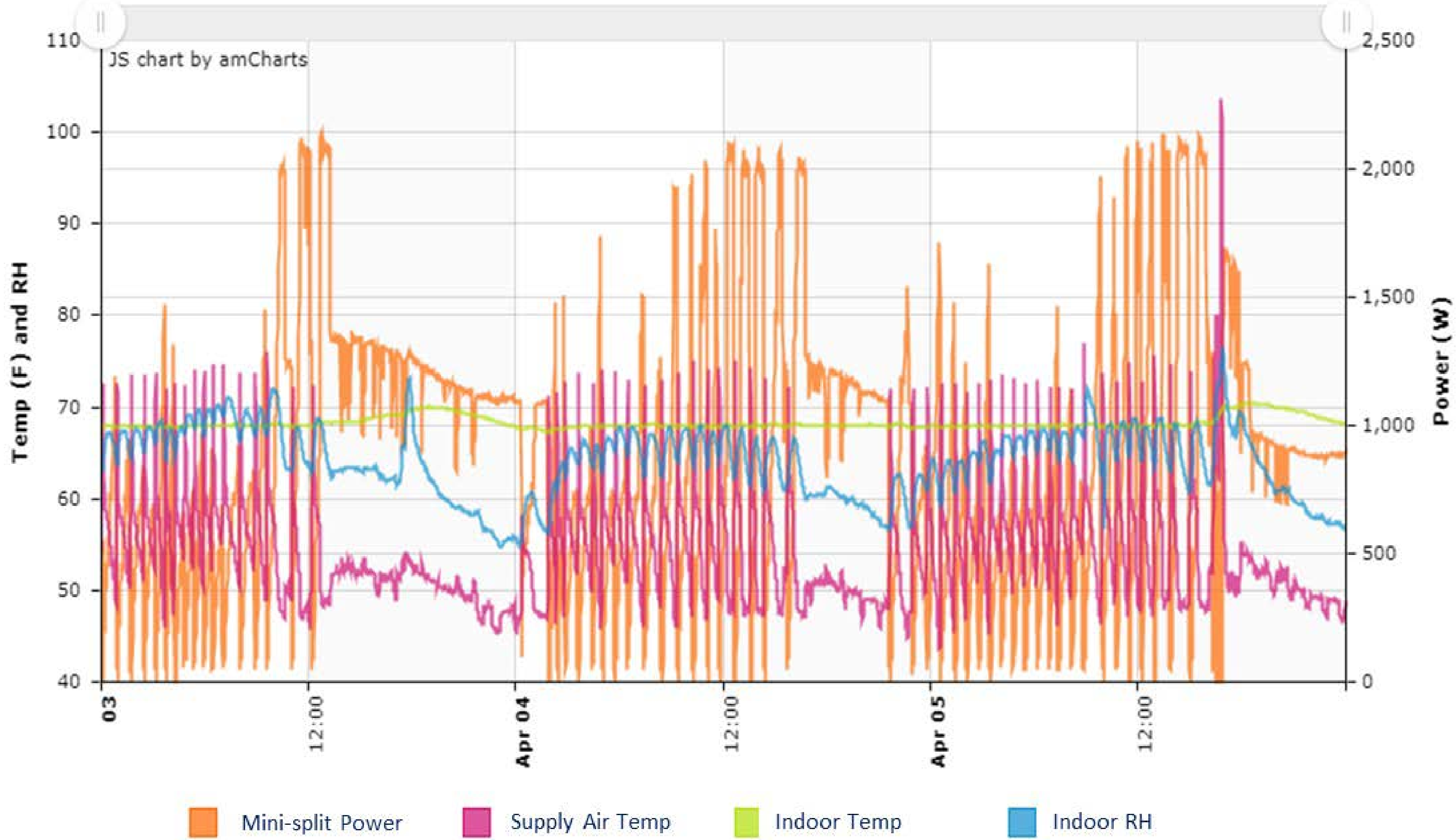
South Sarasota Habitat for Humanity (Florida – HERS 51)

- 3 single family detached houses (1,290 ft^2)
- Cooling Peak = 12,242 Btu/h
- Ducted Mini-split with cassette AHU (15k Btu/h) SEER 15.5
  - Unvented attic
  - Hybrid supply/exhaust system for mechanical ventilation (80-130% of 62.2-2010 43 cfm)

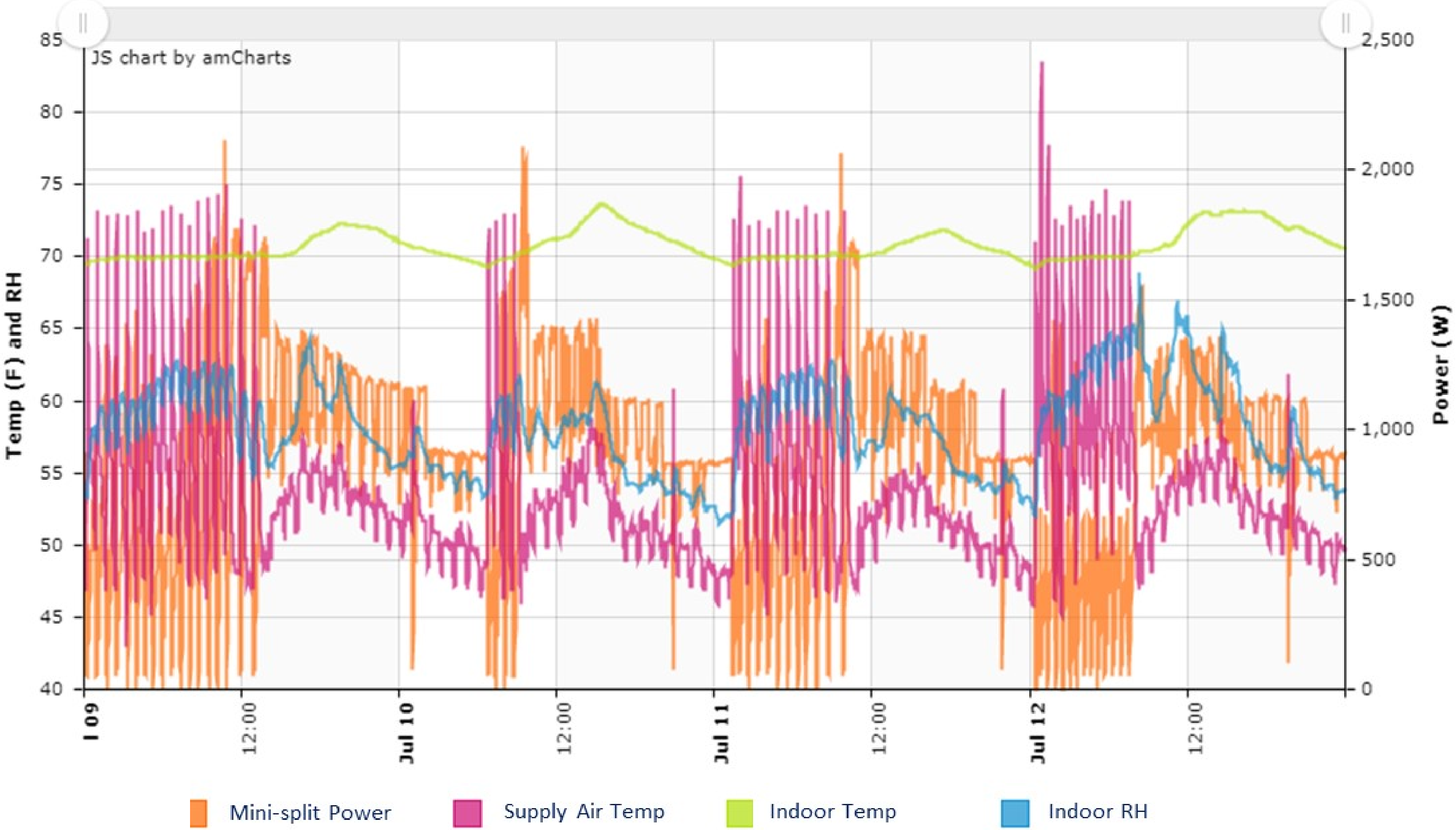
High RH Under Low Load



Low Load Cycling and Inconsistent Indoor RH Control



Sensible Load Prioritization and Inconsistent Indoor RH Control



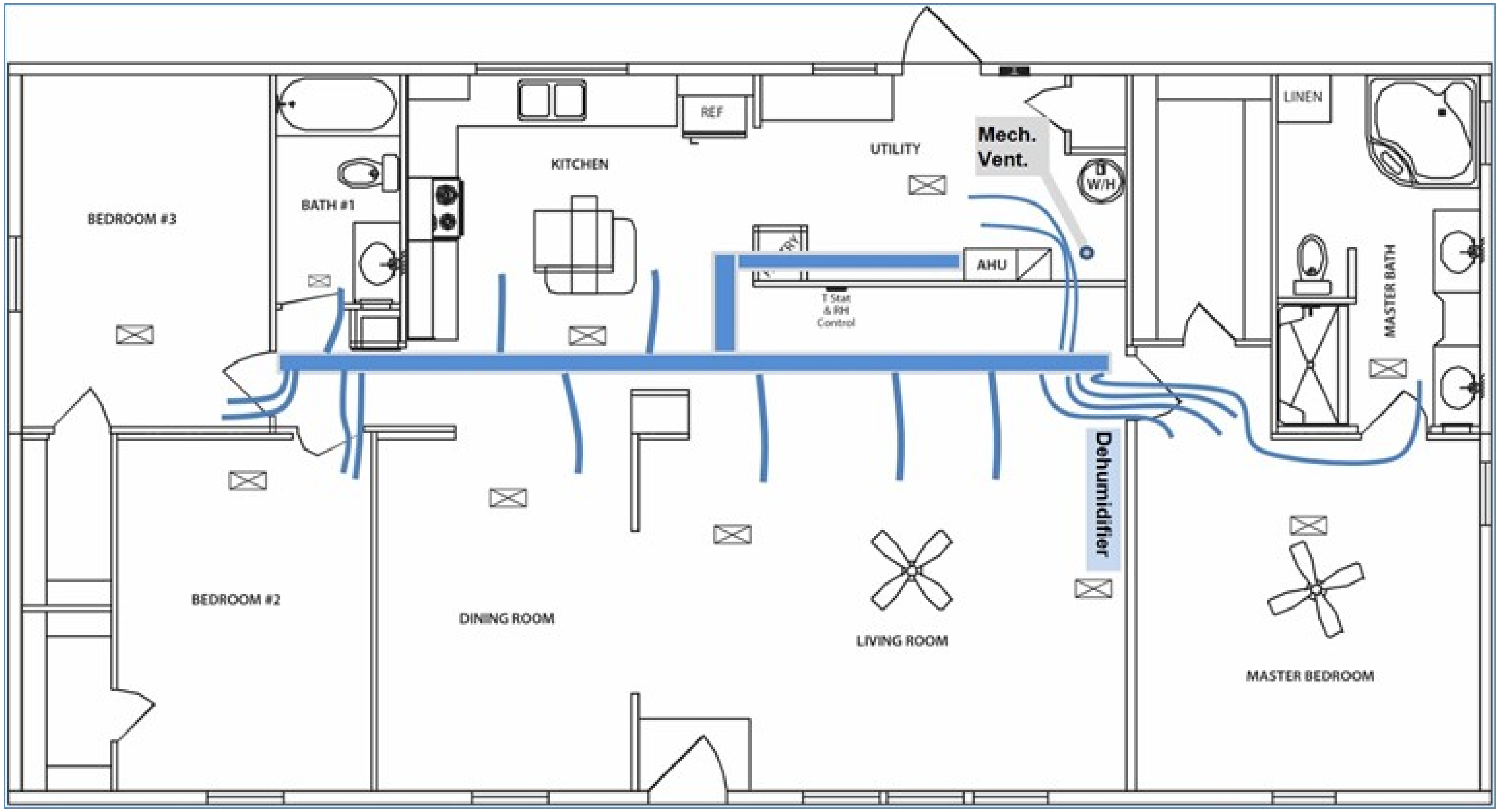
2015 – 2017 Lab Research

- Variable Capacity, centrally ducted, small duct high velocity heat pump
- Unico iSeries heat pump (SEER 14) 29.2 kBtu/h cooling capacity

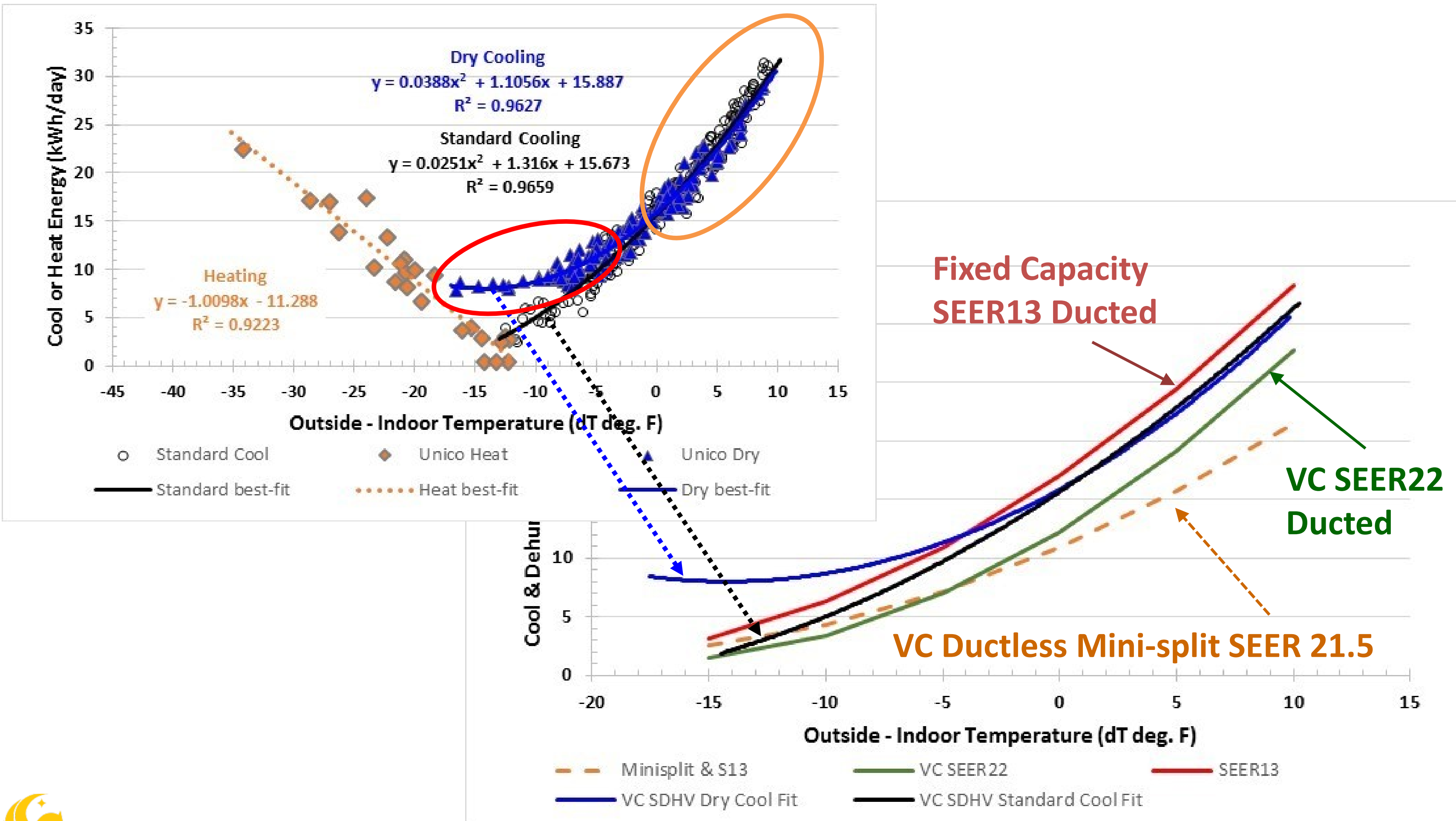
FSEC Manufactured Housing Lab

- 1,600 ft^2, 4.5 ACH50
- Cooling Peak = 18,200 Btu/h
- Continuous mechanical ventilation supplied to utility room (100% of 62.2-2016 57 cfm)
- Stand alone supplemental dehumidifier in living room set to 60% RH

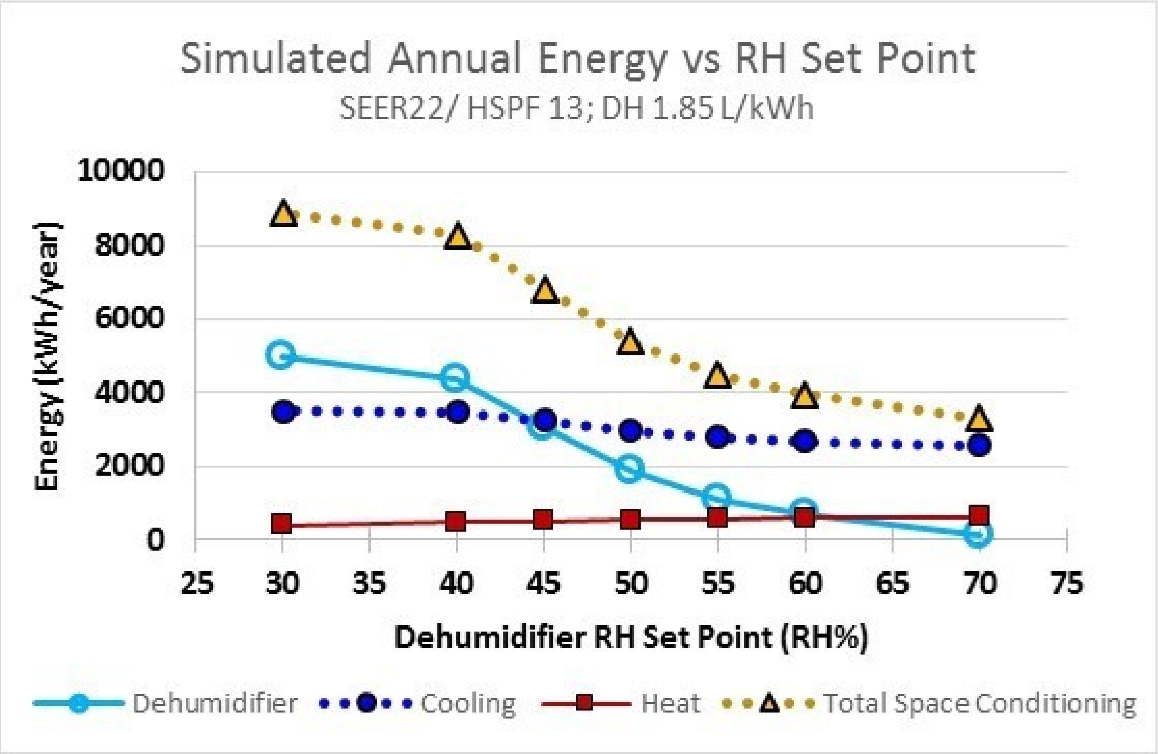
FSEC Manufactured Housing Lab



MH Lab Space Conditioning Energy



Annual Dehumidifier Energy Should Also be Considered in Equipment Selection



Simulated space conditioning energy in the MHL with SEER 22 heat pump and supplemental dehumidification.

AHU Power-Observed

Test Configuration	Fan effic. cfm/W (min-max)	Max. Observed Watts	Fan Standby Watts	Avg. CFM (min-max)	Whr/day Incl. standby	Duct dP in wc (Pa)	*Max. rated cfm (cfm/W)*
Unico SDHV VC SEER14	**5.51** (2.7-25.5)	184	**8**	**340** (300-550)	**1365**	0.41 (103)	*750 (1.7)*
2 ton VC SEER22	**9.7** (6.2-28.1)	160	**25**	**726** (590-990)	**1760**	0.08 (21)	*1088 (5.1)*

- SEER14 SDHV *fan efficiency* 43% lower than SEER22 VC
- SDHV AHU *daily energy* 22% LOWER than SEER22; because-
  - SDHV standby power 68% lower
  - SDHV operated at 45% of its max. flow
- SDHV meets load by SAT 9°F colder

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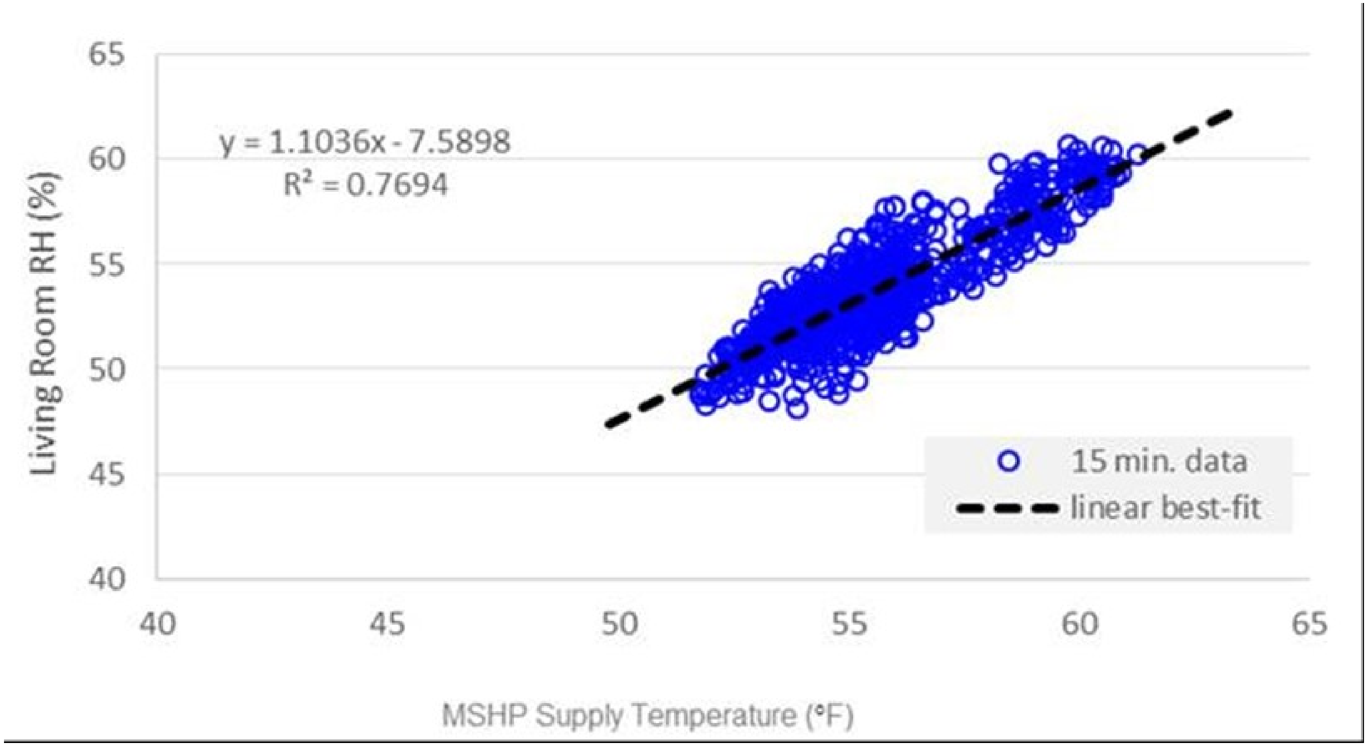
RH Control

Test Configuration	Avg. Out Temp. (°F)	Avg. SAT (°F)	In Temp. at Tstat (°F)	Daily Avg. RH
Unico SDHV VC SEER14	82.1	49.7	77.7	41.2%
2 ton VC SEER22	82.1	58.6	77.1	54.3%

- SDHV Indoor RH daily average 13.0% RH lower (summer day)
- RH increased about 4-5% RH more than shown in table during lower cooling loads overnight 4am-8am when out Tdp>70F

RH Control

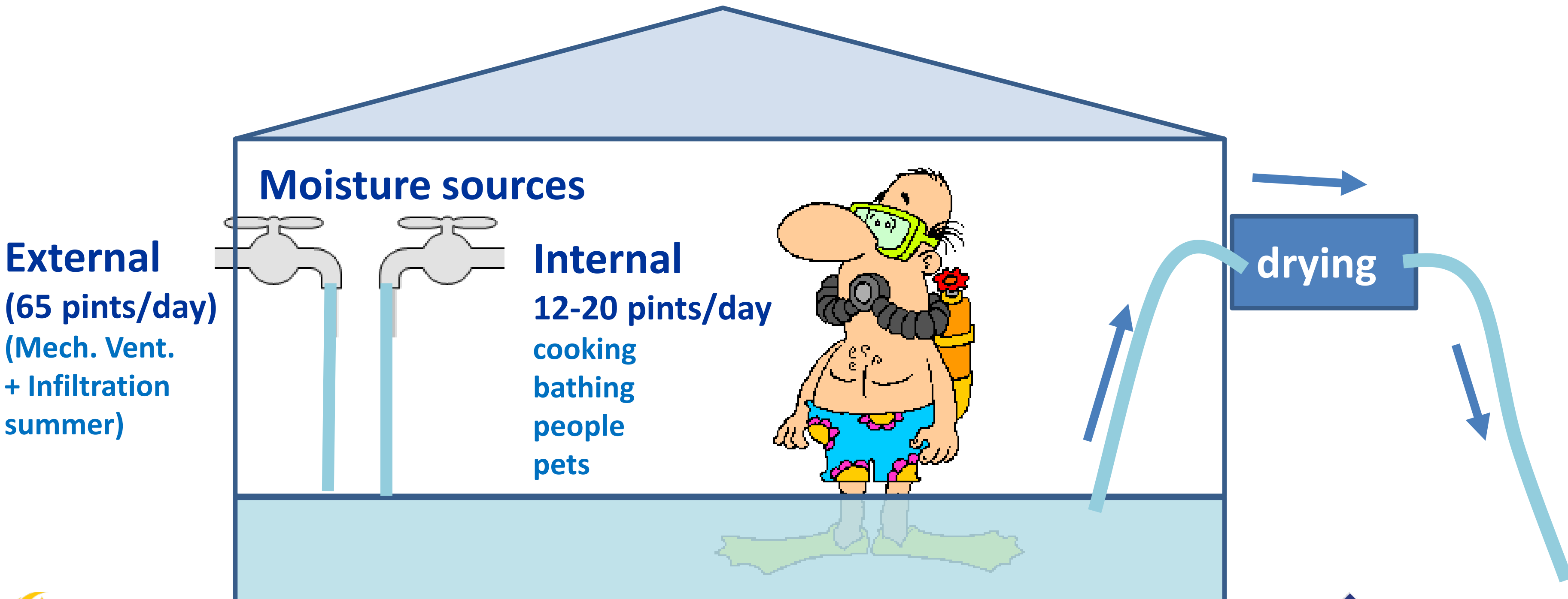
Previous MSHP lab testing showed how important SAT was for good RH control.



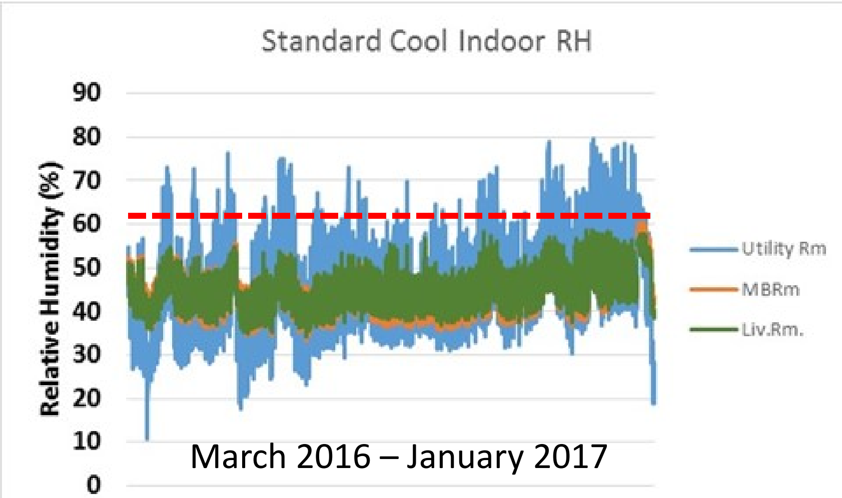
RH Control

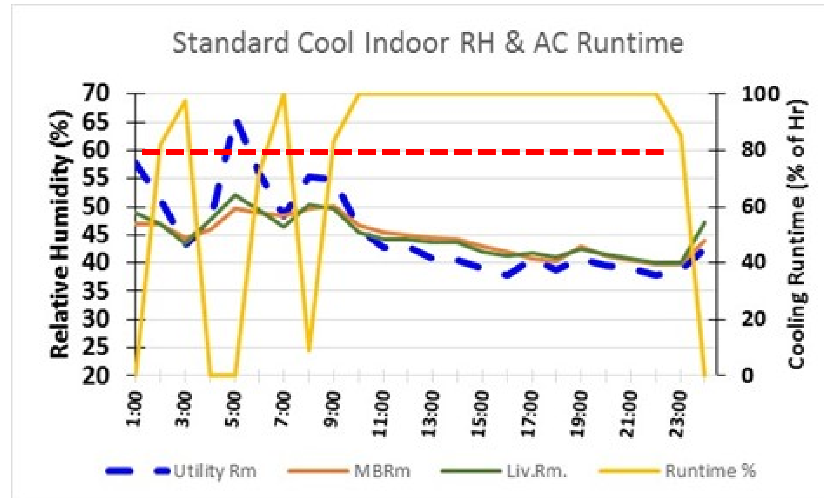
Depends upon rate of removal vs rate of production.

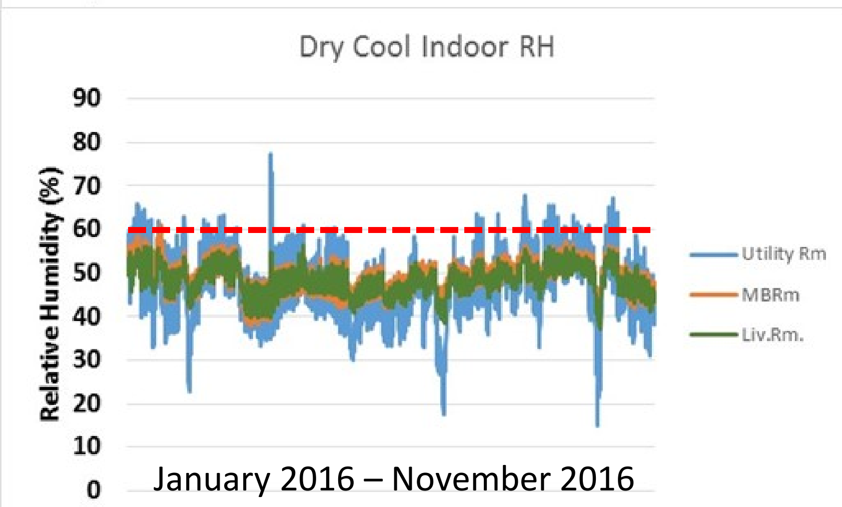
Approximately 10 gallons/day of water must to be removed.

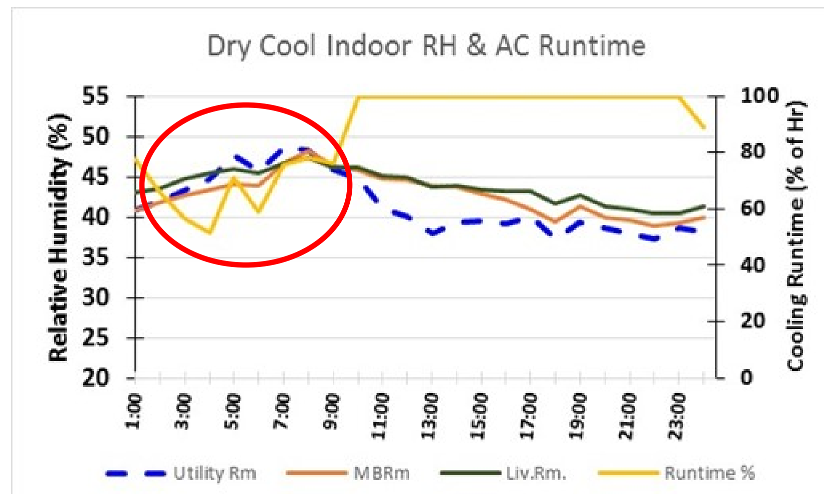


House Lab Indoor RH Control









Indoor RH Control Conclusions

- Indoor RH levels vary based on a number of factors:
  - Mechanical ventilation rates
  - Occupant activities
  - Operational characteristics of air conditioning

Indoor RH Control Conclusions

- Variable capacity systems have great potential to help control indoor RH:
  - Need to maintain colder coil during low load and decrease SHR as much as design allows.
  - Need to utilize lowest capacity consistently over longer periods during low load to avoid 1) cycling and 2) overcooling.
  - Coil airflow needs to be able to operate at the low end of the operational range to achieve these objectives.
  - Cooling should prioritize efficiency over RH in *Standard Mode.*
  - Prioritize RH control over efficiency in *Dry Mode.*
  - Use RH sensor to intelligently move between modes.

Today's Webinar Topics

2015-2017 Smart Mechanical Ventilation Research

- *Real Time Weather Based Smart Ventilation Control:* Vary mechanical ventilation airflow with an algorithm that interprets measurements of current and 24-hour historical outdoor temperature and moisture.

FSEC Flexible Residential Test Facility

Additional Smart Mechanical Ventilation Research

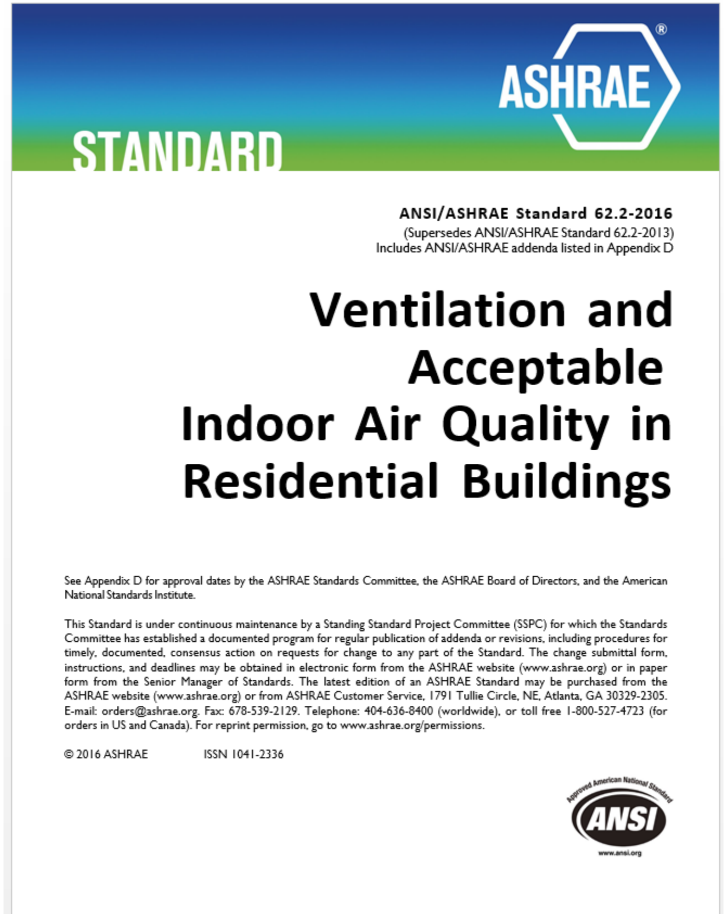
- *Seasonal Temperature Based Smart Ventilation Control*: Shift ventilation away from seasonal time periods that have large indoor-outdoor temperature differences.

- *Occupancy Based Smart Ventilation Control*: Vary operation of a mechanical ventilation fan in response to whether the home is occupied or vacant.

- *Commercialization Activities:* Engage manufacturers and other stakeholders to catalyze product development.

ASHRAE 62.2-2016 Appendix C

- Procedures for evaluation of time-varying ventilation
- Occupant exposure to pollutants relative to continuous ventilation
- Average (annual) relative exposure = 1 (chronic exposure)
- Peak exposure < 5 for any time step (acute exposure)
- No existing system varies flow rate while maintaining relative exposure


STANDARD

ASHRAE

ANSI/ASHRAE Standard 62.2-2016
(Supersedes ANSI/ASHRAE Standard 62.2-2013)
Includes ANSI/ASHRAE addenda listed in Appendix D

Ventilation and Acceptable Indoor Air Quality in Residential Buildings

See Appendix D for approval dates by the ASHRAE Standards Committee, the ASHRAE Board of Directors, and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE website (www.ashrae.org) or in paper form from the Senior Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

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ANSI

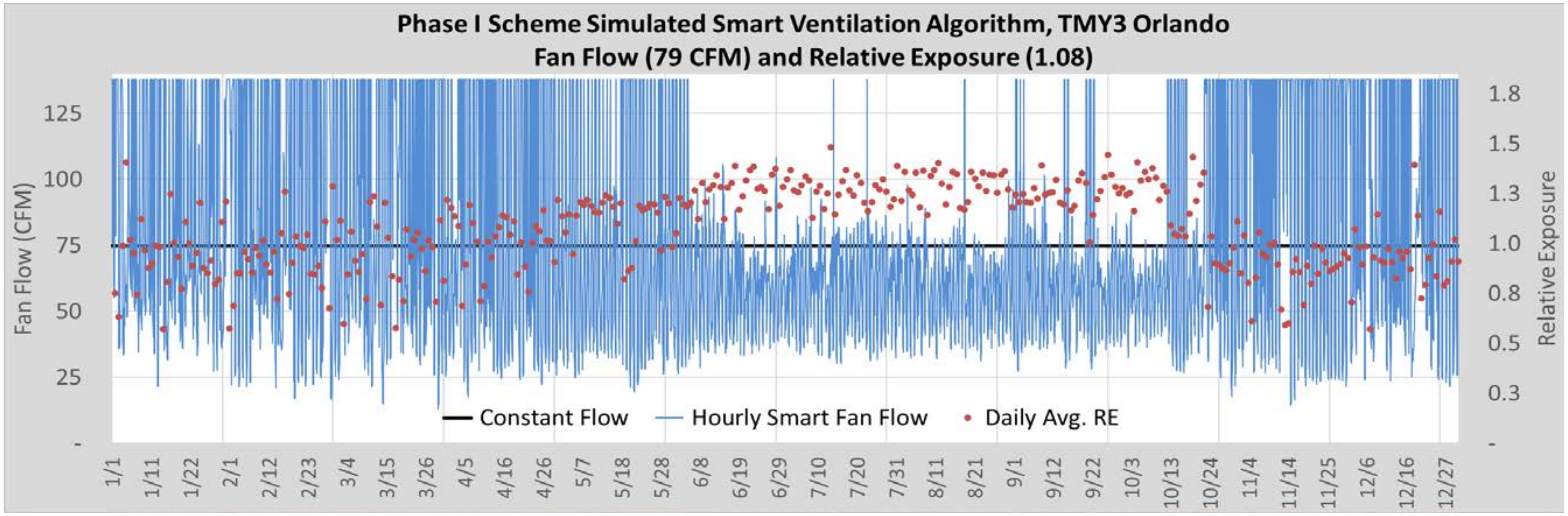
Real Time Weather SVC

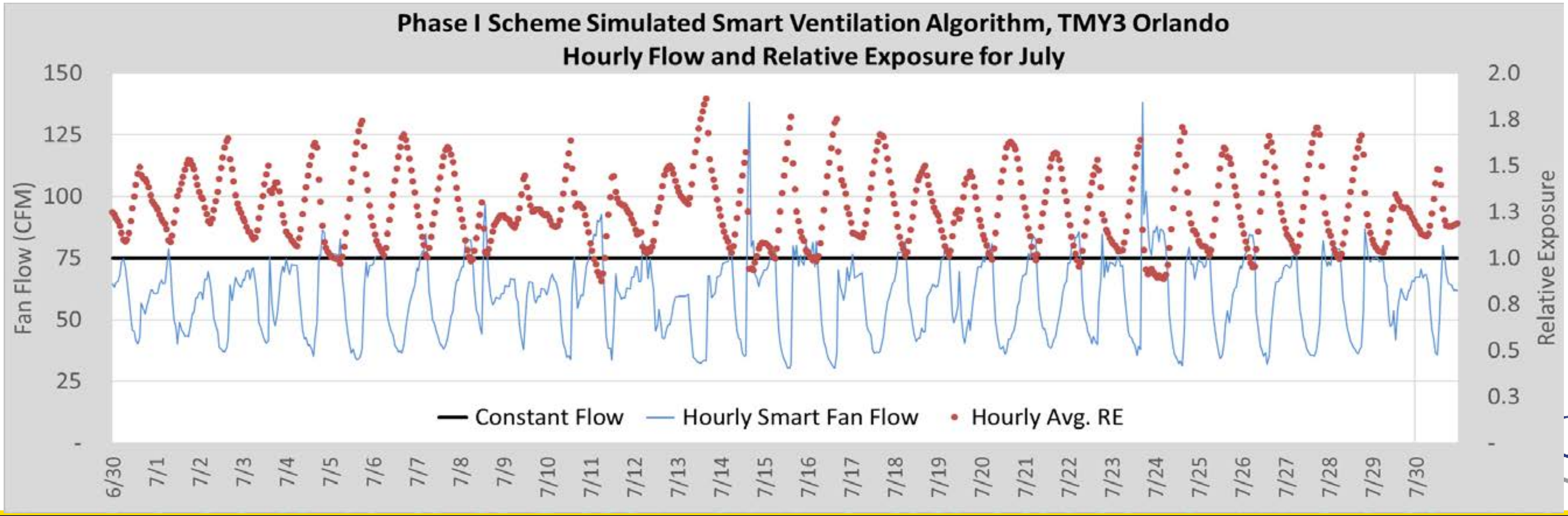
$$RSS = \sqrt{(\Delta T * X_T)^2 + (\Delta W * X_W)^2}$$

Hourly Fan Flow = (Target Fan Flow * (Average RSS_1:RSS_{23}/RSS_{24})

Period (defined by hourly outdoor T)	Parameter	Phase I Scheme Values
Cooling	Outdoor temp range for cooling period target Cooling period target fan flow	> 71.5°F 55 cfm
Heating	Outdoor temp range for heating period target Heating period target fan flow	< 60°F 75 cfm
Floating	Outdoor temp range for floating period target Floating period target fan flow	<= 71.5°F; >= 60°F 138 cfm (fan limit)
All	Indoor temperature Delta-temperature weight (X_T) Indoor moisture (W) Delta-moisture weight (W_W)	64.4°F 2 12g/m^3 1

Phase I Simulated Results





Phase I Simulated Results

Phase I Avg. Hourly Values	Sensible (kBtu/h)			Latent (lbs/h)			Fan Power (Average Watts)			Average	
	Fixed	Smart	% Δ	Fixed	Smart	% Δ	Fixed	Smart	% Δ	Flow (cfm)	RE
Summer[a]	0.25	0.05	79	0.94	0.78	16	40	28	29	65	1.22
Non-Summer Cooling[b]	0.14	0.04	71	0.20	0.12	39	40	17	57	40	1.30
Non-Summer Floating[b]	(0.92)	(1.33)	-45	(0.03)	0.06	285	40	50	-25	116	0.76
Heating[c]	(2.04)	(1.50)	27	(0.90)	(0.67)	25	40	24	41	55	1.27
Annual										79	1.08

Annual Energy	Sensible (kWh)			Latent (kWh)			Fan (kWh)			Total Savings	
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	(kWh)	%
Summer[a]	140	30	110	397	331	65	175	124	51	226	32
Non-Summer Cooling[b]	20	6	15	21	13	8	44	76	(31)	(8)	-10
Non-Summer Floating[b]							117	219	(102)	(102)	-87
Heating[c]	232	170	62				12	104	(91)	(29)	-12
Annual	392	206	186	418	344	74	349	522	(173)	87	7

Laboratory Evaluation

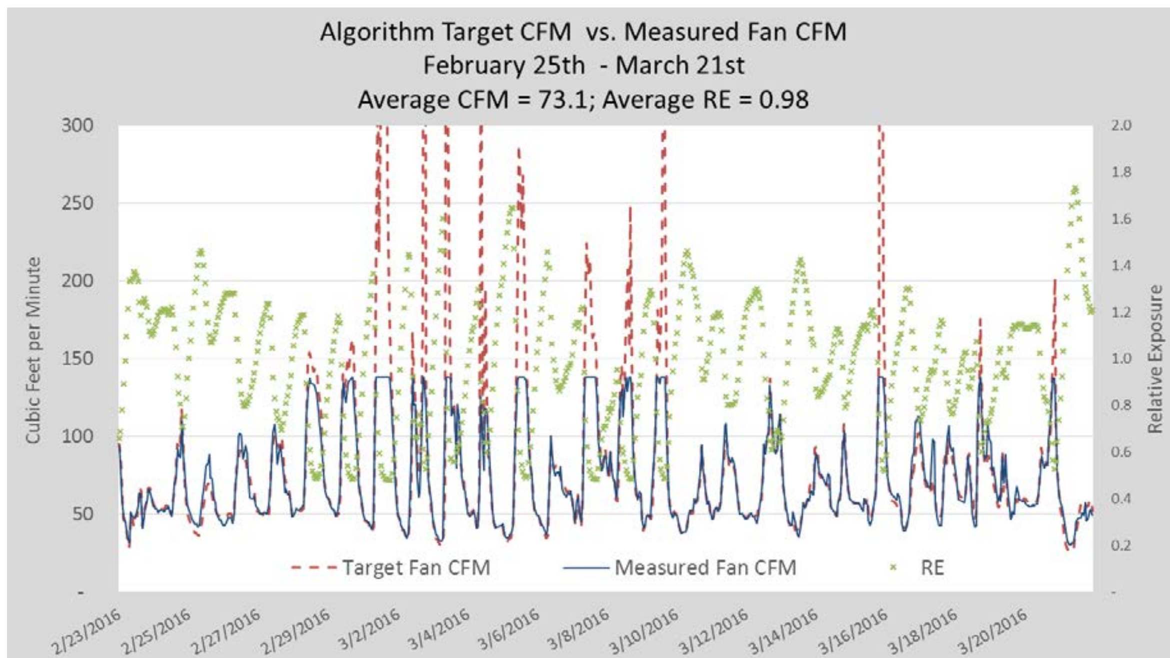
FSEC FRTF Labs

- 1,536 ft^2, 2.2 ACH50
- Supply ventilation
- ASHRAE 62.2-2016

$Q_{total} = Q_{fan} + \phi Q_{inf} = 76.1$ cfm

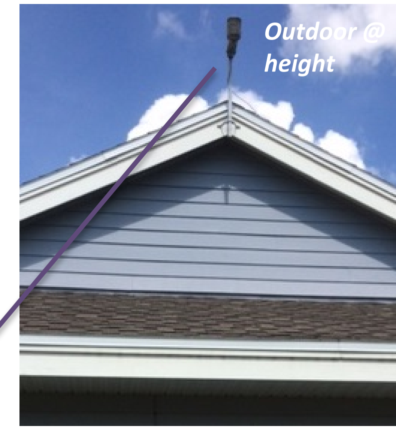
$\phi = 1$, $Q_{fan} = 66$ cfm

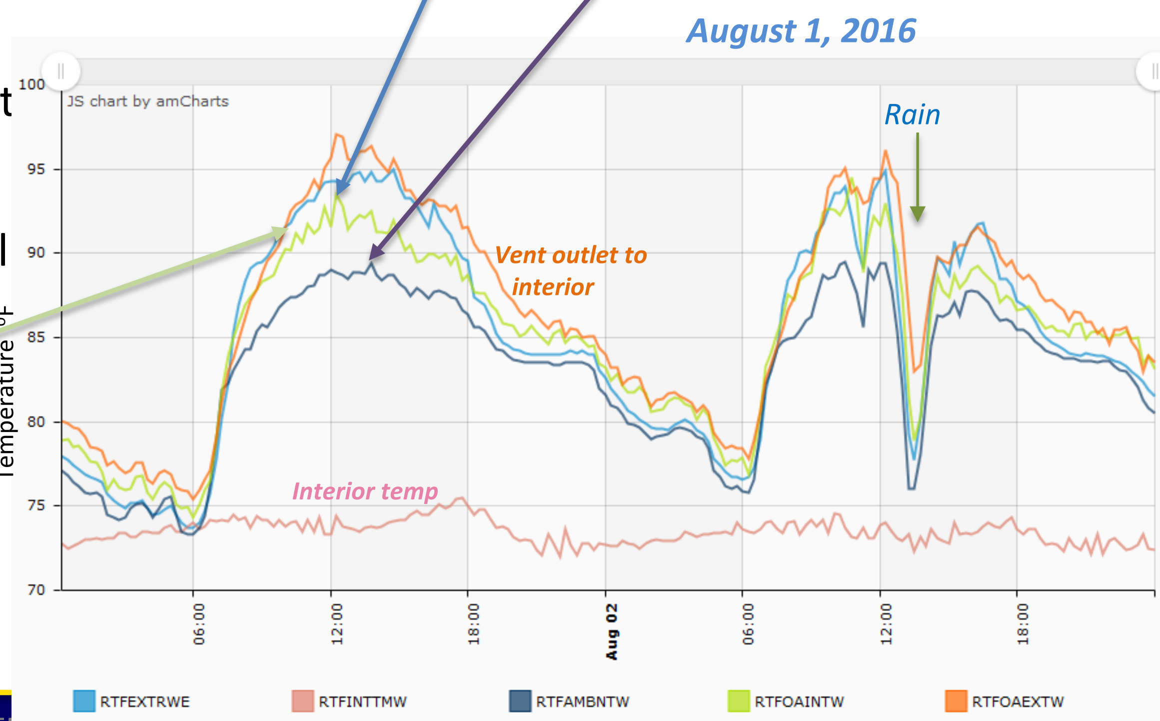
$\phi \neq 1$, $Q_{fan} = 75$ cfm



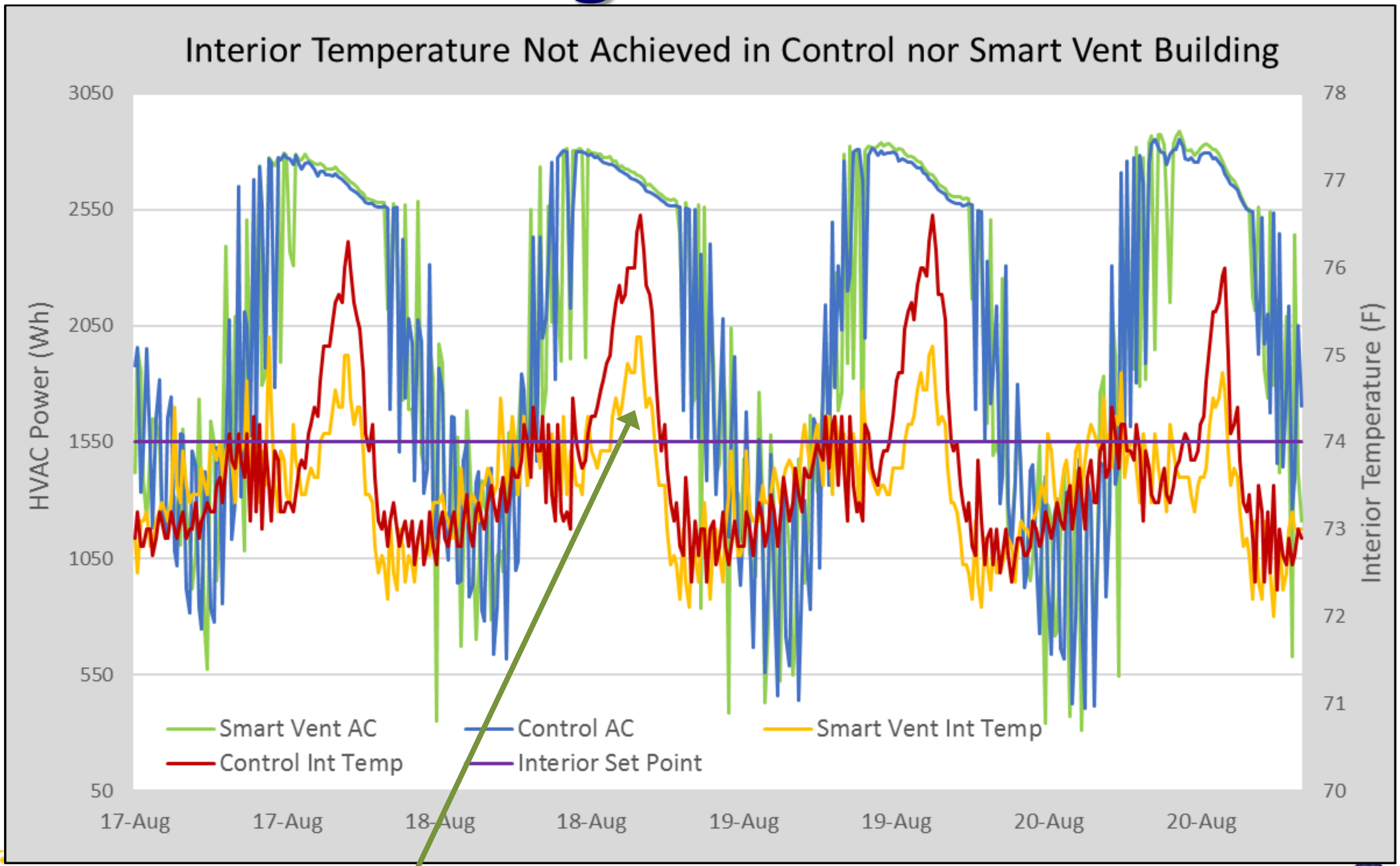
Lesson Learned: Temperature Variation

- Potential to use broadband weather to drive Smart Vent, but…
- Air temperature in summer at 15 ft height 3-4 °F lower than air temperature at soffit inlet
- Increase not coming from attic; wall related heat & ground
- Air temperature higher near ground & varies w/ time of day
- Ideal summer ventilation outdoor target temp not 75, but ~65 °F
- Hi-outlet to interior temps emphasize SV comfort potential





Lesson Learned:
AC Sizing and Peak Load



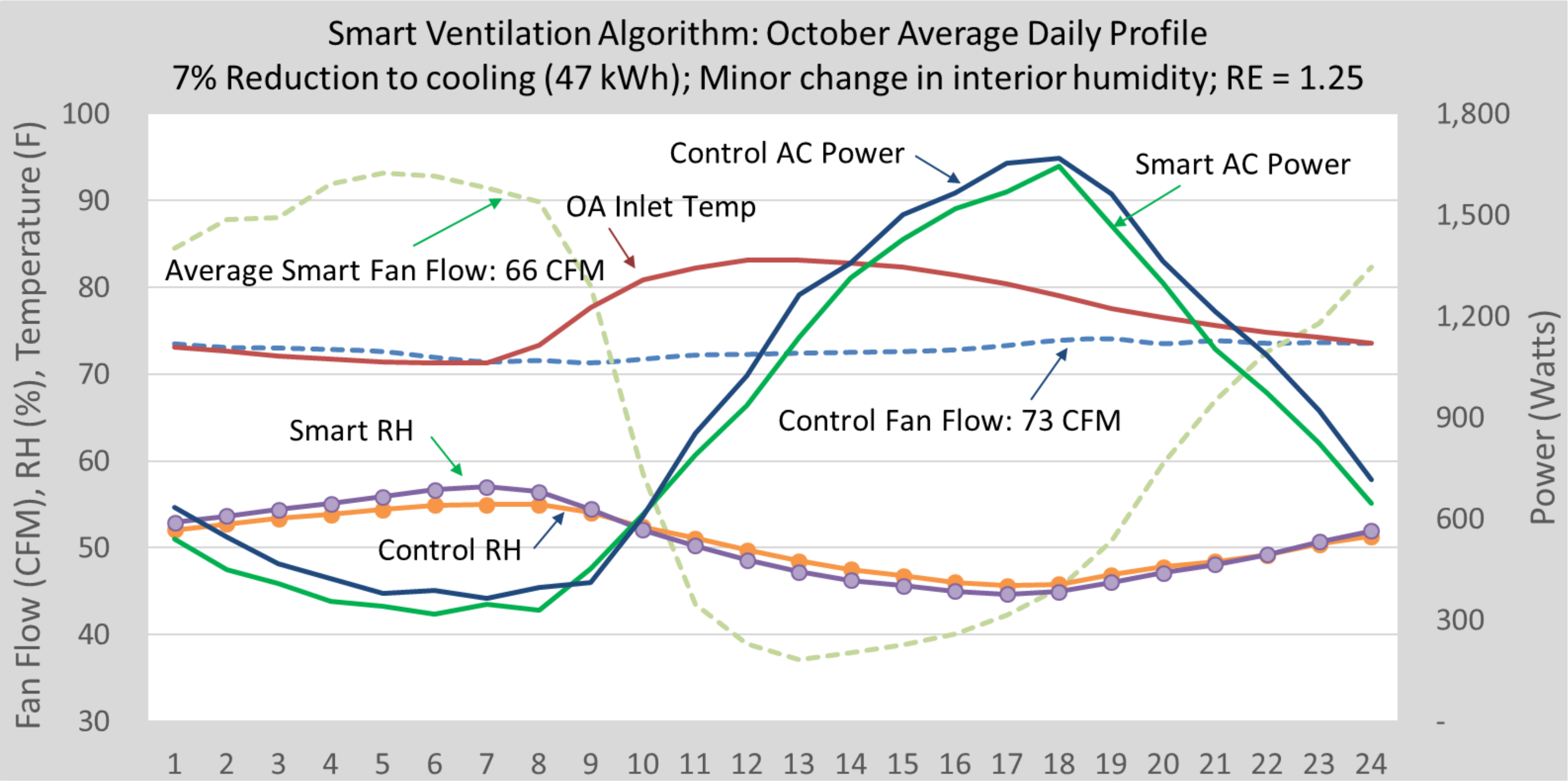
Smart Vent Control will produce superior comfort on extremes

Phase I Experimental Results

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total (kWh)			
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
Aug	1,312	1,295	16	29	18	11	1,340	1,313	27	2%
Sep	1,011	1,013	(2)	29	18	10	1,039	1,031	8	1%
Oct	671	624	47	29	21	8	700	645	55	8%
Nov	295	246	49	29	25	3	324	271	53	16%
Dec	286	234	52	29	27	2	314	261	53	17%
Jan	300	248	53	29	25	3	329	273	56	17%
Avg	**646**	**610**	**36**	**29**	**22**	**6**	**674**	**632**	**42**	**6.2%**

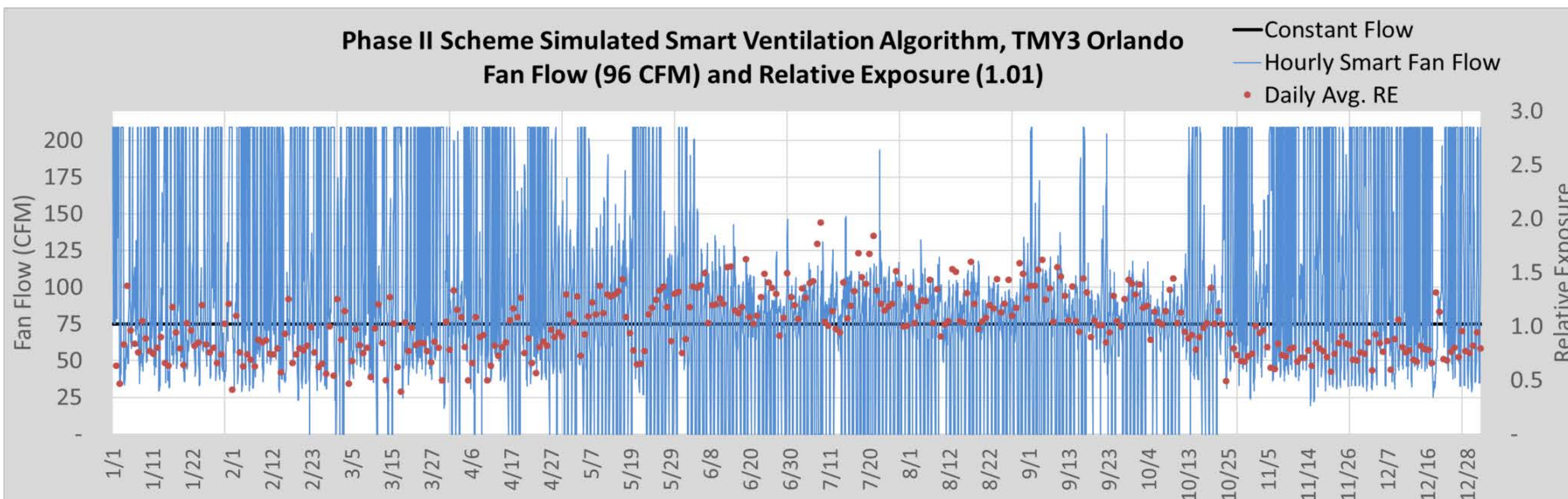
Month	Smart Flow (cfm)	Smart RE	Outdoor OA Inlet T	Control Indoor T	Smart Vent Indoor T	Outdoor OA Inlet DP	Control Indoor RH	Smart Vent Indoor RH
Aug	57	1.33	84.4	73.6	73.6	75.5	52.1	51.2
Sep	59	1.31	81.5	73.6	73.9	73.5	53.1	53.9
Oct	66	1.25	76.8	74.2	74.1	65.8	50.5	50.6
Nov	82	1.08	70.3	74.0	74.1	60.0	50.9	53.3
Dec	87	1.03	69.6	73.9	73.9	61.0	54.0	56.2
Jan	82	1.06	65.3	74.3	73.9	54.0	48.3	52.8

Phase I Experimental Results



Phase II

Period	Parameter	Phase I Scheme Values	Phase II Scheme Values
Cooling	Outdoor temp for cooling period target	> 71.5°F	> 71.5°F
	Cooling period target fan flow	55 cfm	75 cfm
	Outdoor temperature for fan override	n/a	>= 88°F
Heating	Outdoor temp for heating period target	< 60°F	< 50°F
	Heating period target fan flow	75 cfm	75 cfm
Floating	Outdoor temp for floating period target	<= 71.5°F; >= 60°F	<= 71.5°F; >=50°F
	Floating period target fan flow	138 cfm (fan limit)	209 cfm (fan limit)
	Outdoor W to adjust floating period target	n/a	>= 15g/m3
	Floating period target adjusted for W	n/a	75 cfm
All	Indoor temperature (T)	64.4°F	64.4°F
	Delta-temperature weight (X_T)	2	2
	Indoor moisture (W)	12g/m3	12g/m3
	Delta-moisture weight (X_W)	1	1



Phase I vs. Phase II Simulated Results

Phase I Avg. Hourly Values	Sensible (kBtu/h)			Latent (lbs/h)			Fan Power (Average Watts)			Average	
	Fixed	Smart	% Δ	Fixed	Smart	% Δ	Fixed	Smart	% Δ	Flow (cfm)	RE
Summer[a]	0.25	0.05	79	0.94	0.78	16	40	28	29	65	1.22
Non-Summer Cooling[b]	0.14	0.04	71	0.20	0.12	39	40	17	57	40	1.30
Non-Summer Floating[b]	(0.92)	(1.33)	-45	(0.03)	0.06	285	40	50	-25	116	0.76
Heating[c]	(2.04)	(1.50)	27	(0.90)	(0.67)	25	40	24	41	55	1.27
Annual										79	1.08

Phase II Avg. Hourly Values	Sensible (kBtu/h)			Latent (lbs/h)			Fan Power (Average Watts)			Average	
	Fixed	Smart	% Δ	Fixed	Smart	% Δ	Fixed	Smart	% Δ	Flow (cfm)	RE
Summer[a]	0.25	(0.08)	133	0.94	0.90	4	40	41	-3	76	1.19
Non-Summer Cooling[b]	0.14	0.02	83	0.20	0.15	24	40	28	30	51	1.15
Non-Summer Floating[b]	(0.92)	(1.72)	-87	(0.03)	(0.01)	74	40	80	-102	147	0.66
Heating[c]	(2.04)	(1.50)	27	(0.90)	(0.67)	25	40	30	25	55	1.25
Annual										96	1.01

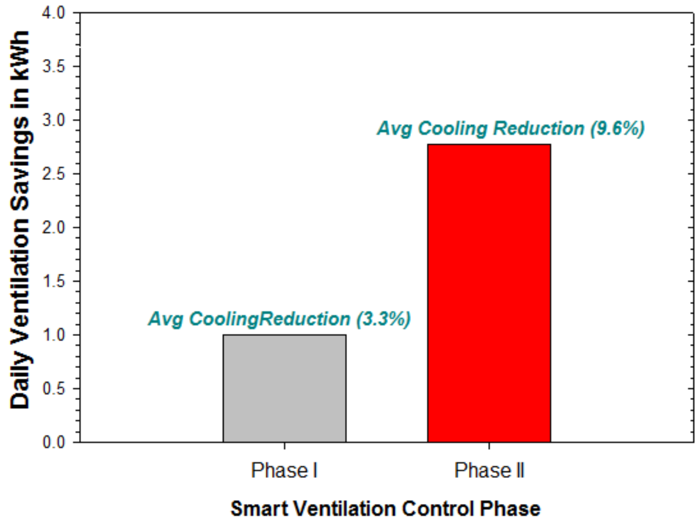
Phase I vs. Phase II Experimental Results

Phase I: Summer

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total (kWh)			
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
Aug	1,312	1,295	16	29	18	11	1,340	1,313	27	2%
Sep	1,011	1,013	(2)	29	18	10	1,039	1,031	8	1%
Oct	671	624	47	29	21	8	700	645	55	8%

Phase II: Summer

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total Energy (kWh)			
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
May	719	630	89	29	36	(7)	748	666	82	11%
Jun	822	749	73	29	20	8	851	770	81	9.5%
Jul	1,011	924	87	29	26	2	1,040	950	89	8.6%



Smart Ventilation (SV) Conclusions

- ***<u>10% summer cooling energy savings can be achieved</u>***
  - *Potential for greater savings with enthalpy heat recovery and optimization of fan energy* (var. speed motor)
  - <u>Certainty of improved comfort</u> & likely acceptability
  - Reduction in fan power critical to positive ann. savings
  - Need evaluation of SV control method across climates
- Benefits must justify costs
- No systems exist: control flow for relative exposure
- BA helping with commercialization:
  - Better fans & variable speed motors essential
  - Device integration to reduce cost, match with ERVs
  - Fault detection, code/ratings credit, commissioning

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