Duct Location and Airtightness Energy Impacts on SEER 21 and SEER 13 Heat Pumps

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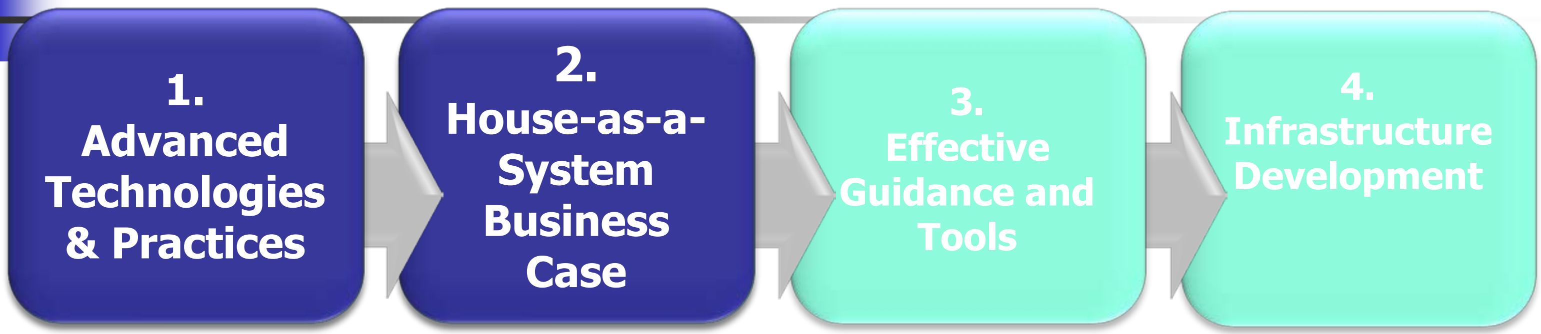
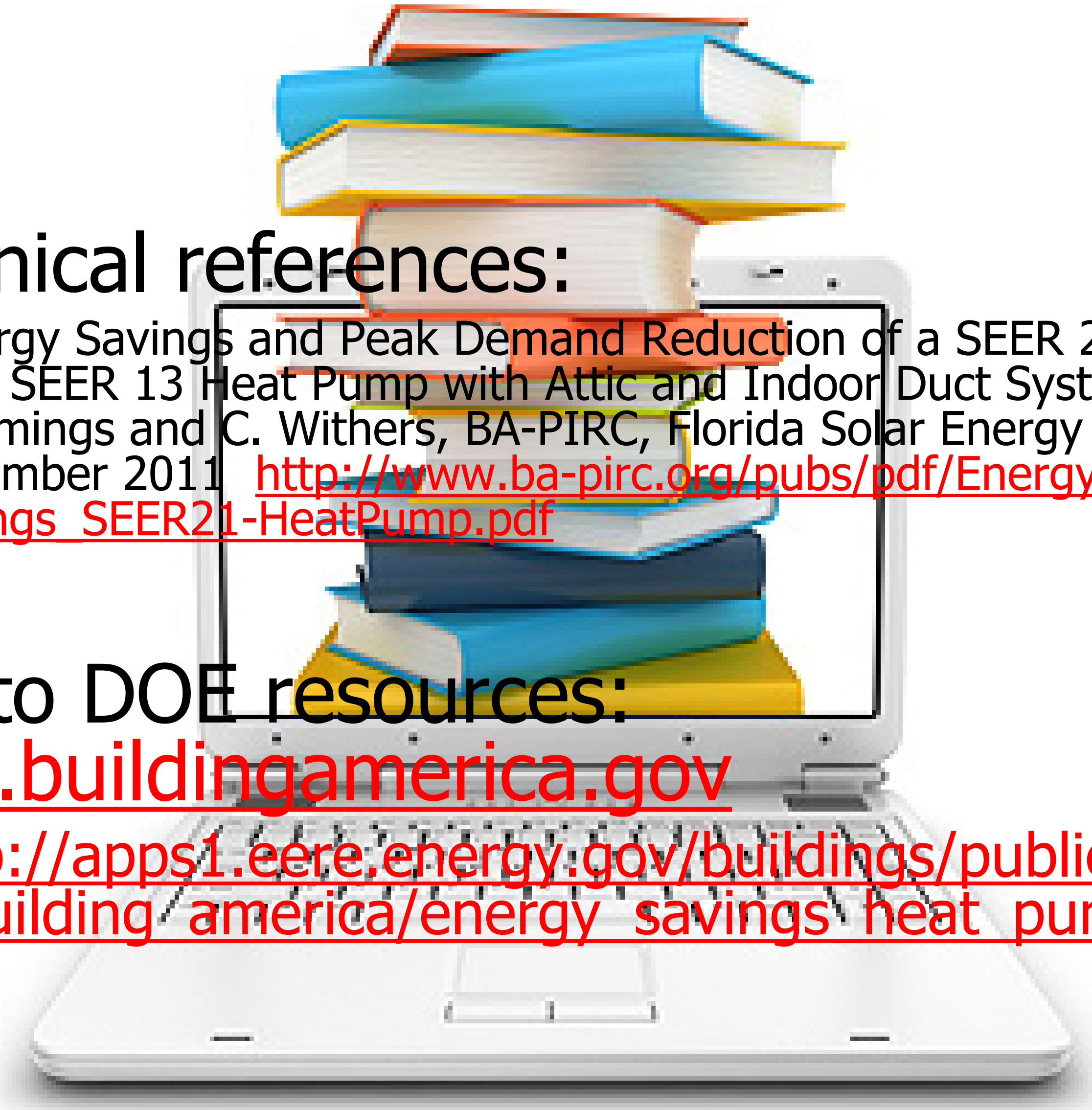
Building America Innovations



- This research is paving the way for key innovations:
  - Very high efficiency space conditioning
  - Improved air distribution systems
  - Optimized RH and load control in low-sensible load homes

BA-PIRC's Builder Resources



- Technical references:
  - "Energy Savings and Peak Demand Reduction of a SEER 21 Heat Pump vs. a SEER 13 Heat Pump with Attic and Indoor Duct Systems", J. Cummings and C. Withers, BA-PIRC, Florida Solar Energy Center, December 2011 http://www.ba-pirc.org/pubs/pdf/Energy-Savings_SEER21-HeatPump.pdf

- Link to DOE resources: www.buildingamerica.gov
  - http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/energy_savings_heat_pumps.pdf

Variable capacity heat pump

- Nordyne Corp. has introduced a line of variable capacity A/C and heat pump systems, in sizes of 2, 3, and 4 tons, with SEER ratings of 21 to 24.5.
  - Capacity varies from 40% to 118% of nominal capacity, and 34% to 100% of maximum capacity.
  - The compressor, AHU fan, and condenser fan all operate independently, with control signals from 15 to 60 hertz.
- Testing has found that system performance matches and in some cases considerably exceeds its ratings.
  - For seasonal and peak demand savings

Problem Statement

- As load declines, the equipment modulates capacity so system runtime is greatly extended.
  - The dwell time of air within the air distribution system (ADS) is substantially increased.
  - Conductive losses of the system may therefore be considerably increased.

Problem Statement (cont'd)

- Phase 1 experiments assess duct conduction losses
  - Compared the performance of a Nordyne iQ drive 3-ton variable capacity 21 SEER heat pump to a standard 3-ton 13 SEER unit, for cooling and heating
  - Using both an attic duct system and an indoor duct system.
- Phase 2 experiments assess duct leakage impacts
  - Return and supply leaks were introduced to the attic duct system.
  - The energy impacts of return leaks, supply leaks, and combined leaks are presented, including whether duct leak impacts are greater for the SEER 21 system.

MH Lab

- Experiments were carried out in a double-wide home, manufactured in 2000
  - HERS rating of 86
  - Medium-tan asphalt shingles and hot attic space (~120^{o}F peak)
  - Has original R6 attic ductwork
  - Has an indoor duct system; installed later.
  - Automated internal sensible and latent loads of a 3-person family were implemented.

Heat pumps installed side by side

- Instrumentation:
  - Conditional measurement of T/RH/cfm in return and T/RH in the supply
    - These measurement occur only when the AHU fan is operating
  - Measurement of condensate
  - Power for heat pump components and automated internal load sources
  - A wide variety of interior and ambient conditions are measured
  - 145 channels of 15-minute data.

Extent of problem to be addressed

- How does the SEER 21 heat pump perform versus a SEER 13 unit?
  - For cooling and heating
  - For seasonal energy and peak demand impacts
- How does the air distribution system impact the SEER 21 and SEER 13 systems?
  - What are the impacts of <u>duct conductive losses</u> on the two systems?
    - This is a function of delta-T and duct surface area.
    - This is a function of dwell time of highly conditioned air within the ducts.
  - What are the impacts of <u>duct leakage losses</u> on the two systems?

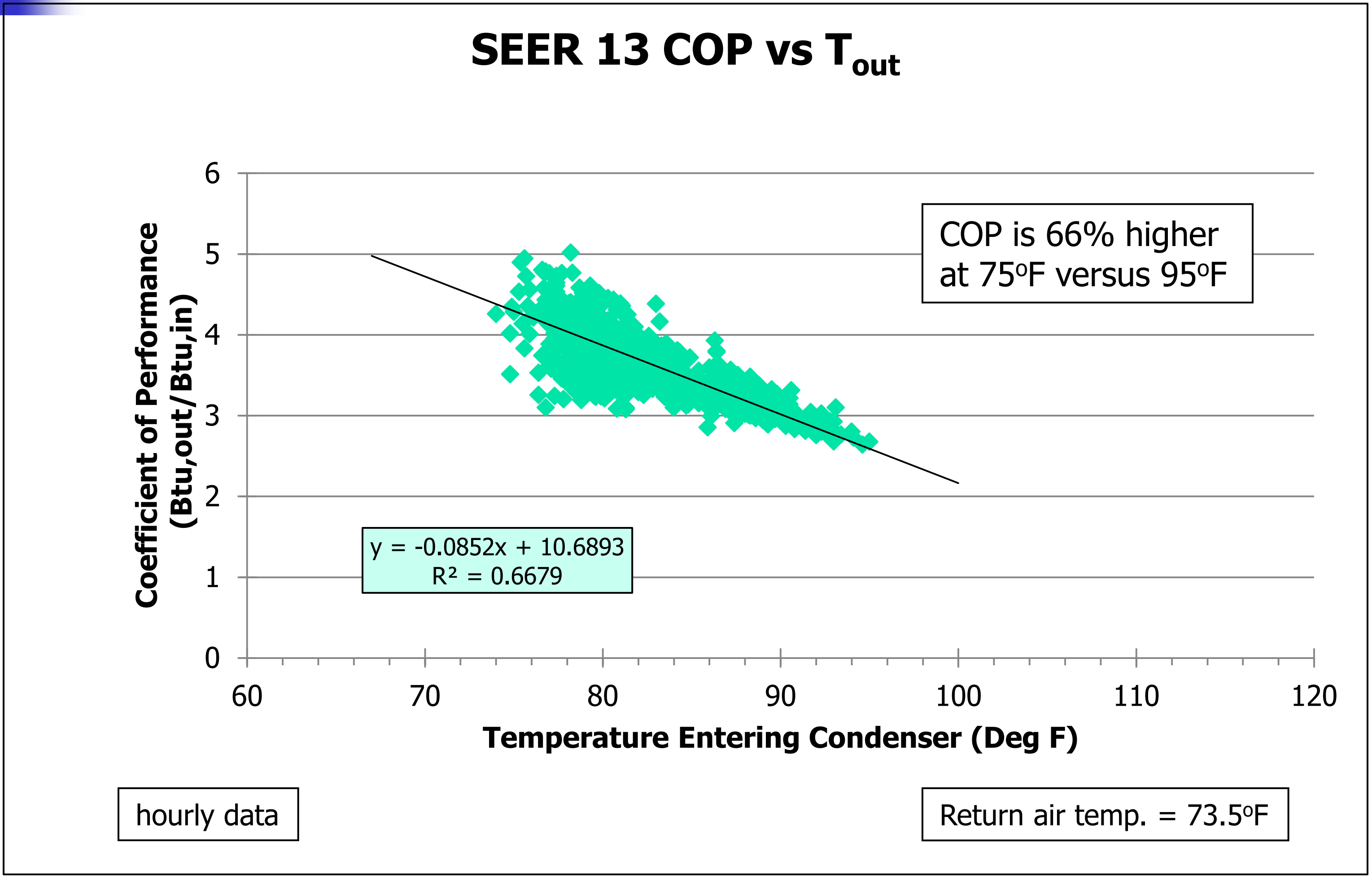
Why is this research question important?

- Variable capacity systems can yield significant benefits
  - High SEER
  - Potential for excellent RH control
  - Enhanced comfort
- Duct conductive and air leakage losses can be quite large
- The answers can provide direction regarding where and how to construct air distribution systems.

Phase 1 Performance Mapping

- Cooling capacity and efficiency of a heat pump are a function of delta-temperature (outdoors minus indoors)

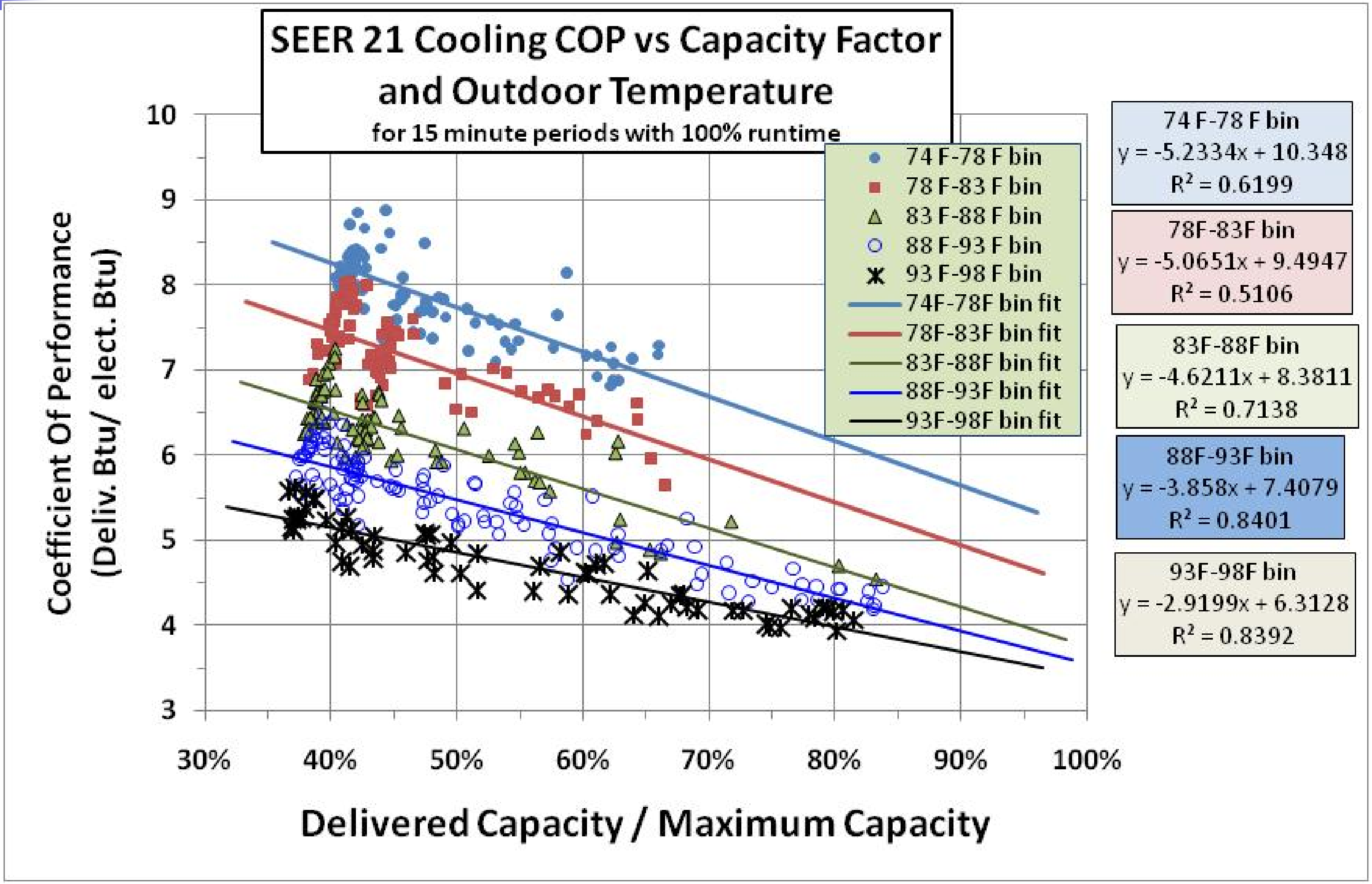
SEER 13 cooling efficiency (COP) versus outdoor temperature



Phase 1 Performance Mapping

- For the SEER 21 unit, cooling capacity and efficiency are also a function of capacity fraction
  - The iQ Drive system is as much as 61% more efficient at 40% of nominal capacity compared to 100% of nominal capacity with ambient temperature held constant

SEER 21 cooling efficiency versus outdoor temperature and capacity factor



How the Variable Capacity SEER 21 Heat Pump Operates

- Three elements of the system vary
  - AHU fan speed, compressor speed, and condenser fan speed can each vary from 15 to 60 Hz.
  - As room temperature falls below the set point, the unit does not (at first) turn off, but rather the compressor slows.
  - When load falls to below its lowest capacity (40% of nominal), the unit will cycle off.
  - With attic ducts, the SEER 21 operated 16 - 19 hours per day
  - By contrast, the SEER 13 operated 8 - 9 hours per day

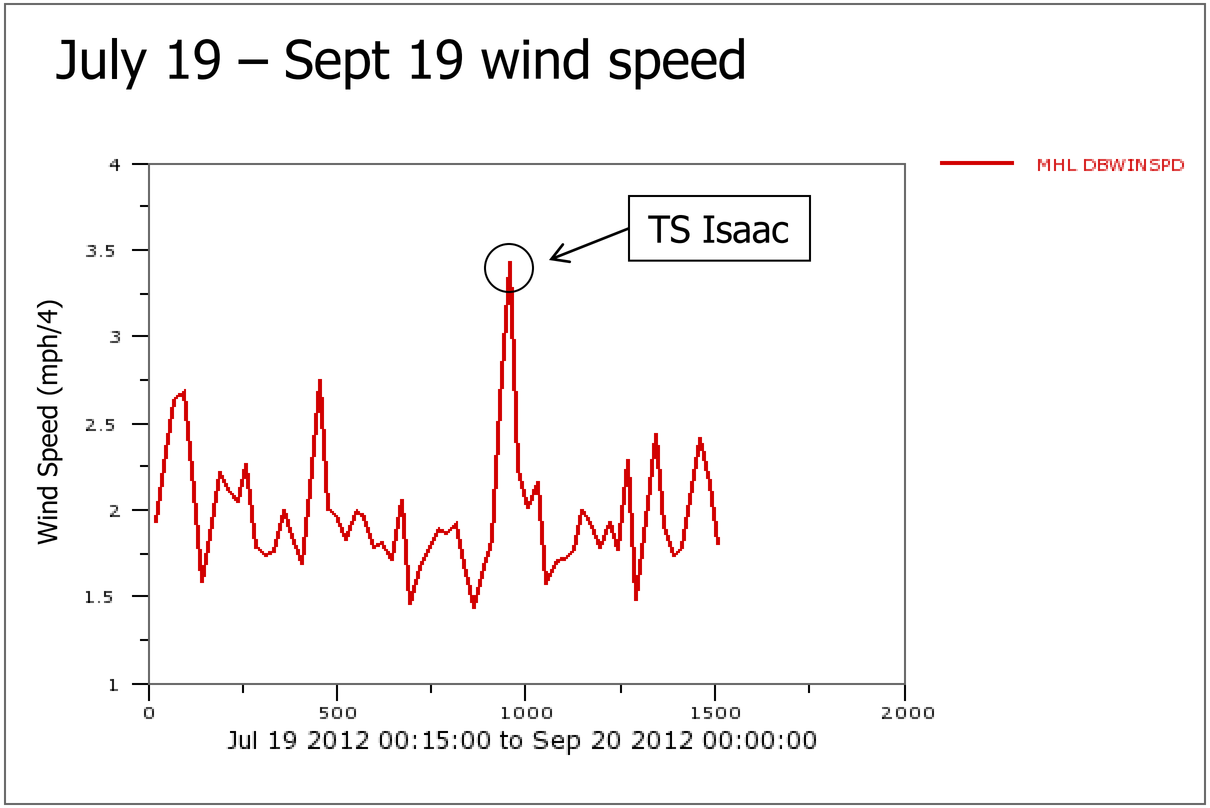
How the Variable Capacity SEER 21 Heat Pump Operates (cont'd)

- In standard control mode, air flow is about 640 cfm/ton, which is not ideal for RH control.
  - However, it still produced about 52% indoor RH
- In RH control mode, air flow declines gradually over an approximate 20 minute period, to as low as 230 cfm (190 cfm/ton).
- If the coil declines to 38^{o}F, higher cfm kicks in to avoid icing of the coil.

Variable capacity systems are ideal for indoor RH control

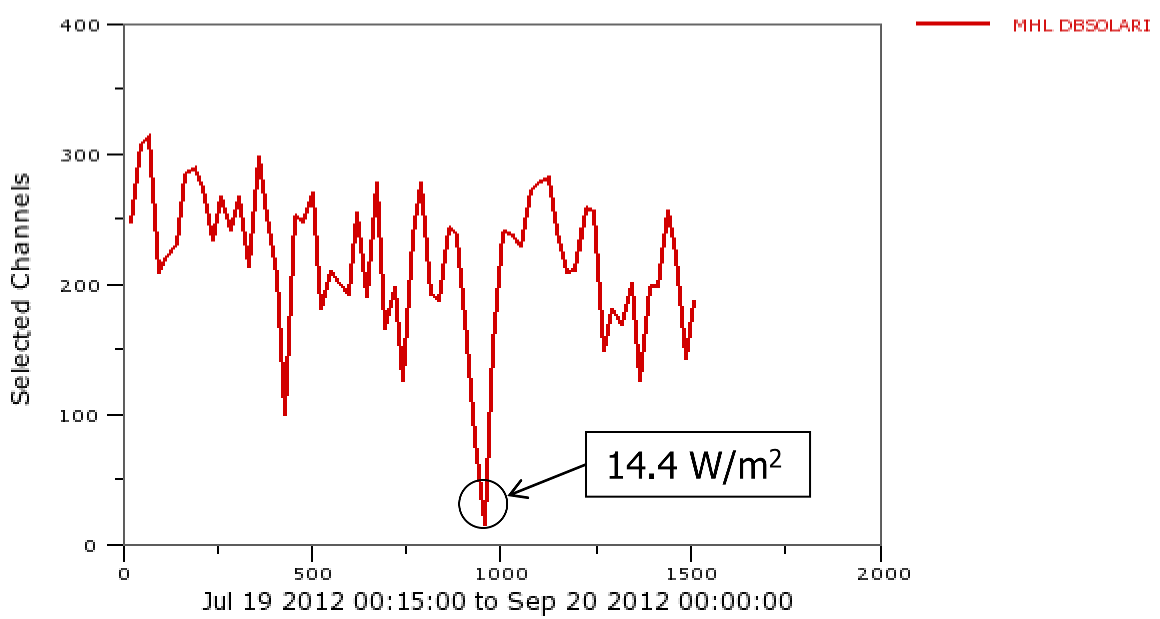
- Because they vary capacity from 34% to 100% of maximum capacity, they are rarely oversized.
- They operate for up to 15 hours without shutting off, so latent cooling inefficiencies caused by cycling off (evaporation from the coil) are minimized.
- Because they can modulate cfm/ton in real time (based on an RH setpoint), the system SHR can be modulated for optimum RH control.
- The effectiveness of the iQ Drive system was illustrated about 4 weeks ago during TS Isaac.

Worst Case Day: SEER 21 Yields Excellent RH Control



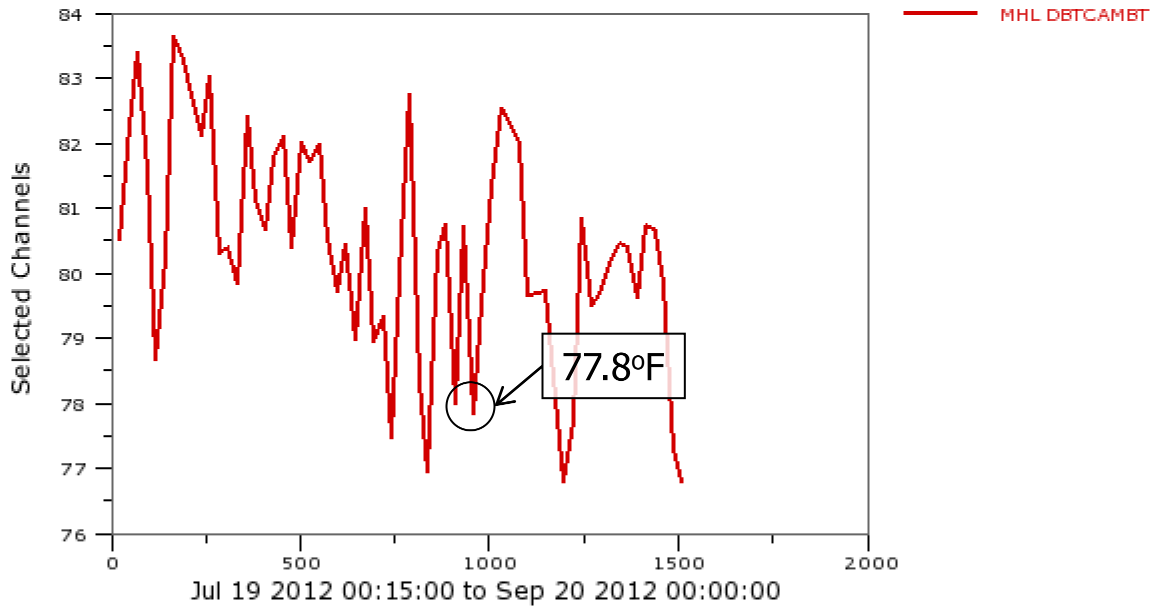
Worst Case Day: SEER 21 Yields Excellent RH Control

July 19 – Sept 19 solar radiation (W/m^2)



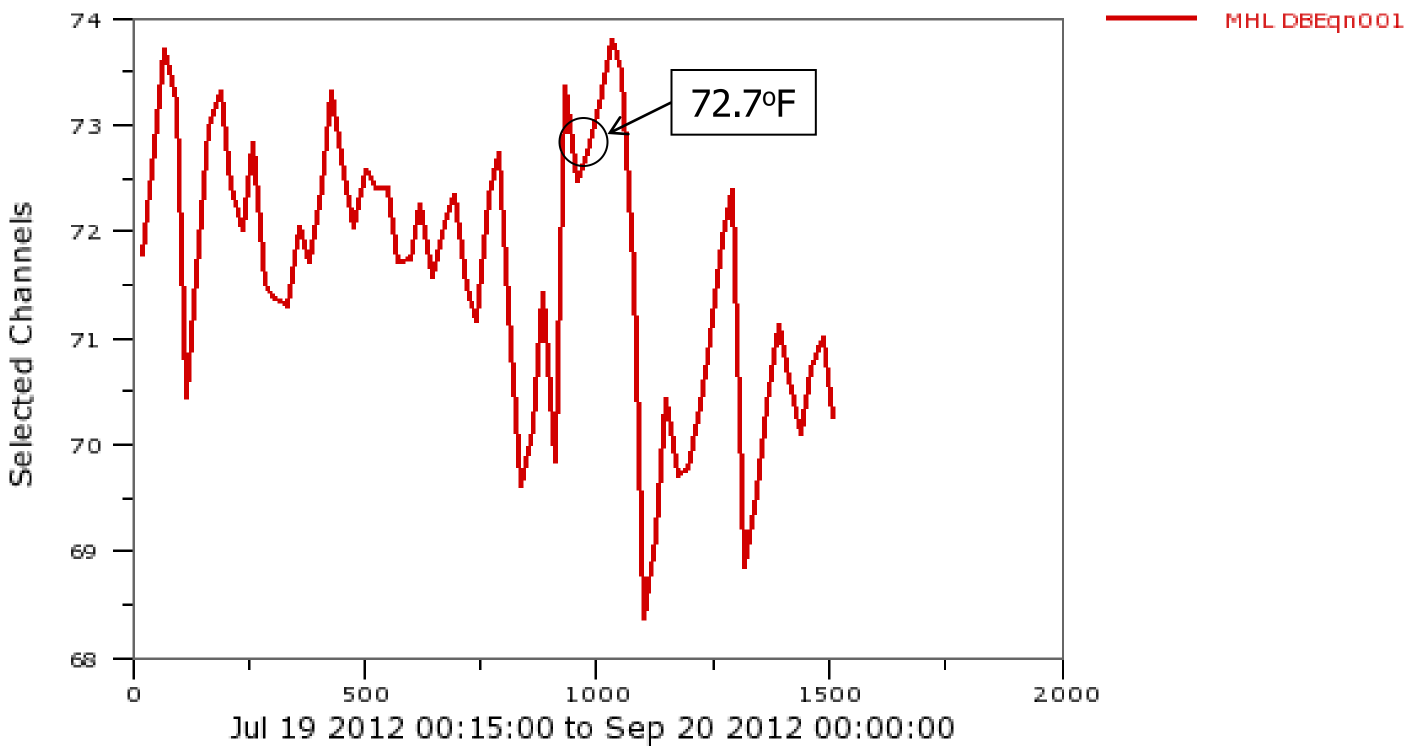
Worst Case Day: SEER 21 Yields Excellent RH Control

July 19 – Sept 19 ambient dry bulb temperature



Worst Case Day: SEER 21 Yields Excellent RH Control

July 19 – Sept 19 ambient dew point temperature



Worst Case Day: SEER 21 Yields Excellent RH Control and High Efficiency

- In challenging circumstances, RH control was excellent in another house with the iQ Drive system.
- In spite of high winds, high dew point temperatures, moderately low outdoor drybulb temperature, and extremely low solar radiation, indoor RH produced by the iQ Drive system (with RH control activated) was 44% and the system was operating at an EER of about 25.

Avoid the use of dehumidifiers

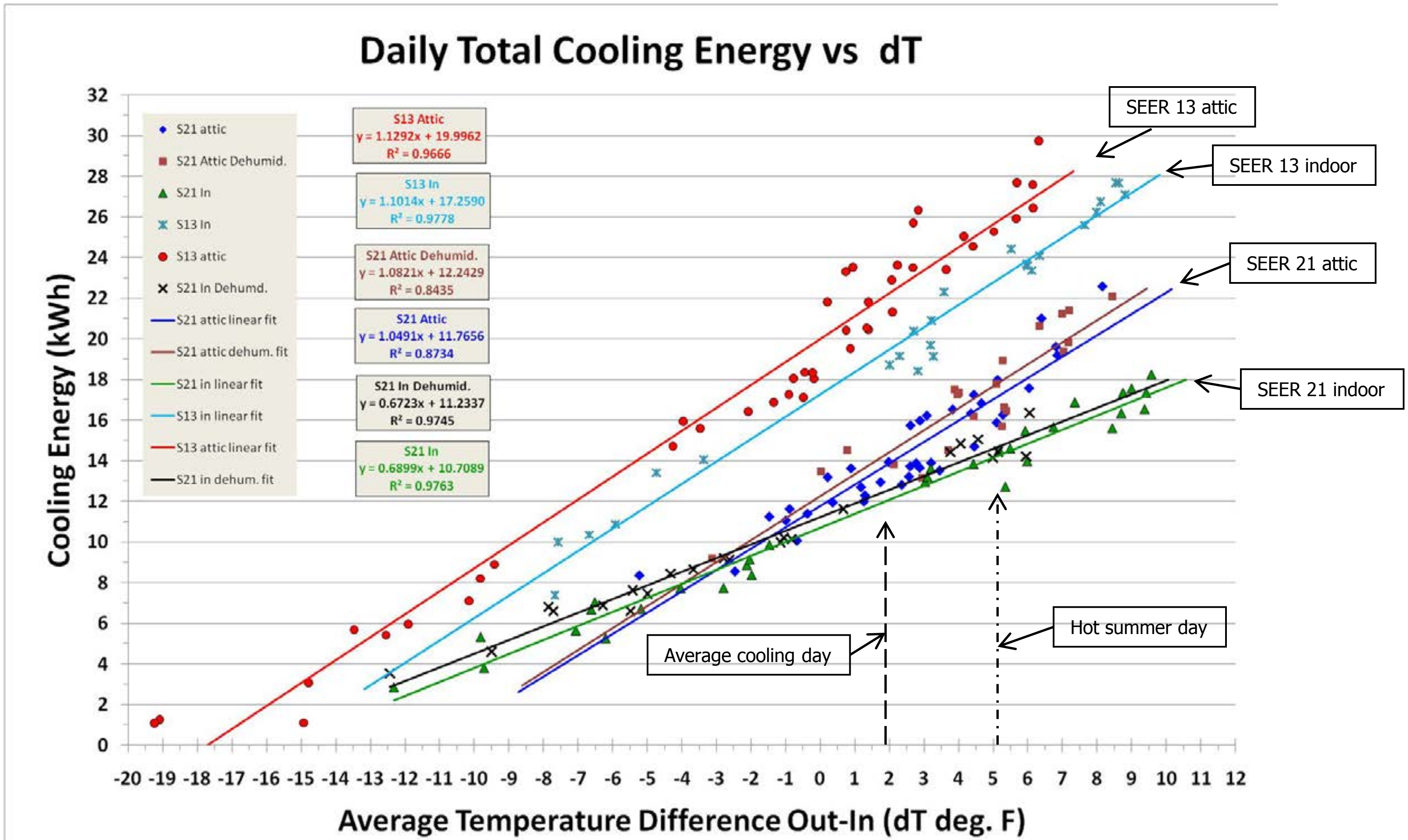
- Conclusion from this worst-case day:
  - Properly designed and optimized A/C systems can control indoor RH effectively even when building sensible loads are very small and latent loads are high
  - In low sensible-load homes, RH-control optimized A/C systems should be installed as an alternative to dehumidifiers
    - Because they are much more energy efficient
    - Dehumidifiers should be used as a last resort

Cooling season conditions for six experimental configurations

Average outdoor and indoor temperature, indoor RH, and cooling system runtime for hot and humid weather (periods with outdoor dew point temperature of 70°F or higher).

	SEER 13 attic	SEER 21 attic	S21 (45) attic	SEER 13 in	SEER 21 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

Cooling energy of SEER 13 and SEER 21 systems with indoor and attic ducts



SEER 21 cooling energy savings versus the SEER 13 system

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-^{o}F	1129.2	1049.1	1082.1	1101.4	689.9	672.2
Wh/day @ 82^{o}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%	

Cooling energy savings from use of the indoor duct system

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
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Wh/day @ 82^{o}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%	

Cooling energy; impact of conductive losses for attic location

- Using attic ducts (leak free) produced
  - 12.6% increase cooling energy use compared to indoor ducts for the SEER 13 system
  - 20.9% increase in cooling energy use compared to indoor ducts for the SEER 21 system
- CONCLUSION: Variable capacity systems lose a portion of their efficiency advantage to duct conductive losses because of lengthened dwell time of conditioned air in the ducts

SEER 21 unit matches rated seasonal performance

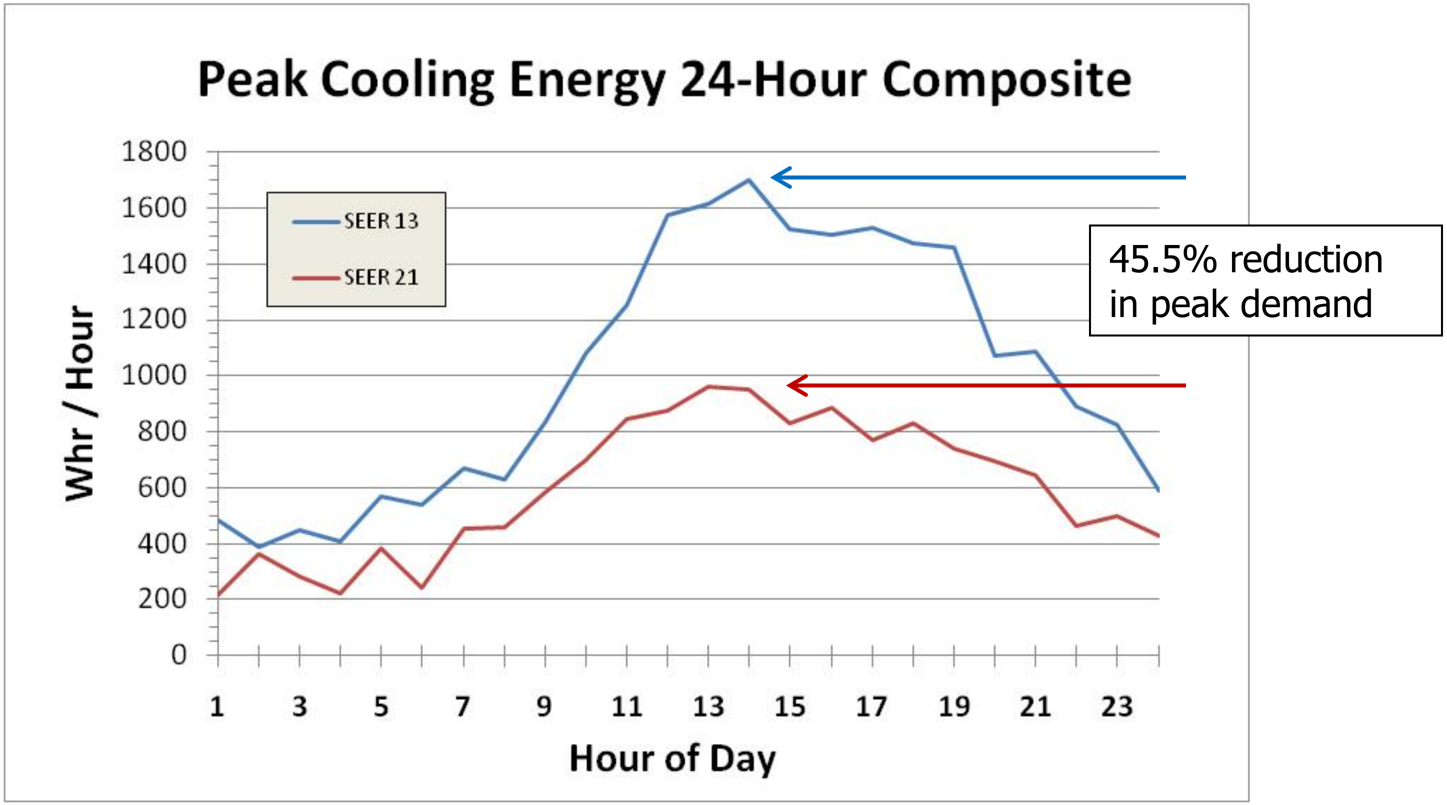
- Based on SEER ratings alone, one would expect 38.1% cooling energy savings for the SEER 21 unit compared to the SEER 13 unit.
  - For a fairly hot summer day (82^{o}F average outdoor temperature), measured data finds that
    - the SEER 21 system saves 37.8% compared to the SEER 13 system when using the <u>indoor duct system</u>
    - the SEER 21 system saves 33.7% compared to the SEER 13 system when using the <u>attic duct system</u>

Cooling peak demand – rated vs. measured

- The SEER 13 and SEER 21 units have EER ratings of 11.8 and 13.0, respectively (EER rated at 95oF $_{out}$ /80F$_{EAdb}$ /67F$_{EAwb}$)
  - From this, one would expect 9.2% peak demand reduction.
  - In actual fact, the SEER 21 unit produces a 45% peak demand reduction, with the indoor duct system.
    - Peak demand savings are five times greater than what would be expected based on EER ratings alone.
  - However, with attic duct system, the SEER 21 unit yields a 22.7% reduction in peak demand.
    - While the duct conductive losses reduce demand savings by a factor of two, they are still 2.5 times greater than what would be expected based on EER ratings alone.
    - Electric utilities would benefit most strongly from indoor ducts

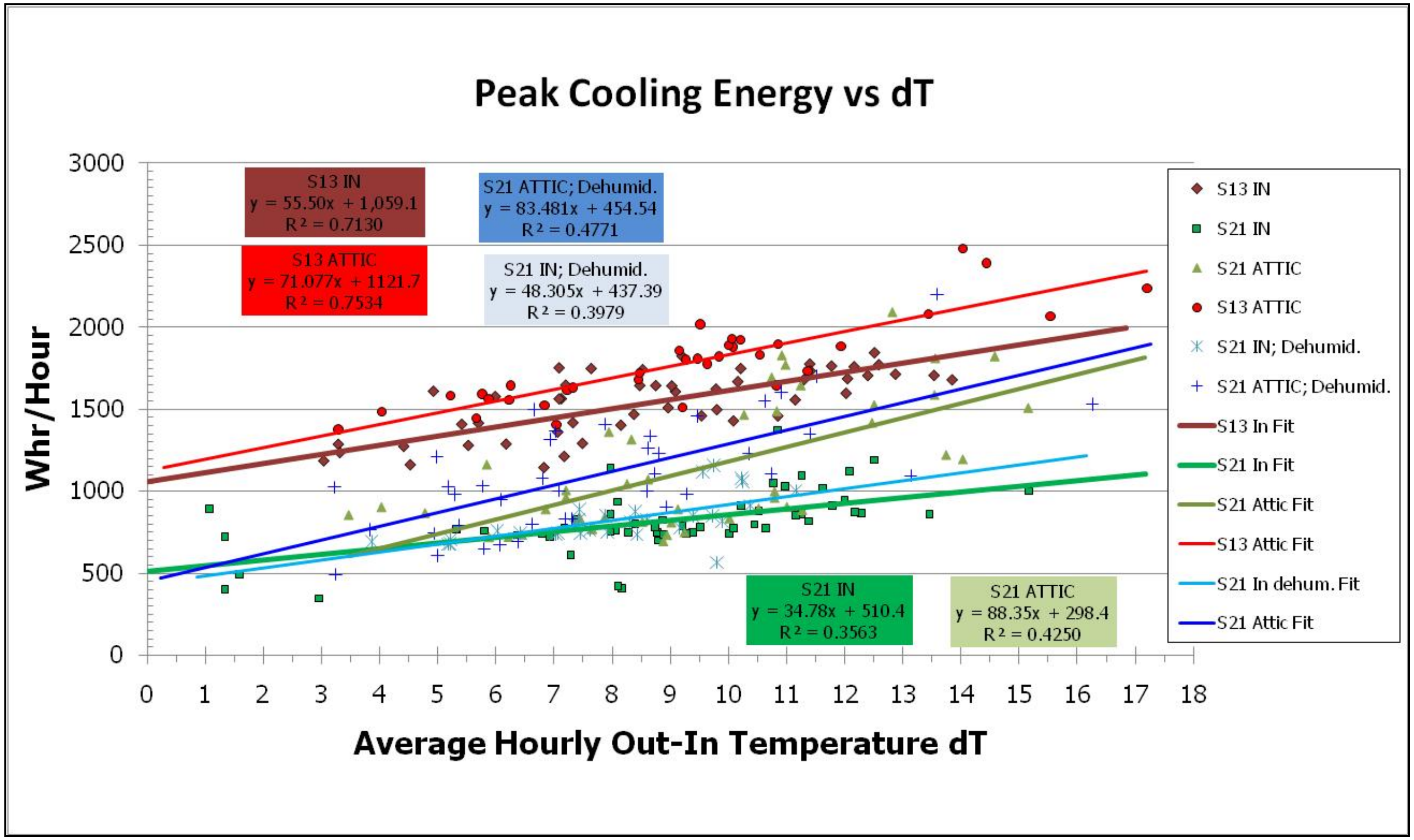
Cooling peak demand; with indoor ducts

24-hour composite from two groups of equally hot summer days (peak 94°F outdoors), one group for the SEER 13 experiments and one group for the SEER 21 experiments, each with indoor ducts



Cooling peak demand; regression analysis

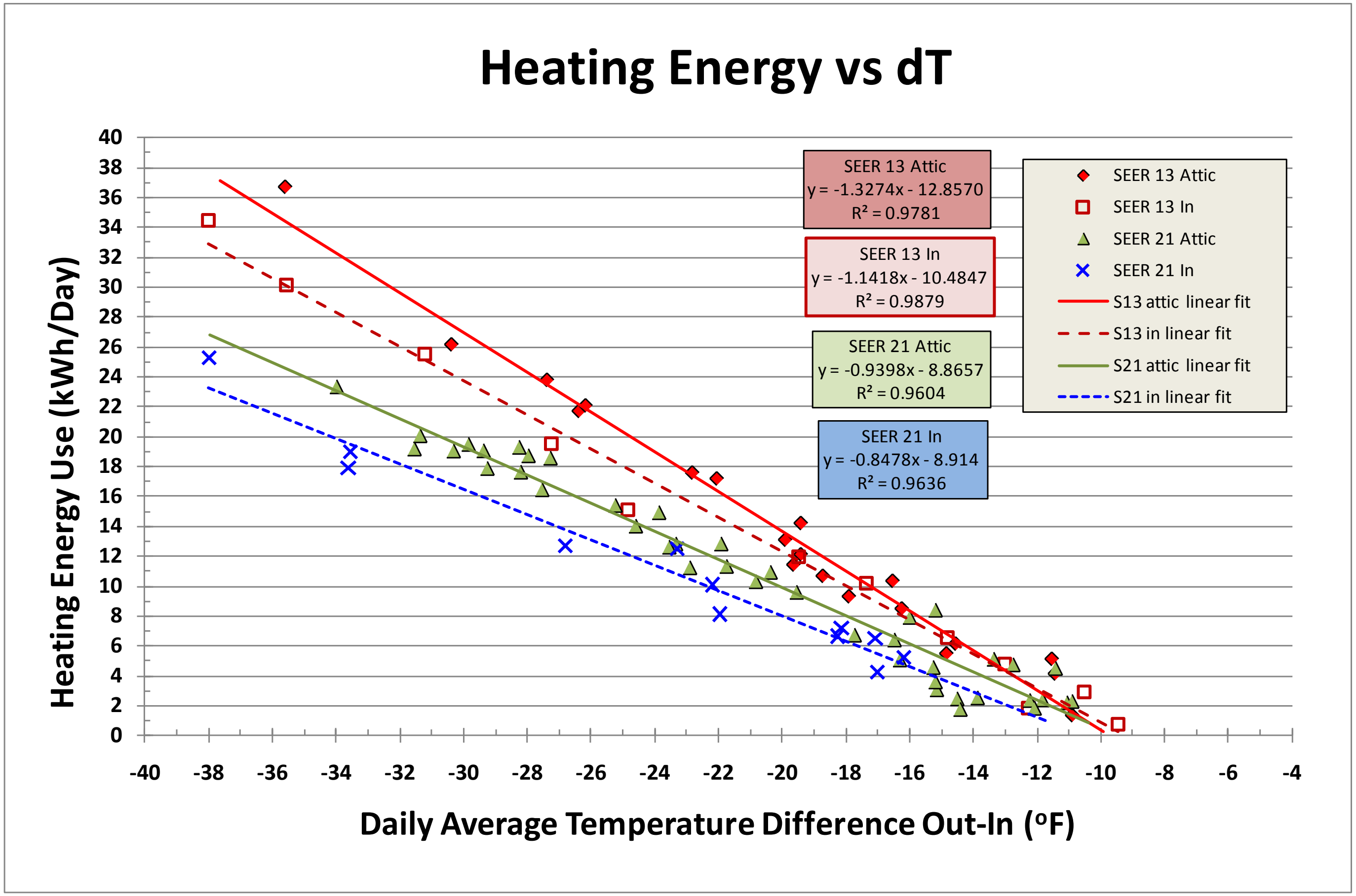
Least-squares best-fit regression analysis using hourly data was performed for the hours of 2 to 7 PM from a number of hot summer days for each test configuration



Cooling peak demand analysis

- There is good agreement between the two methods (peak 94°F outdoors),
  - 45.5% peak demand reduction from the composite method
  - 45.0% peak demand reduction from the regression method

Heating energy savings

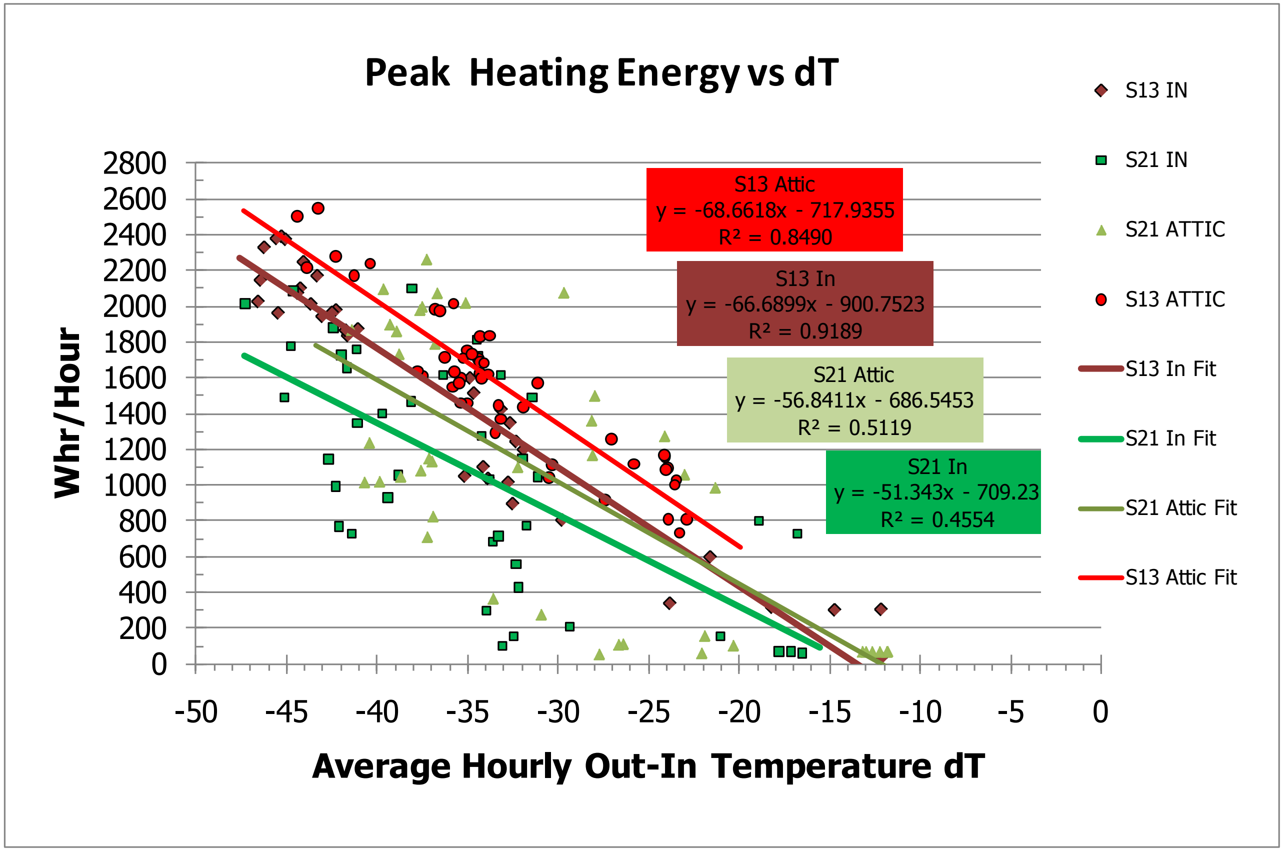


Heating energy savings

- Based on the heat pump HSPF ratings alone (9.6 and 8.0, respectively, for the SEER 21 and SEER 13 units), one would expect 16.7% heating energy savings for the SEER 21 unit compared to the SEER 13 unit.
- For a typical central Florida winter day (50ºF average outdoor temperature; low 40ºF and high 60ºF), the measured data finds that
  - the SEER 21 system saves 33.4% compared to the SEER 13 system when using the <u>indoor duct system</u>
  - the SEER 21 system saves 27.8% compared to the SEER 13 system when using the <u>attic duct system</u>
- <u>Conclusions:</u>
  - 1) the SEER 21 heat pump outperforms its rating (relative to the SEER 13 system) by a factor of 2.0 (100% outperformance relative to the SEER 13 system)
  - 2) conductive duct losses degrade system performance more for the SEER 21 (variable capacity) system than for the SEER 13 system

Heating peak demand – regression analysis

Least-squares best-fit regression analysis was performed for the hours of 3 to 8 AM from a number of cold winter days using hourly data for each test configuration.



Heating peak demand savings

- Based on manufacturer's "expanded performance" COP data (3.15 and 3.01, respectively, for the SEER 21 and SEER 13 units),
  - One would expect peak demand reduction of 4.4% at 30^{o}F ambient temperature.
  - In actual fact, the SEER 21 unit performs considerably better than these COP ratings would suggest.
  - The measured data shows that the SEER 21 unit reduces peak demand, at 30^{o}F outdoor temperature, by 23.8% compared to the SEER 13 unit when using the <u>indoor ducts</u> and 21.5% when using the <u>attic ducts</u>.

What have we learned? (Summary and Conclusions)

- Seasonal cooling performance of the SEER 21 unit approximately matches expectations (relative to the SEER 13 unit).
  - 38.1% energy savings expected
  - 37.8% energy savings achieved (with indoor ducts)
  - 33.7% energy savings achieved (with attic ducts)
- Seasonal heating performance of the SEER 21 unit exceeds expected outperformance by a factor of two.
  - 16.7% energy savings expected
  - 33.4% energy savings achieved (with indoor ducts)
  - 27.8% energy savings achieved (with attic ducts)

Summary and Conclusions (cont'd)

- Peak cooling performance of the SEER 21 unit greatly exceeds expectations (relative to the SEER 13 unit).
  - 9.2% peak demand savings expected
  - 45.0% peak demand savings achieved (with indoor ducts)
  - 22.7% peak demand savings achieved (with attic ducts)
- Peak heating performance of the SEER 21 unit exceeds expected outperformance by a factor of five.
  - 4.4% peak demand savings expected
  - 23.8% peak demand savings achieved (with indoor ducts)
  - 21.5% peak demand savings achieved (with attic ducts)

Summary and Conclusions (cont'd)

- IMPACT OF DUCT CONDUCTIVE LOSSES
  - Extended system run times degrades system performance of the SEER 21 unit due to increased conductive losses.
  - Seasonal cooling impact
    - The SEER 21 unit has about 92% greater runtime (vs SEER 13 unit)
    - Placing the ducts indoors saves 16.8% for the SEER 21 unit
    - Placing the ducts indoors saves 11.2% for the SEER 13 unit
  - Seasonal heating impact
    - The SEER 21 unit has about 24% greater runtime (vs SEER 13 unit)
    - Placing the ducts indoors saves 17.5% for the SEER 21 unit
    - Placing the ducts indoors saves 10.5% for the SEER 13 unit

How will this knowledge affect innovations and solutions?

- Smart contractors and consumers will look for ways to reduce duct conductive losses with variable capacity systems
- The importance of using indoor ducts will become more widely recognized
  - Government and utility programs should encourage indoor ductwork when using variable capacity systems

How will this knowledge affect innovations and solutions?

- Various programs should allow or even encourage oversizing of variable capacity systems because (early evidence indicates that) they operate at much higher efficiency at part capacity
  - Experiments to verify this are currently underway
  - Electric utilities will find that variable capacity systems have the potential to greatly reduce peak electrical demand,
    - Especially when using indoor ductwork

PHASE 2: Duct leak experiments

RESEARCH QUESTION:

Do duct leaks impact the energy efficiency of the SEER 21 system more or less than the SEER 13 system?

Duct leak experiments (cont'd)

- The research was set up to examine the seasonal energy and peak demand impacts of various duct leak configurations
  - Three duct leak configurations for each system
    - 8% RL & 0% SL
    - 0% RL & 8% SL
    - 8% RL & 8% SL ("combo" leaks)
  - For <u>cooling</u> with SEER 13, SEER 21, and SEER 21 systems with RH control
  - For <u>heating</u> with the SEER 13 and SEER 21 systems

Duct leak experiments (cont'd)

- Duct leaks were introduced to both heat pump systems, for only the attic duct system.
  - 8% return leak; 50% from outdoors and 50% from the attic
    - Conditional* monitoring of return leak T/RH/cfm
  - 8% supply leak; 100% being delivered to the attic
    - Away from where the return leak air is drawn into the 4% return leakage
    - Conditional* monitoring of supply leak cfm

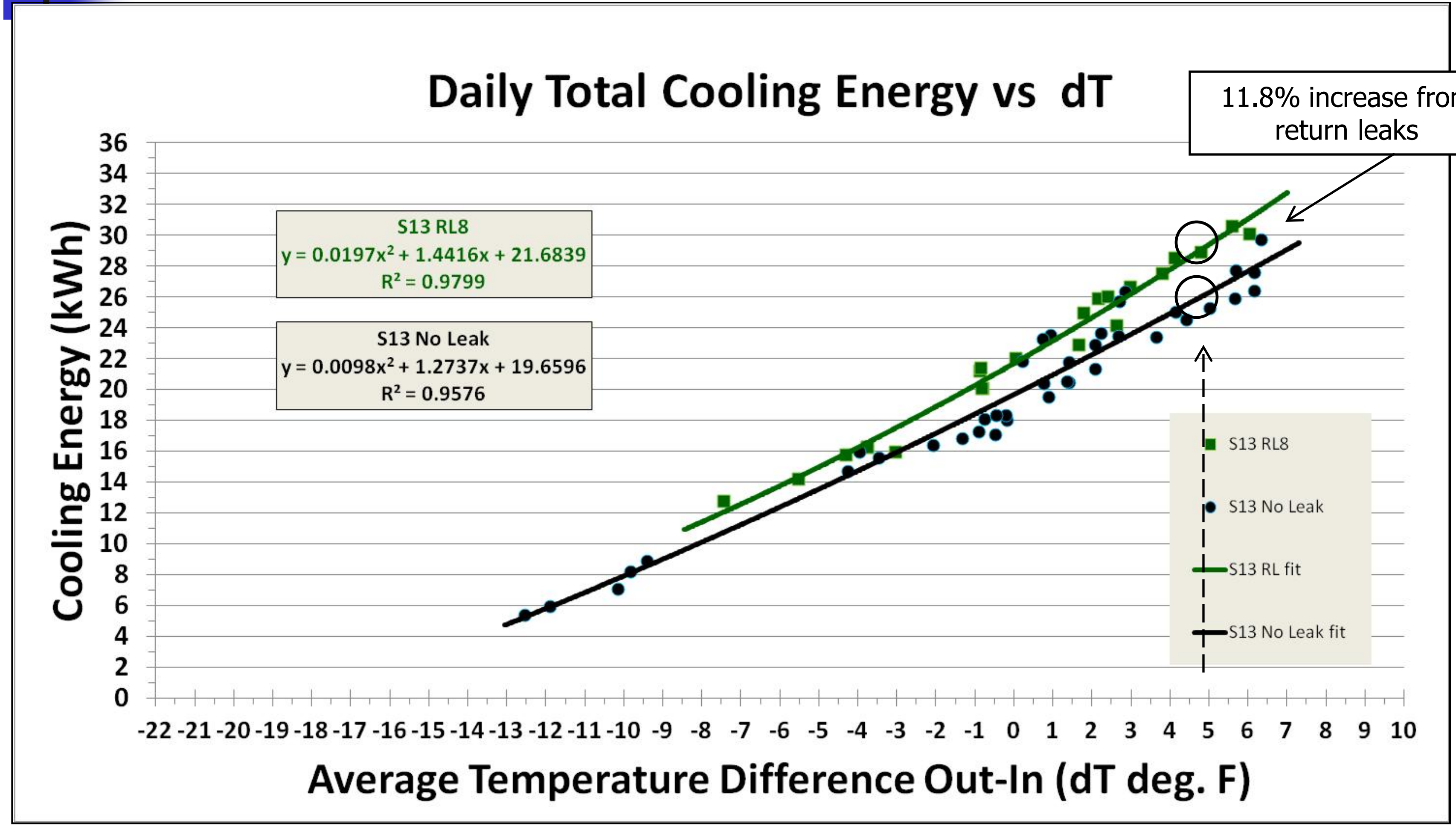
* Conditional means recording data only when the AHU fan is operating

Cooling season conditions for eight experimental configurations

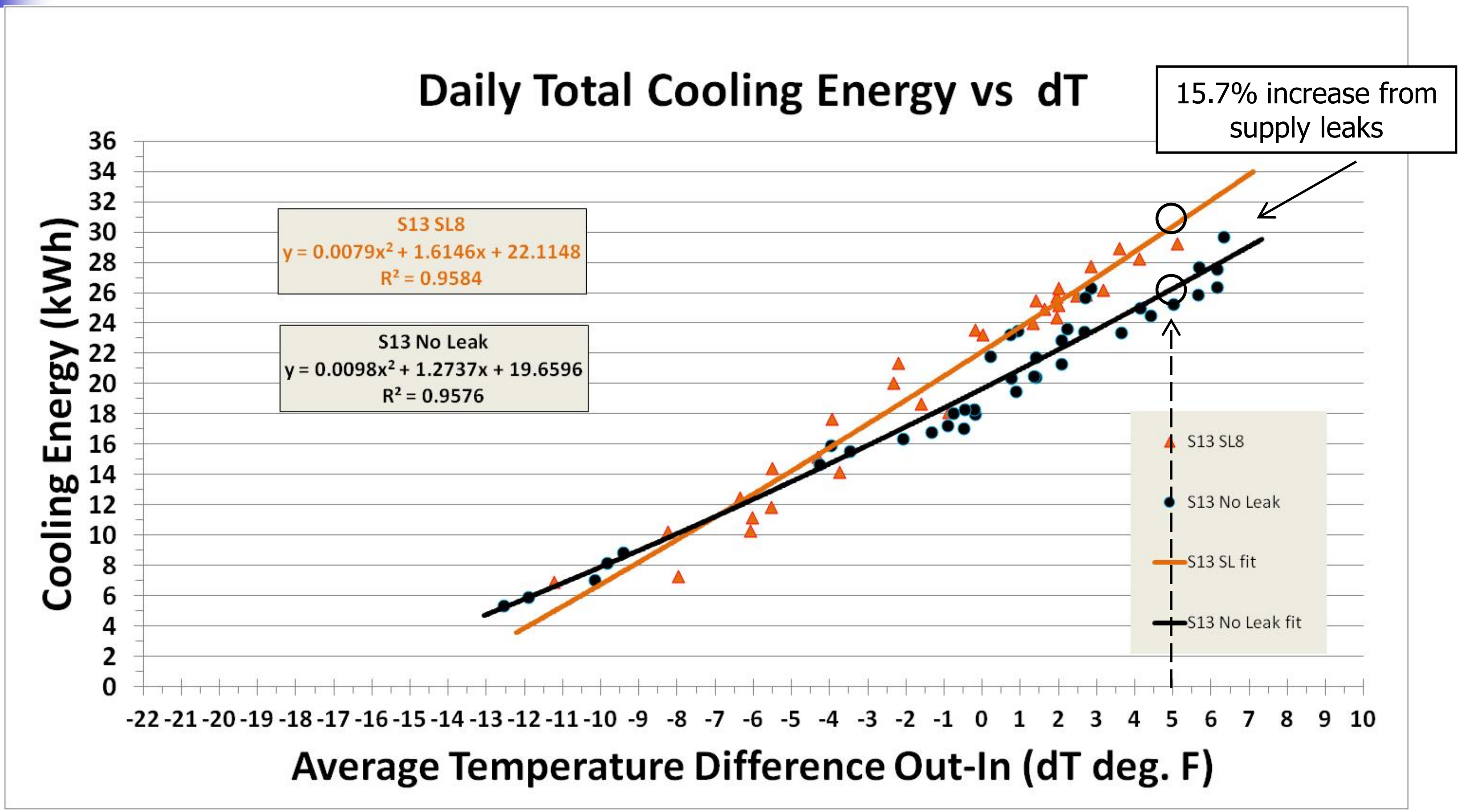
Average outdoor and indoor temperature indoor RH, and cooling system runtime for Phase 2 experimental periods with outdoor dew point temperature of 70°F or higher.

	S13 SL	S13 RL	S13 SL+RL	S21 SL	S21 RL	S21 SL+RL	S21(45) SLSL	S21(45) RL
Average Tout (°F)	80.6	80.4	79.8	79.6	80.2	81.2	81.0	81.0
Average Tin (°F)	78.0	78.1	78.0	76.9	77.1	77.1	77.0	77.0
Delta-T (out-in; (°F))	2.6	2.3	1.8	2.7	3.1	4.1	4.0	4.0
Indoor RH (%)	51.4	48.9	51.2	56.8	54.3	55.0	52.5	52.3
System runtime (%)	38.9	37.4	38.3	72.1	69.4	77.8	78.5	74.1

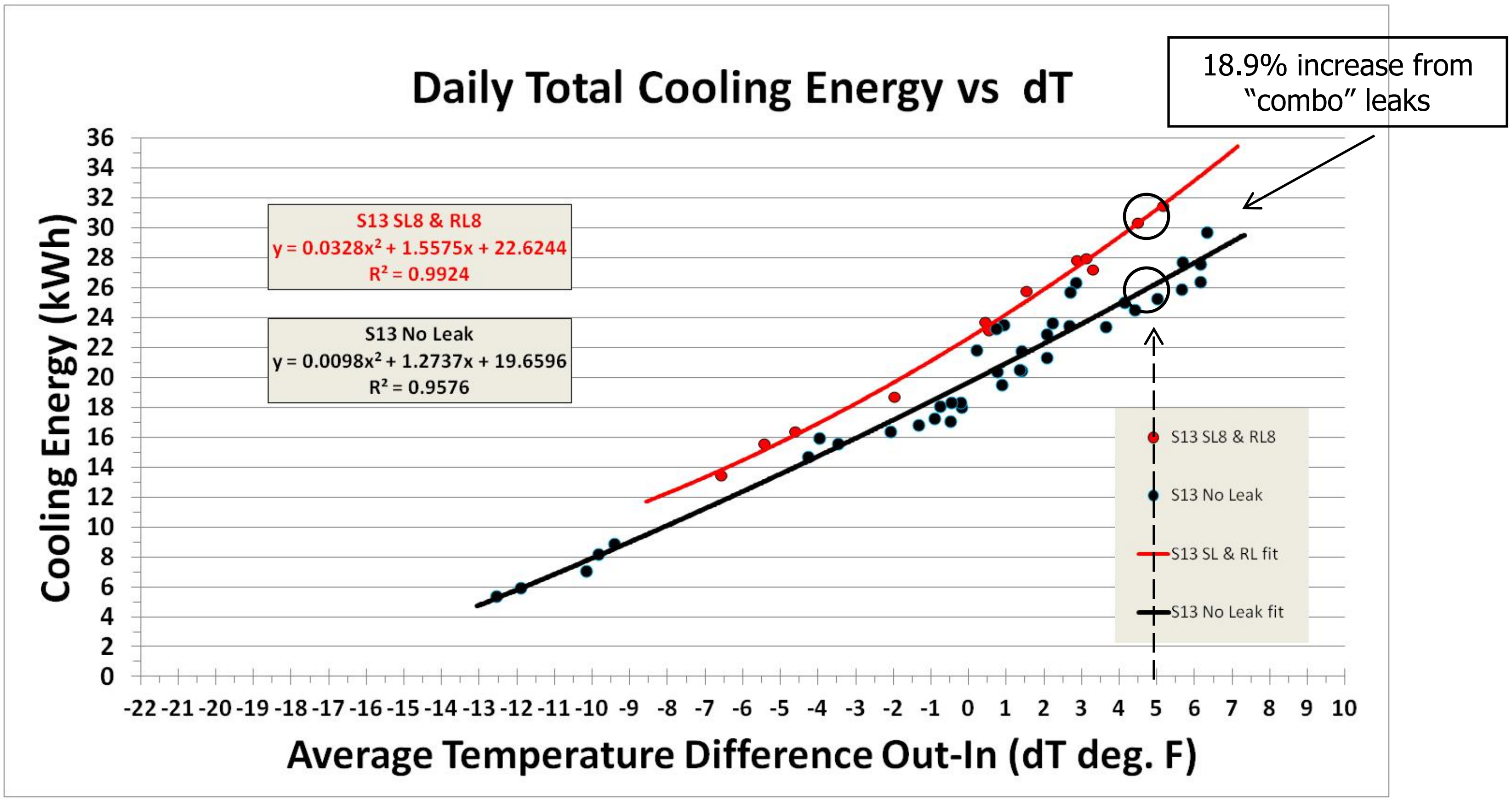
Cooling energy for SEER 13 unit with and without return leaks (8% RL)



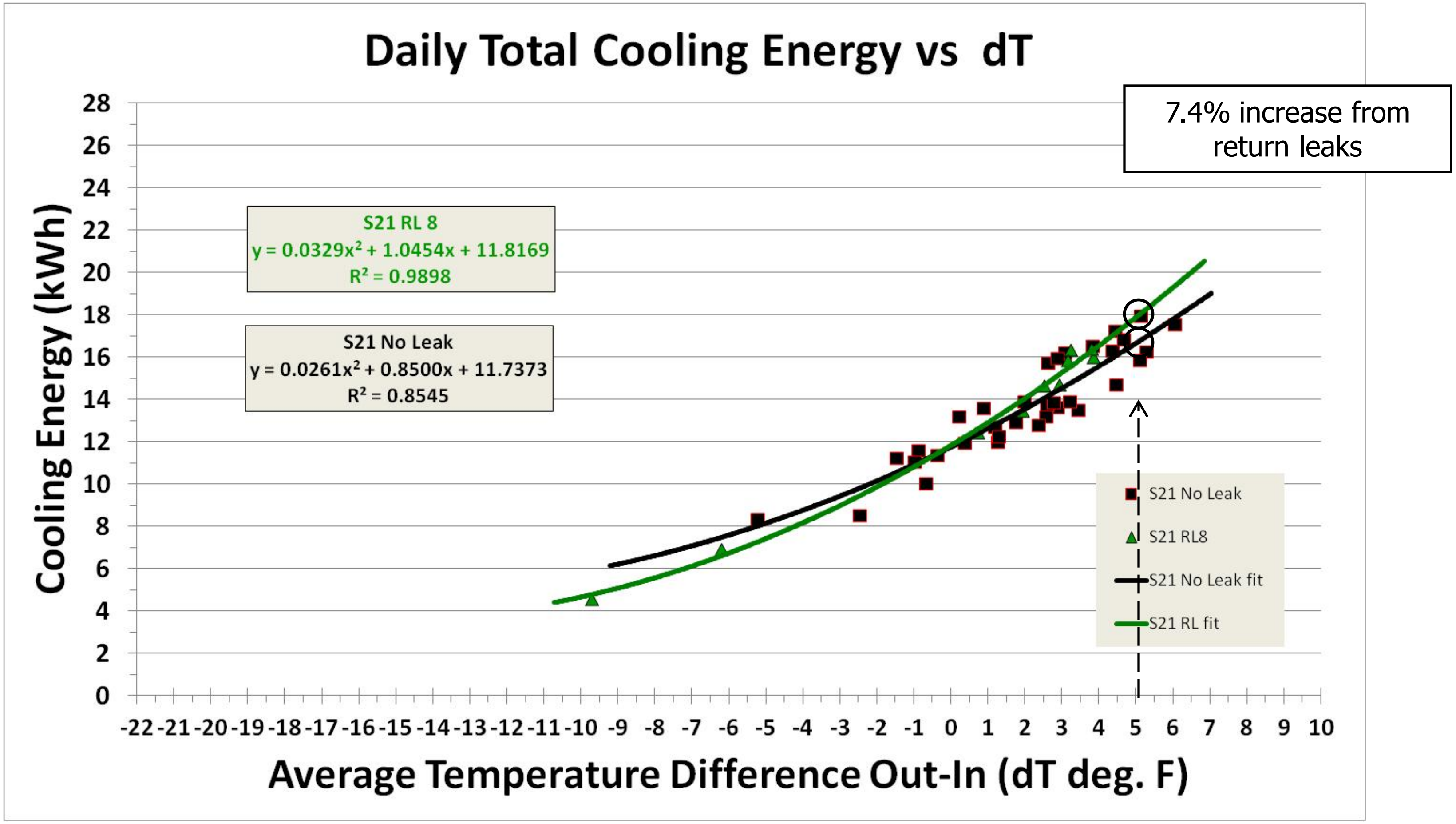
Cooling energy for SEER 13 unit with and without supply leaks (8% SL)



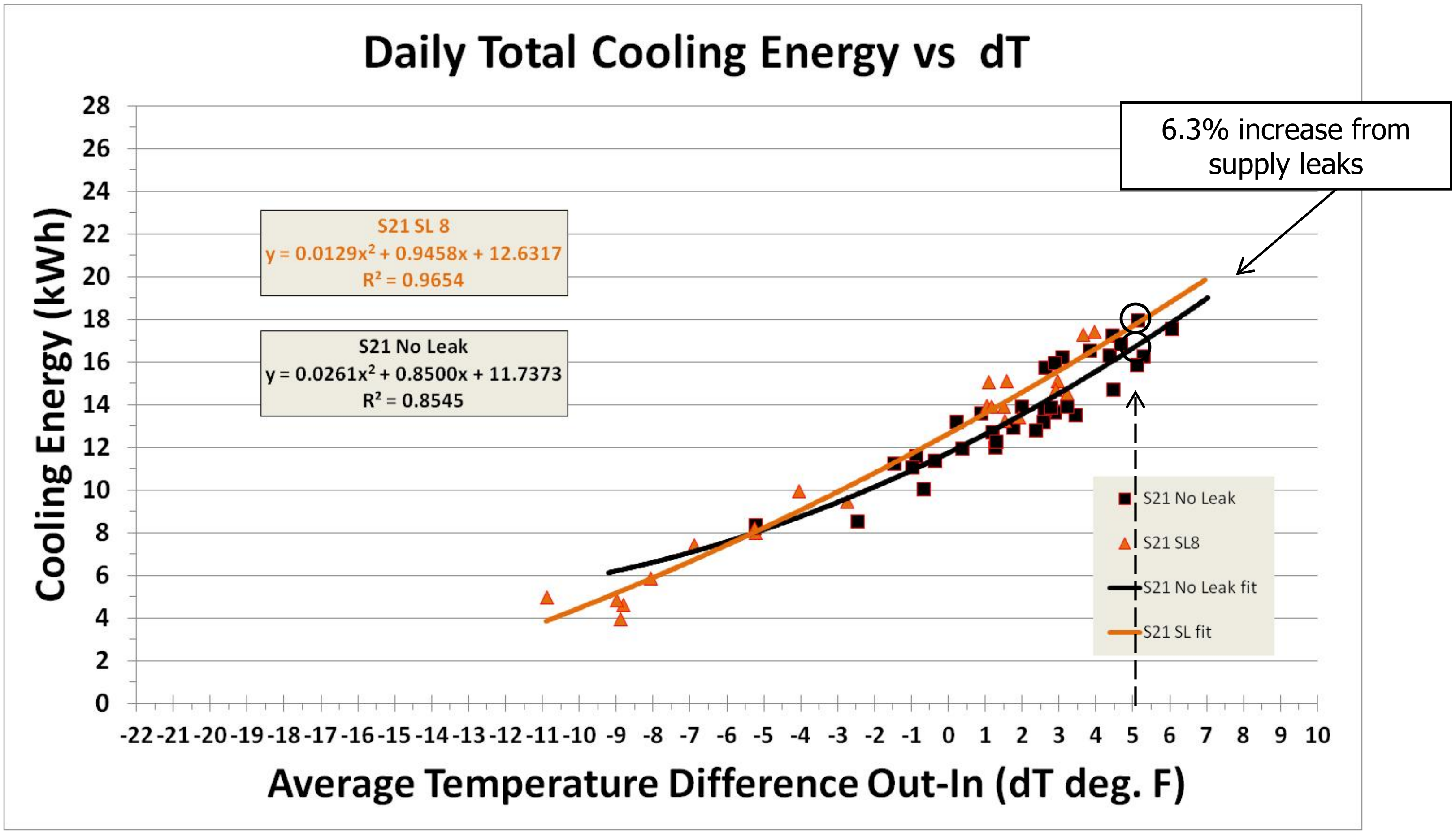
Cooling energy for SEER 13 unit with and without "combo" leaks (RL8% + SL8%)



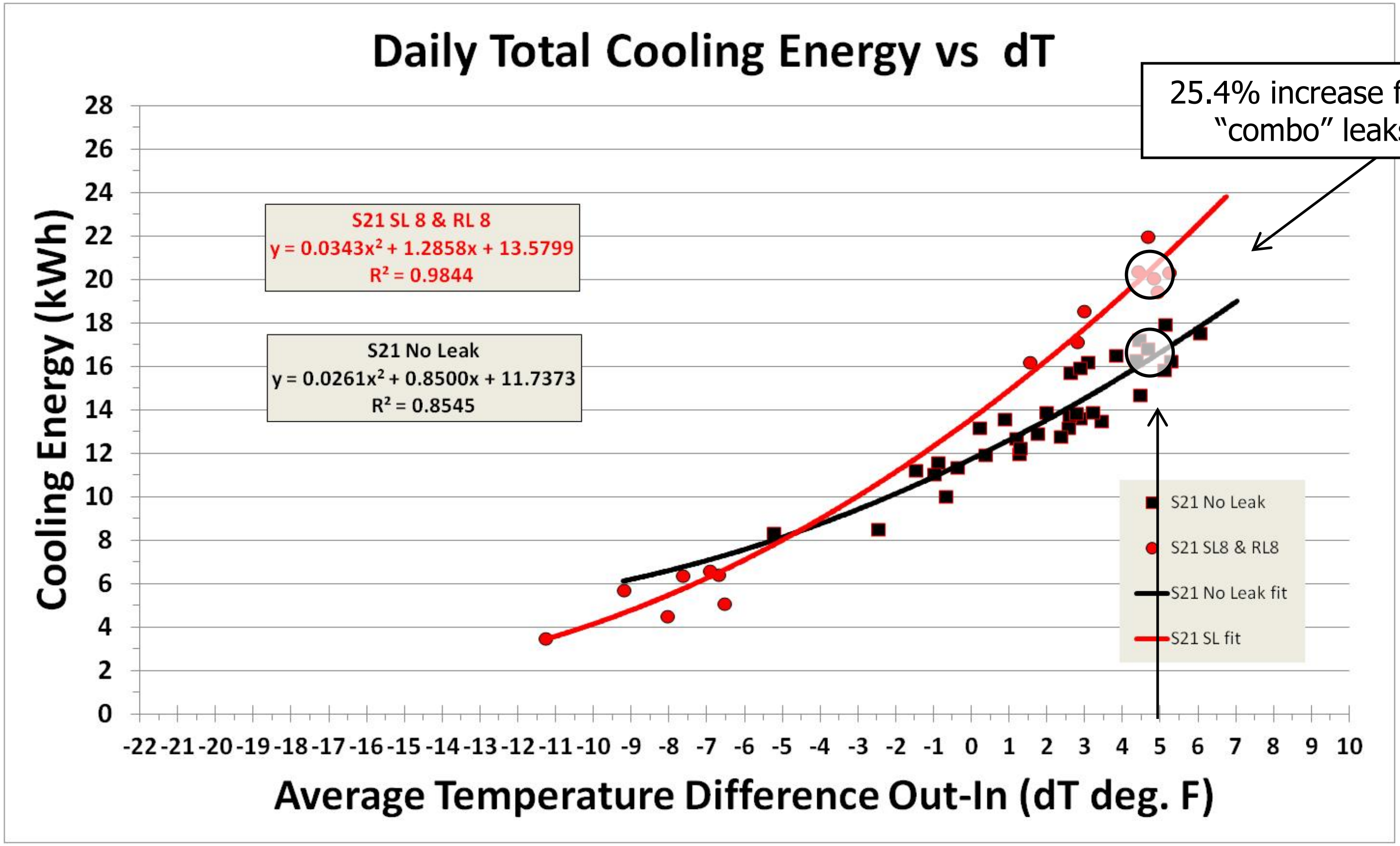
Cooling energy for SEER 21 unit with and without return leaks (8% RL)



Cooling energy for SEER 13 unit with and without supply leaks (8% SL)



Cooling energy for SEER 21 unit with and without “combo” leaks (RL8% + SL8%)



Duct leak seasonal energy impact summary

- 8% RL causes
  - 11.8% cooling energy increase for SEER 13
  - 8.4% cooling energy increase for SEER 21
- 8% SL causes
  - 15.7% cooling energy increase for SEER 13
  - 15.1% cooling energy increase for SEER 21
- 8% RL + 8% SL causes
  - 18.9% cooling energy increase for SEER 13
  - 25.4% cooling energy increase for SEER 21

Seasonal cooling duct leak conclusions

- There are two duct leak trends to report
- 1) When considering the SEER 13 and SEER 21 systems together
  - Return leaks cause less energy increase than supply leaks (about 10%)
  - Supply leaks cause less energy impact than “combo” leaks (about 15%)
  - “Combo” leaks cause the greatest energy impact (about 22%).

Seasonal cooling duct leak conclusions (cont'd)

- 2) There appear to be small differences in duct leak impacts between the SEER 13 and SEER 22 systems. However, averaged over all three duct leak types, there appears to be no real (detectable) difference in duct leak impacts for the SEER 13 versus the SEER 21 systems.
  - Return leaks appear to cause slightly <u>less impact</u> for the SEER 21 system compared to the SEER 13 system (about 8.5% vs 11.5%).
  - Supply leaks appear to cause approximately <u>equal impacts</u> for SEER 13 and SEER 21 systems (about 15.5% vs 15%).
  - "Combo" leaks appear to cause <u>greater impact</u> for the SEER 21 system compared to the SEER 13 system (about 25.5% vs. 19%)

Cooling peak demand impact of duct leaks; SEER 13 regression analysis

Peak demand increase. Best-fit equation intercepts and coefficients in the form of $Y = A + B(X^2)$, where Y is the hourly cooling electrical energy use and X is the hourly average temperature difference between indoors and outdoors for the SEER 13 system with various duct leaks compared to no duct leaks.

	SEER 13	SEER 13 RL	SEER 13 SL	SEER 13 RL+SL
(A) W	1122.54	1223.21	1365.70	1075.16
(B) W/°F	71.02	84.80	72.47	128.06
W @ 94°F (delta-T = 17°F)	2329.8	2664.8	2597.7	3252.2
Energy increase vs. SEER 13 w/no duct leaks (W)	-	335.0	267.9	922.4
Energy increase vs. SEER 13 w/no duct leaks (%)	-	14.4%	11.5%	39.6%

* RL = 8% return leak, SL = 8% supply leak, and RL+SL = 8% return leak plus 8% supply leak

Cooling peak demand impact of duct leaks; SEER 21 regression analysis

Peak demand increase. Best-fit equation intercepts and coefficients in the form of $Y = A + B(X^2)$, where Y is the hourly cooling electrical energy use and X is the hourly average temperature difference between indoors and outdoors for the SEER 21 system (no RH control implemented) with various duct leaks compared to no duct leaks.

	SEER 21	SEER 21 RL	SEER 21 SL	SEER 21 RL+SL
(A) W	601.43	432.58	689.22	657.71
(B) W/°F	56.67	76.90	62.98	84.07
W @ 94°F (delta-T = 17°F)	1564.8	1739.9	1759.9	2086.9
Energy increase vs. SEER 21 w/no duct leaks (W)	-	175.1	195.1	522.1
Energy increase vs. SEER 21 w/no duct leaks (%)	-	11.2%	12.5%	33.4%

* RL = 8% return leak, SL = 8% supply leak, and RL+SL = 8% return leak plus 8% supply leak

Duct leak peak demand impact summary

- 8% RL causes
  - 14.4% cooling peak demand increase for SEER 13
  - 11.2% cooling peak demand increase for SEER 21
- 8% SL causes
  - 11.5% cooling peak demand increase for SEER 13
  - 12.5% cooling peak demand increase for SEER 21
- 8% RL + 8% SL causes
  - 39.6% cooling peak demand increase for SEER 13
  - 33.4% cooling peak demand increase for SEER 21

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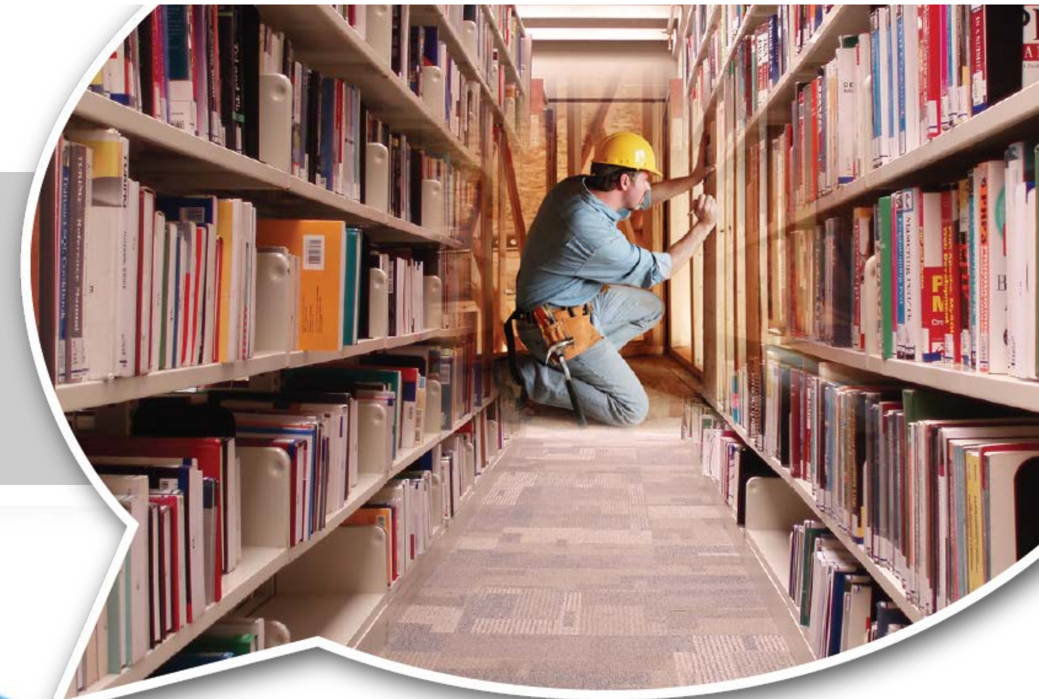

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