LOAD BASED TESTING OF HEAT PUMP(S)

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Westford Symposium on Building Science XXVI 2024/08/06

“BSC AI, Write a limerick about …”

- There once was a man named **Lstibure**k, Whose building science knowledge was sure. He wrote guides and papers, On vapor and capers, Making buildings safe, sound, and secure.

- There once was a man named **Straube**, Whose building science knowledge was probe. He wrote guides and papers, On vapor and capers, Making buildings safe, sound, and snobe.

Snobe: one who tends to rebuff, avoid, or ignore those regarded as inferior … do buildings do this???

And…

Write a limerick about Betsy Pettit

There once was an architect named Betsy
Whose designs were always quite zesty.
She built homes with care, with energy to spare
Making each one a cozy nesty

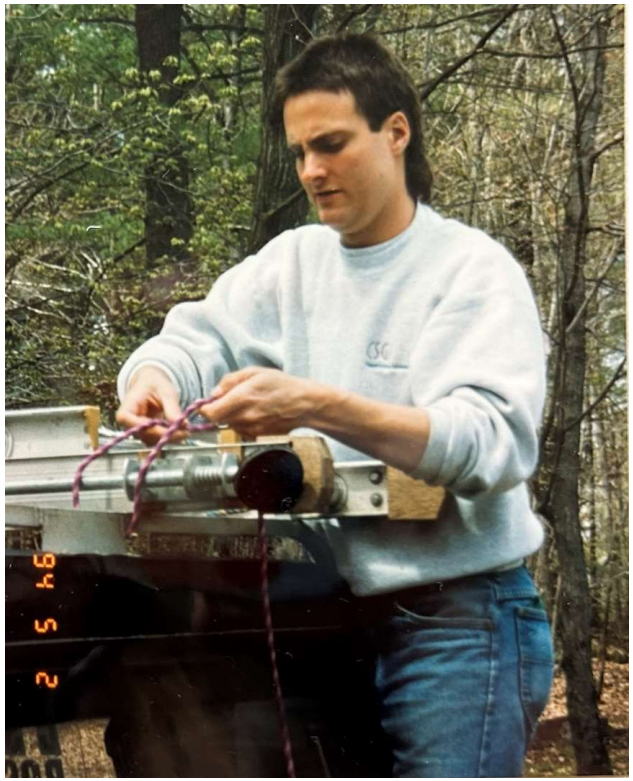
Outline

- Residential air source heat pumps: brief history and context
- A look at conventional test and rating systems
- Load-based heat pump testing and rating
  - Where we've been, where we're going
- A few tips to stay out of trouble with heat pumps

Summer camp "numbers", personally

- This year's Symposium is significant for me in a few ways:
  - **60** revolutions around the sun….34 involved with buildings
  - **20th** time at summer camp (2002)
  - **10** miles from the house where I grew up (5 years…)
  - **10** years since last time I presented at camp
  - **5th** year playing in the band (in person)
  - **5th** electric guitar
  - **1st** time to express in public
  - **10^6** **thanks to Betsy and Joe !!**

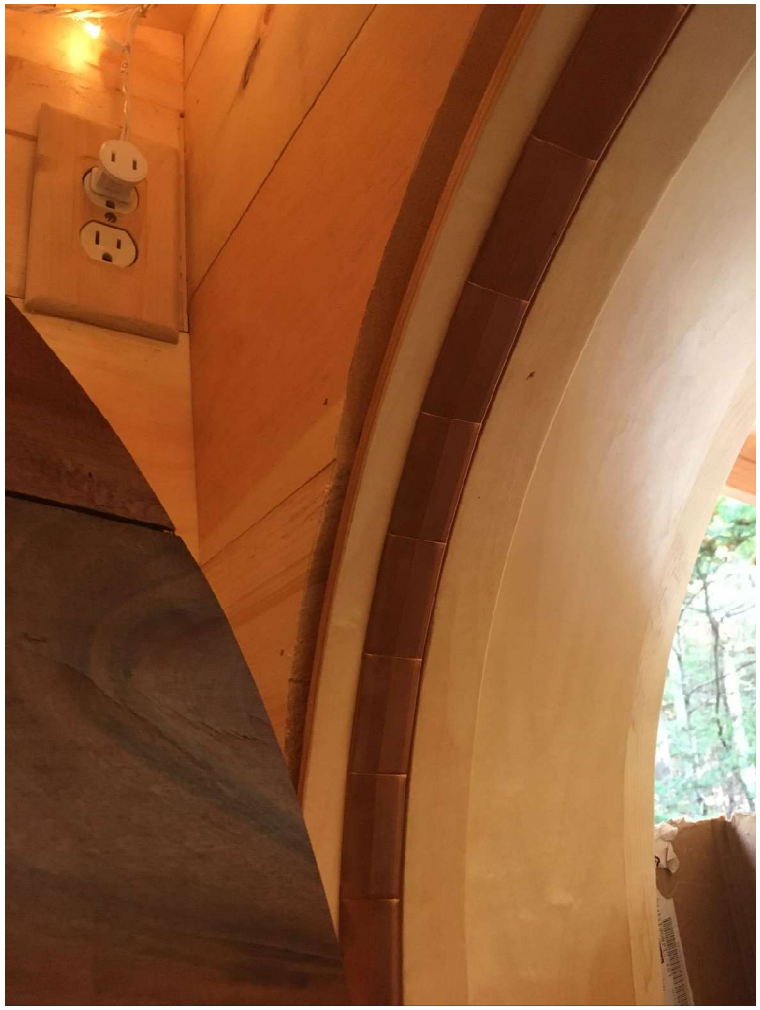
1994



2024

2020


CONCRETE
MIX



...and no mice!

Some stuff Joe has taught ~~me~~ us

- Drain the rain on the plane
- If you want to save cash, flash
- To control the air, you must contain the air
- Don't do stupid stuff
- Thermodynamic rules: can't win, can't break even, no free lunch…
- Dense pack cellulose isn't safe in IECC CZ5+

Good judgment comes from experience. Experience comes from bad judgment.

Some stuff Joe has taught ~~me~~ us

- Drain the rain on the plane
- If you want to save cash, flash
- To control the air, you must contain the air
- Don't do stupid stuff
- Thermodynamic rules: can't win, can't break even, no free lunch…
- Dense pack cellulose isn't safe in IECC CZ5+
- And… **watch what you tell people**

Heat Pumps

- I am VERY tired of people saying "Heat pumps …
  - … don't have enough capacity in cold weather"
  - … deliver uncomfortably cool air in cold weather"
  - … need 100% backup heat source in any climate"
  - … have poor efficiency in cold weather, might as well use gas"

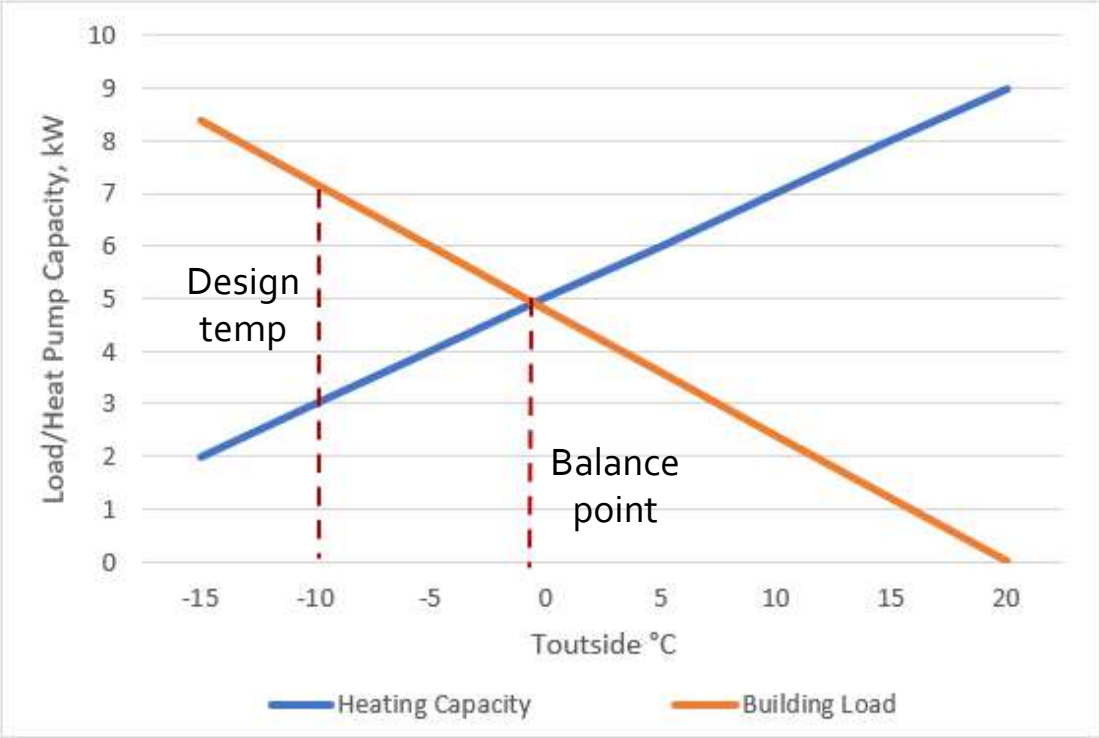
My first heat pump experiences

- Trying to seal ducts: badly installed ducted units in 1980s condos
  - Duct leakage (incl. building cavities as ducts = attic, crawlspace)
  - Undersized ducts, low air flow
  - Poorly charged, not maintained
- In winter, resistance heat compensates – hides performance problems
  - $$$$$$ operating cost

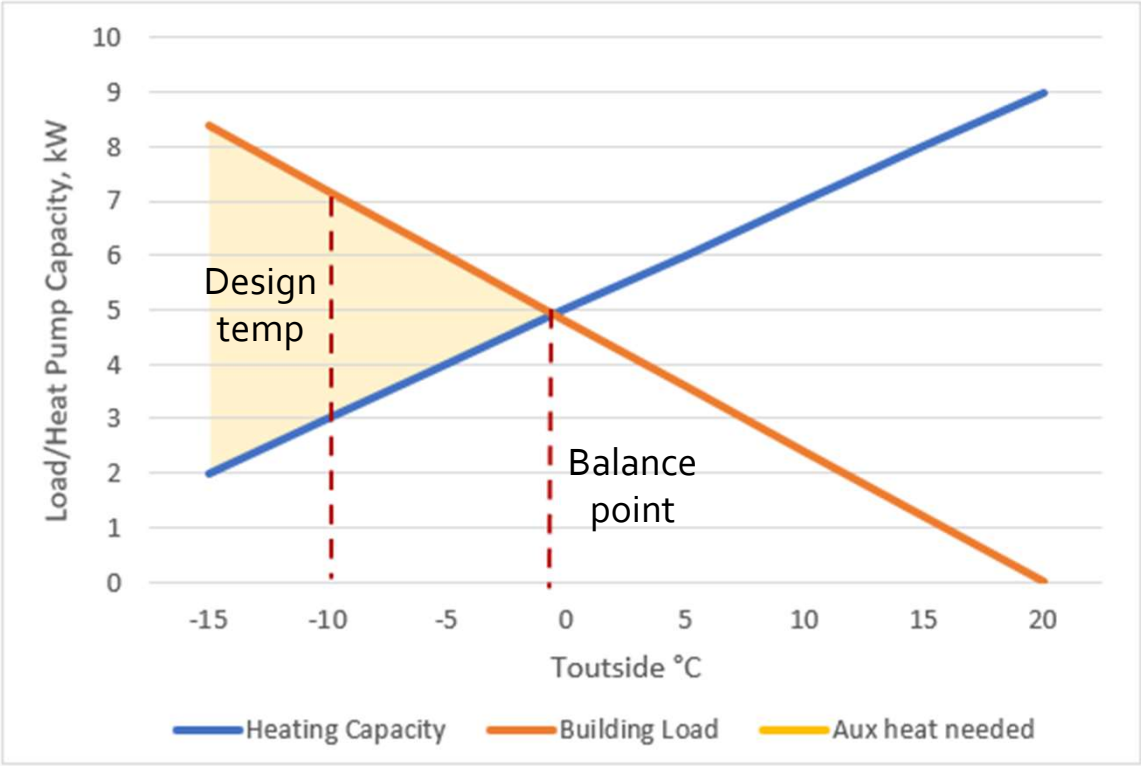
Heat pumps ~~– rules of thumb~~ *outdated*

- Size for cooling, let auxiliary heat make up the difference
  - Auxiliary heat = giant toaster in supply duct
- Or design for a balance point (e.g. 30°F)
  - Because "heat pumps don't have much/enough/any output below freezing"
- Always depend on a backup heating source
  - Aux electric or gas, for at least 100% of the design heating load

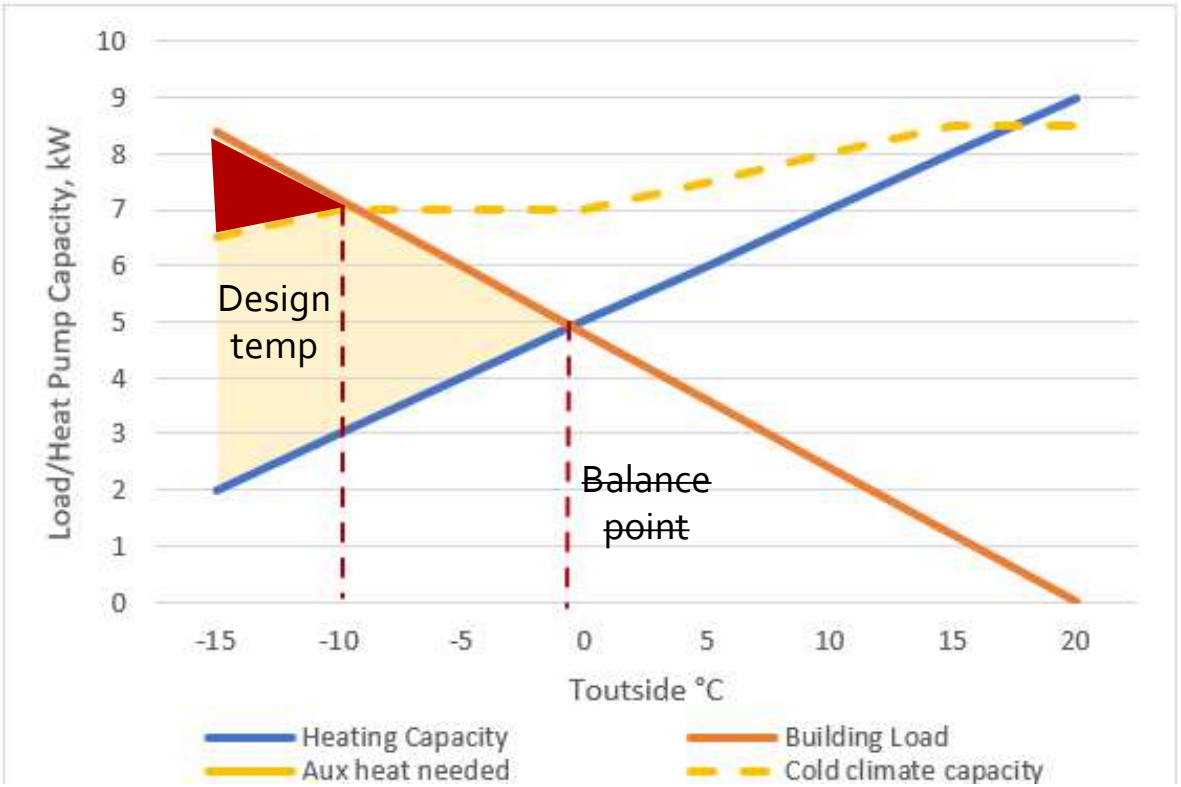
Auxiliary heat balance point diagram



Auxiliary heat – conventional heat pump



Cold climate heat pump



Residential HVAC – in the code

- Design requirements in the IRC and IECC:
- Heating and cooling load calculations – ACCA Manual J
  - Roughly 20-30% margin of safety built into the procedure
  - Users often add another 50%-100% on purpose (and by accident)
- Sizing equipment - ACCA Manual S (2014)
  - Variable speed heat pumps sized to cooling load, regardless of climate or customer needs
- **New** ACCA Manual S:
  - Has provisions to size variable speed ASHPs to 100% of heating load
  - Requires active dehumidification (if you're not in a dry climate) or equipment that has adequate latent capacity *at low speed*
- **The 2024 IRC cites 2023 Manual S** (exception for multi- and variable speed)

A few terms

- Coefficient of Performance
  COP = delivered energy / electric input (dimensionless)
  - A COP of 1 = 100% efficiency
  - COP drops as temperature lift increases (capacity ↓, power ↑)
- Heating Season Performance Factor (*DOE rating* for heating)
  HSPF = delivered heat (Btu) / electric input (W)
  - So *conceptually* HSPF is a winter seasonal COP = HSPF / 3.41
- Seasonal Energy Efficiency Rating (*DOE rating* for cooling)

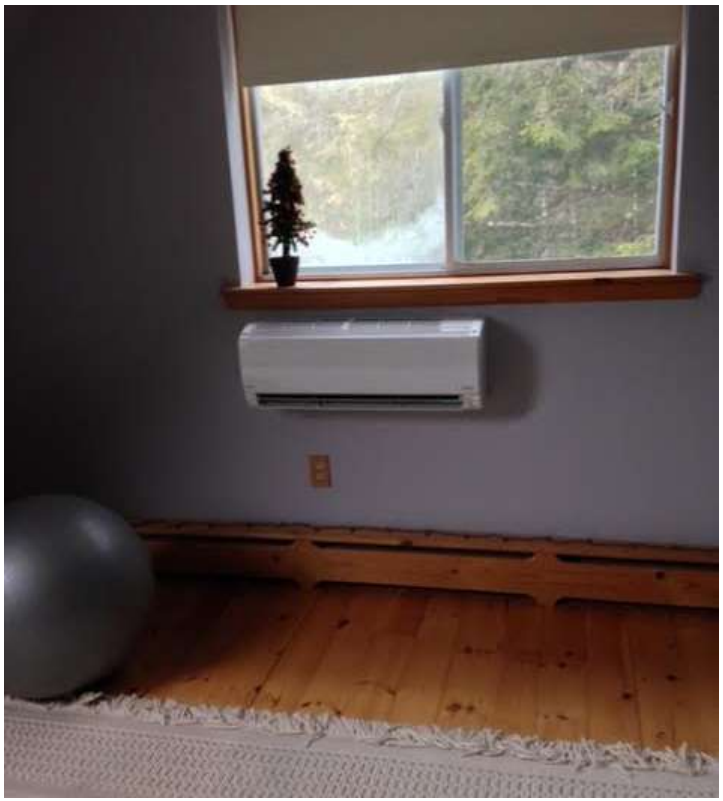
  SEER = extracted heat (Btu) / electric input (W)

My 2014 presentation in a nutshell

- I installed 2 heat pumps in my house in 2012
  - 2400 ft^2 on 3 levels, house has high R-values, had mediocre low-e windows, not very tight (1200 CFM50)
  - Design load was ~20,000 Btu/h at 0 °F
- 2 mini-splits (living room 1 zone, upstairs is 2-zone)
  - 3 ton nominal size total

1st Floor Unit - 12 HSPF

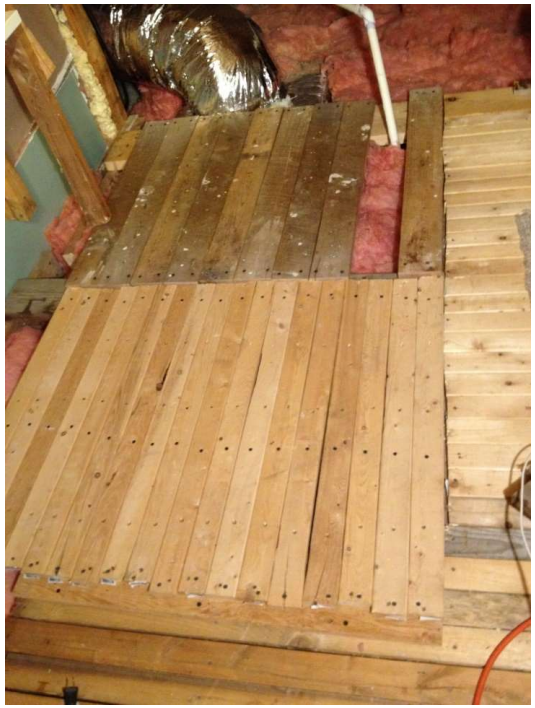
Attic room - 2nd floor



2-zone, 9 HSPF

(not “cold climate”)

2nd Floor Air Handler



Outdoor Unit

My 2014 presentation in a nutshell

- I installed 2 heat pumps in my house in 2012
  - 2400 ft² on 3 levels, house has high R-values, had mediocre low-e windows, not very tight
  - Design load was ~20,000 Btu/h at 0 °F
- 2 mini-splits (living room 1 zone, upstairs is 2-zone)
  - 3 ton nominal size total
- Measured COP ~ 2.8
- Plenty of capacity below 0 °F (rated at 5 °F, works below -20)

Modern cold-climate heat pumps

- Variable speed
- Much higher capacity in colder weather
  - Warmer air delivery, higher efficiency, little or no aux heat
  - All these are improving over time
- Despite outdated myths, advocates can be far too optimistic:
  - Assume higher tier of HSPF ratings of 12-13 =

  COPs close to 4, with no reality check (2.3-2.4 typical, 3 is good)
  - Not all installations are ideal
  - HSPF is reported for Region IV (not as cold as IECC Cz 5-8)
  - The HSPF rating methodology is too optimistic…

Heat pump ratings: HSPF2 and SEER2

- AHRI 210/240-2023 (2020) ~ (Appendix M1 of CFR 430B)
  - HSPF and SEER were changed slightly to be more "realistic"
    - HSPF2 and SEER2 are current rating standards
    - Increasing duct static pressure requirement decreased the values
- All ratings are models, including efficiency ratings
  - HSPF and SEER use bin model and a bunch of test results
- "All models are wrong, but some of them are useful"
  - George Box

HSPF test points vs load line

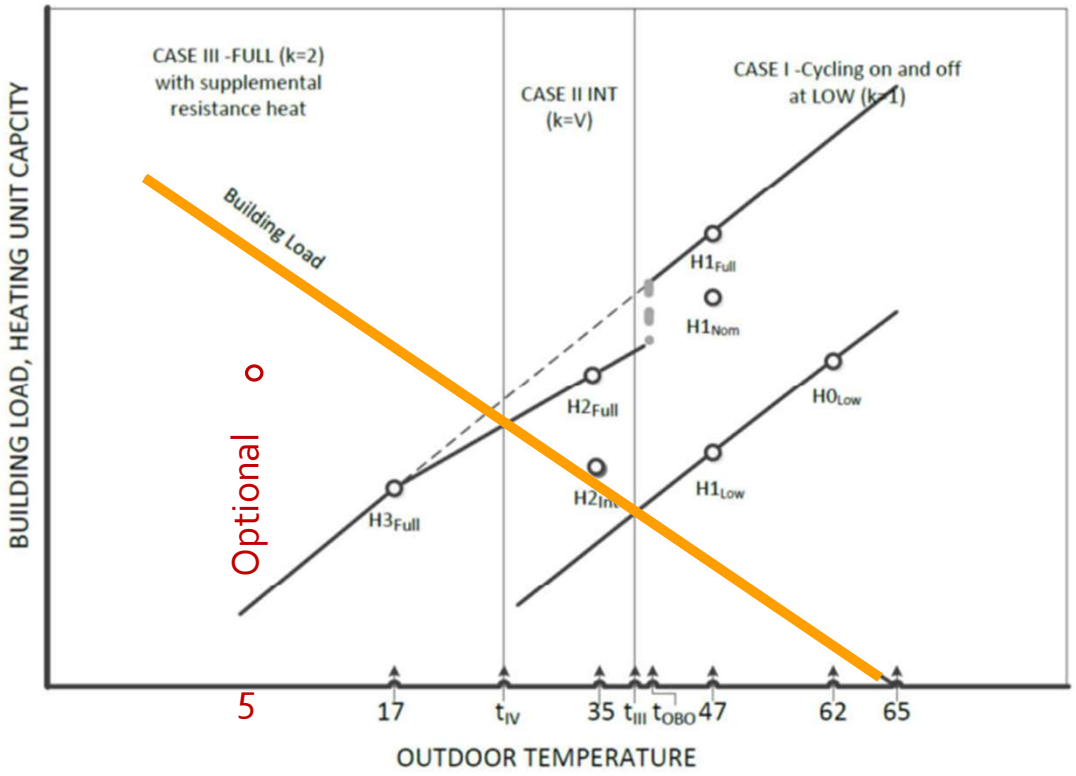


Figure 9. Schematic of a Variable capacity Heat Pump Operation in Heating Mode

- All these tests are conducted with fixed compressor & fan speeds
- Locked "test mode" – not accessible to users
- Good for repeatability
- ~80 equations interpolate/extrapolate test results to load line

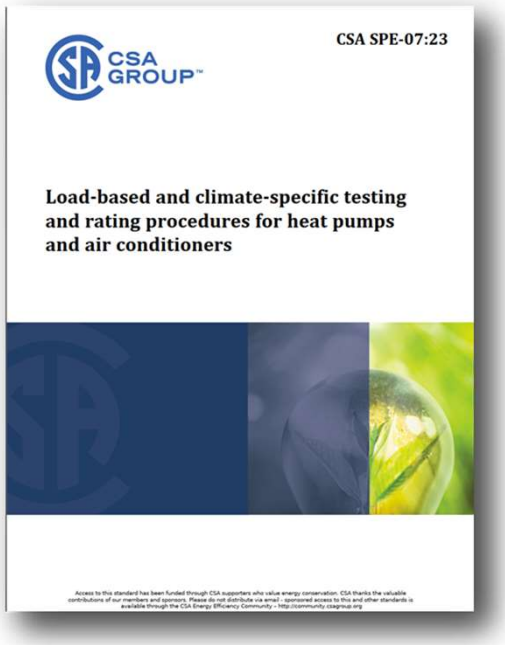
So how wrong is this model?

Background – Load based testing

- Load based testing of heat pumps
  - Emerging alternate to traditional test methods that use fixed compressor speeds for variable-capacity (VC) systems
  - Fixed-speed tests don't reflect performance well
  - Worldwide development of similar approaches
    - Research: BAM (Germany), Waseda U (Japan), CEPT U (India), others
    - International Energy Agency (IEA), International Organization for Standardization (ISO) getting involved in load-based testing
  - Canadian Standards Association (CSA) published first in 2019

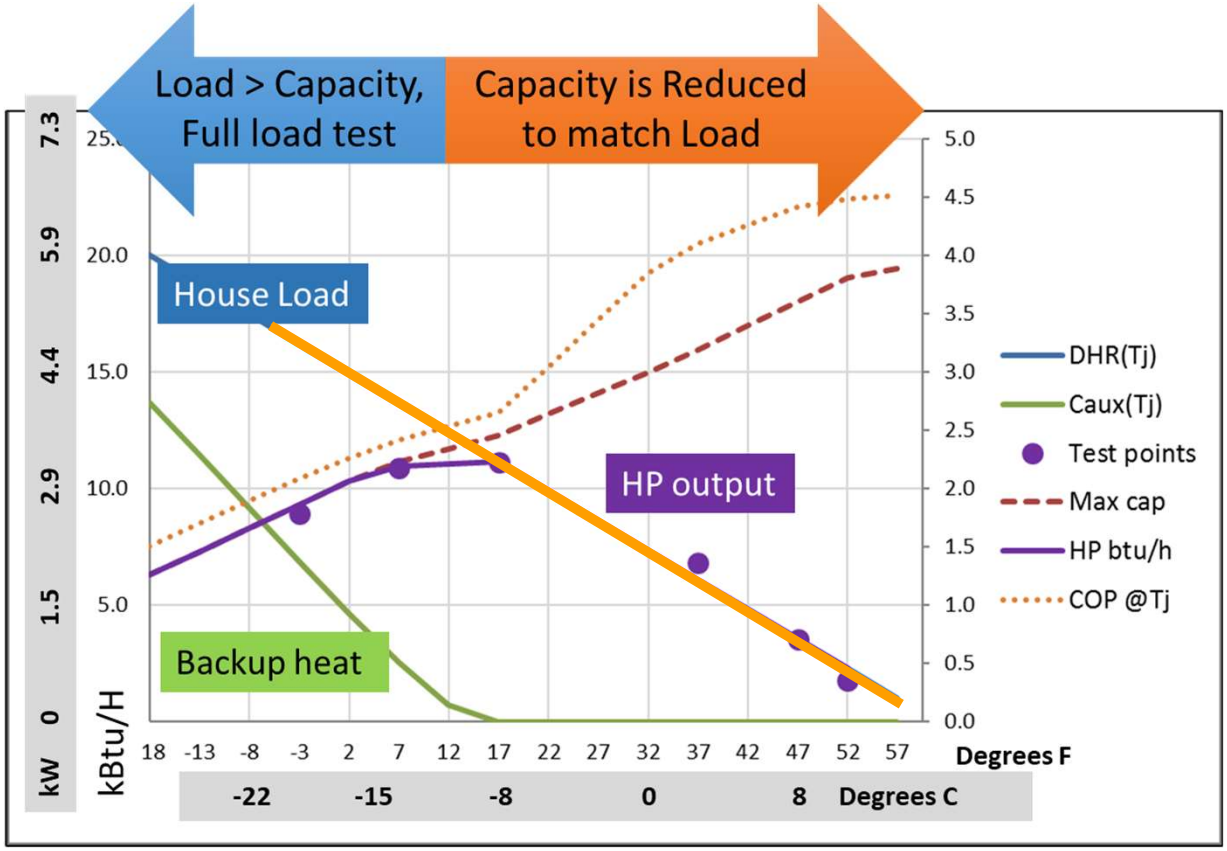
SPE07-23

- Applies a simulated "virtual" building load to approximate realistic performance
  - Magnitude of load is based on outdoor conditions
  - **Uses native controls**
- Virtual building model sets indoor condition
  - Adjusts in real time based on unit capacity
  - Drives unit's controls to maintain setpoint



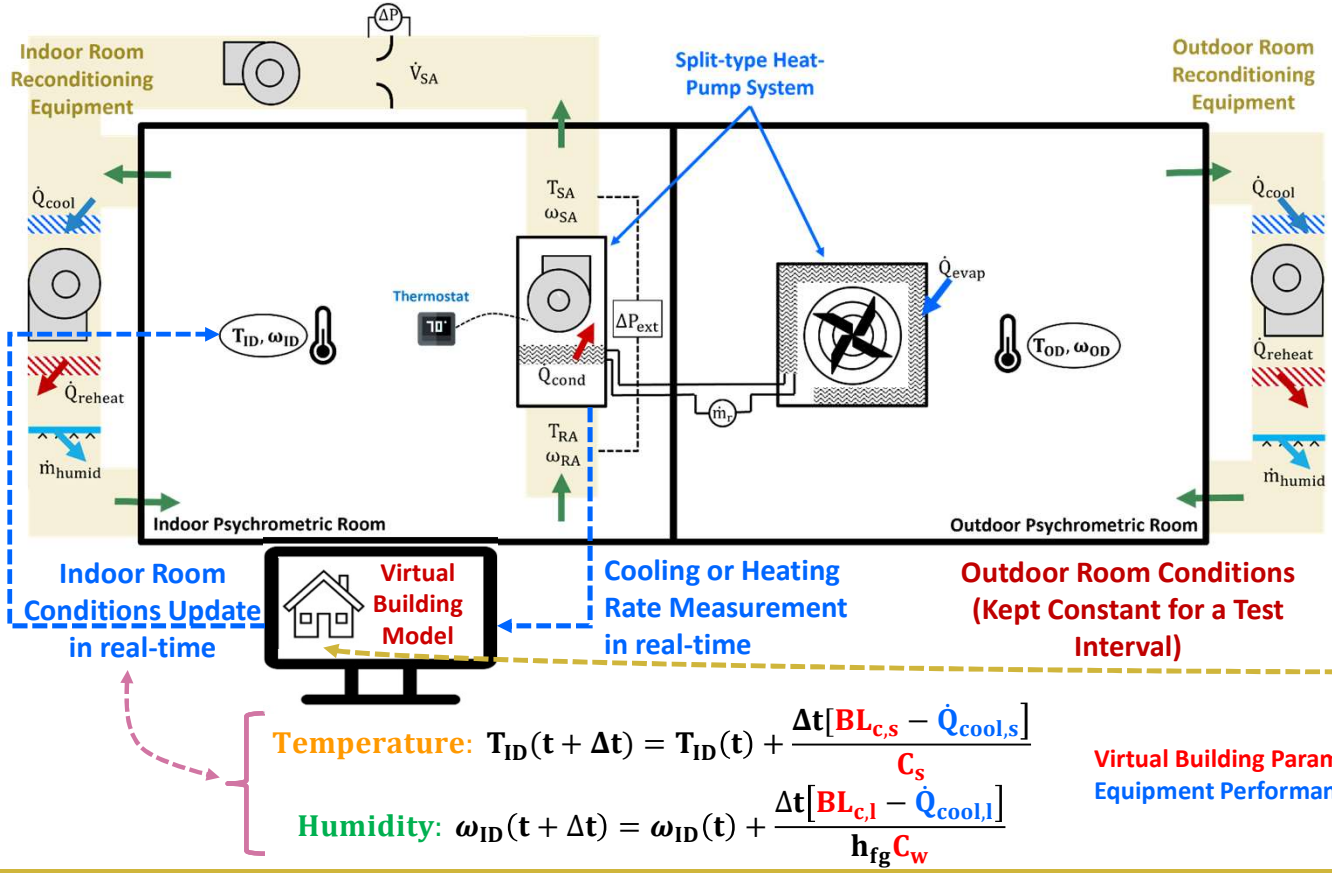
SCOPE: <=19 kW (65k Btu/h) single zone air-to-air

SPE07-23 Concept (heating)

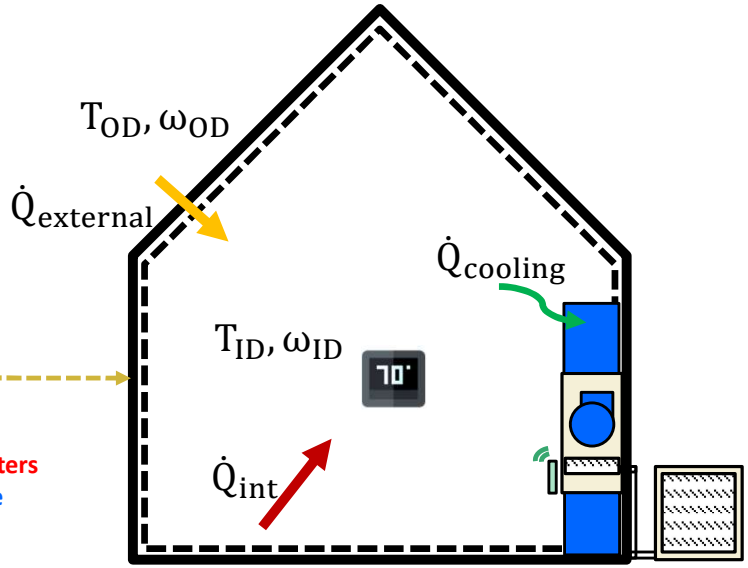


Load-Based Testing Methodology

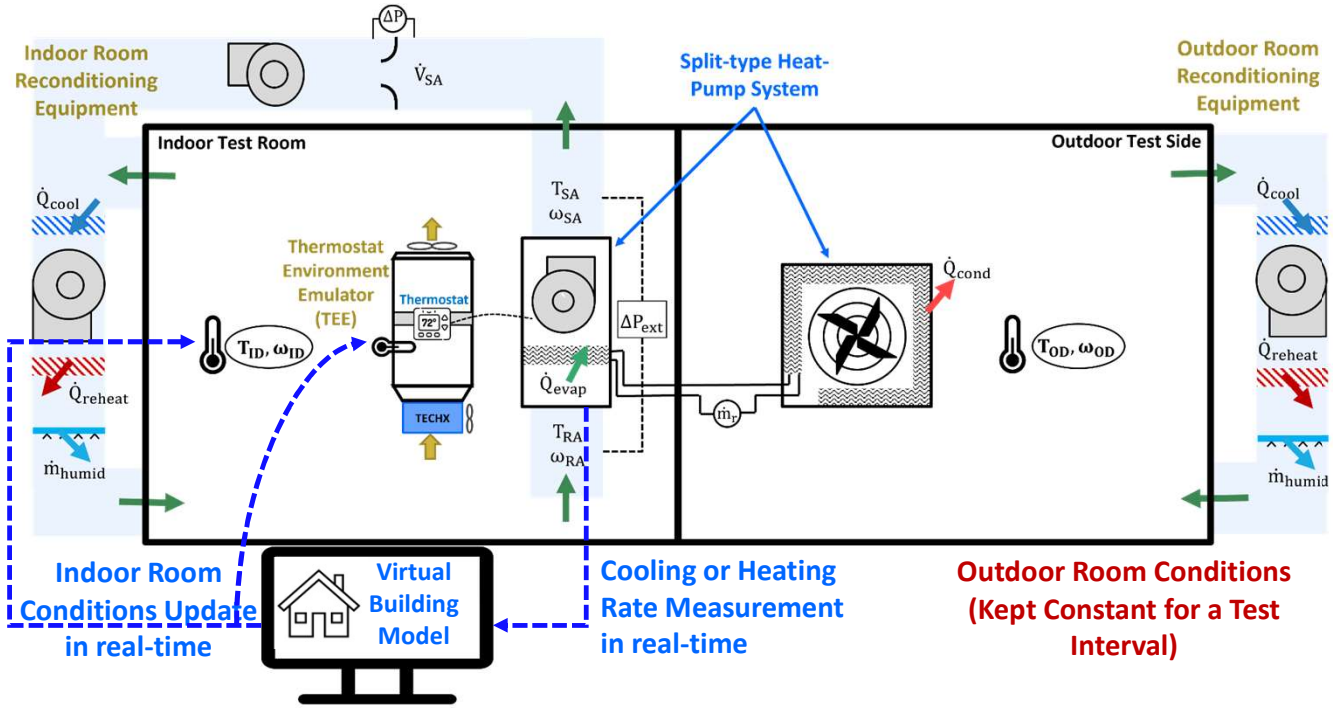
Emulate the response of a representative building load and dynamics to a test unit with its controls and thermostat utilizing a virtual building model

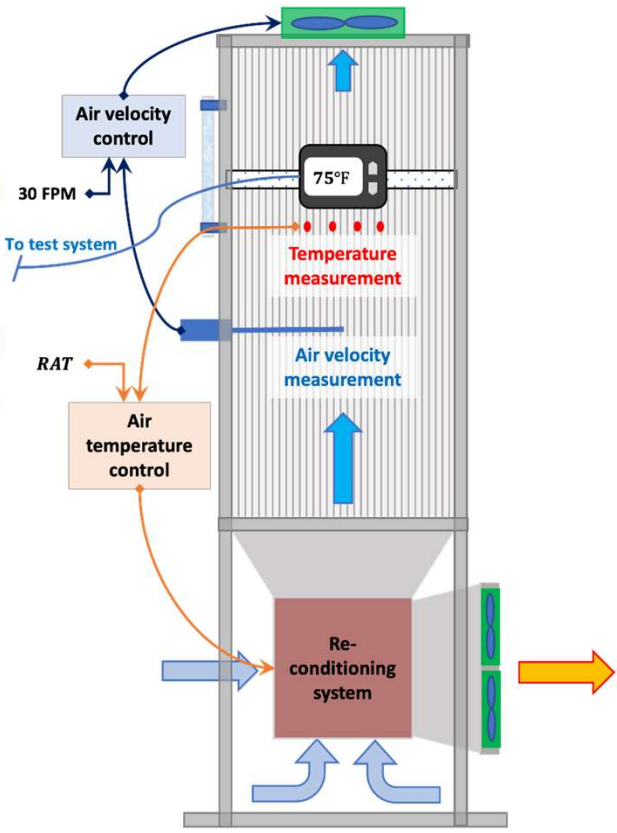


- Enables dynamic performance evaluation of a heat pump with its integrated controls and thermostat coupled to a representative building load and dynamics.



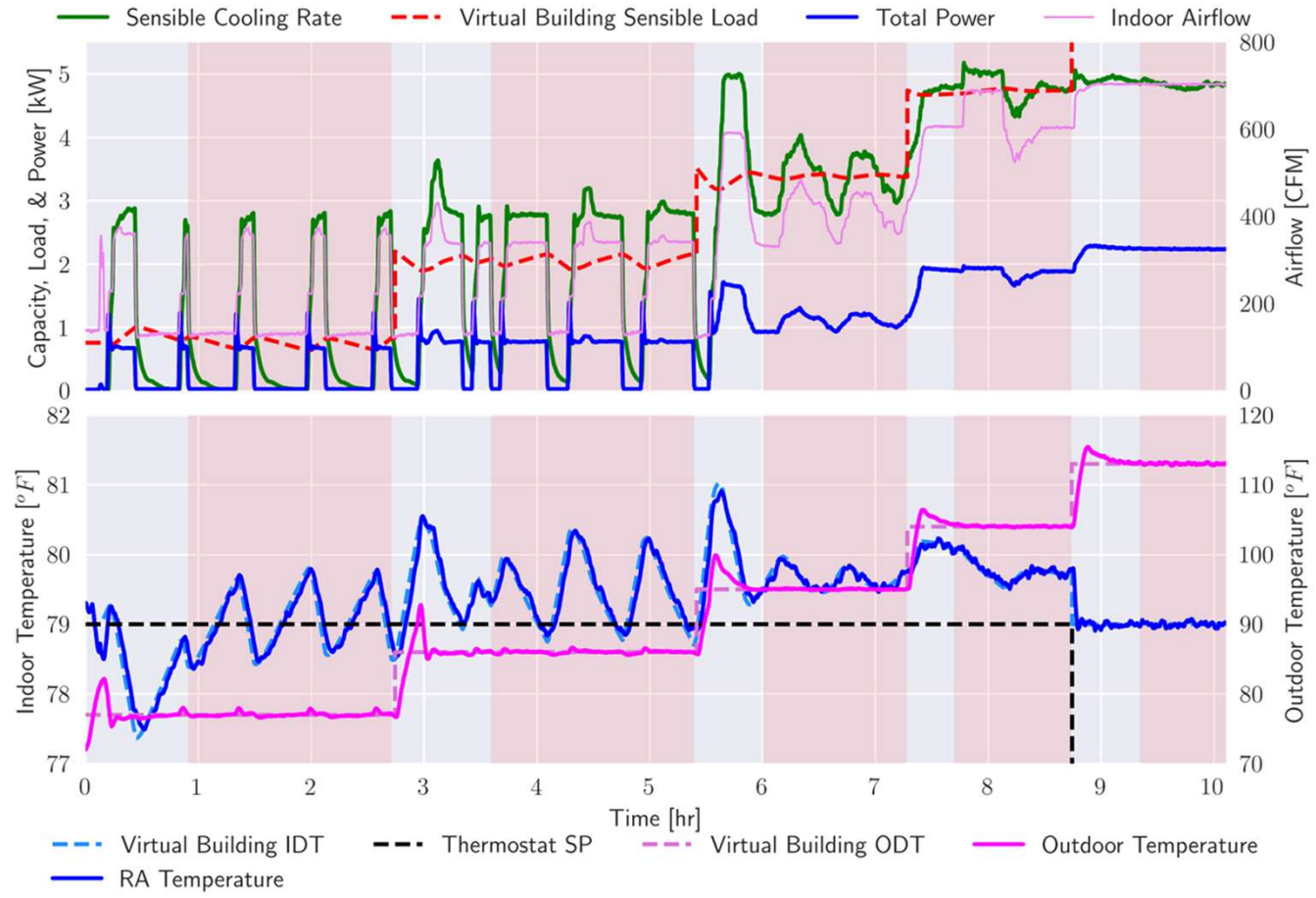
Thermostat Environment Emulator (TEE)





- Thermostat environment emulator (TEE) to provide representative and reproducible conditions to the thermostat
  - Can dynamically control the thermostat inlet air temperature to the virtual building temperature setpoint as well as velocity over the thermostat

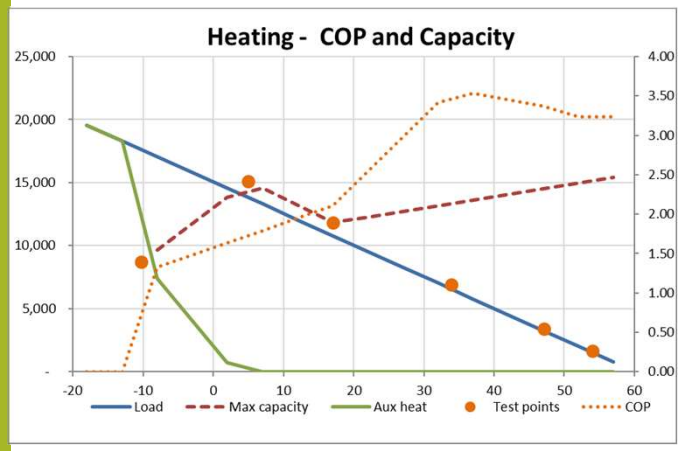
Load Based Test Results: Cooling Dry Coil



- Cooling Dry Coil Load Based Test
  - Indoor Target (Thermostat Setpoint): 79°F
- Unit Behavior
  - Cycling (77°F and 86°F)
  - Variable Speed (95°F and 104°F)
  - Full Load (113°F)
- RA temperature tracks virtual building IDT well
- Indoor temperature maintained near the thermostat setpoint
- Convergence period highlighted

Seasonal COPs for 8 climates:

Lab Data
COP & Capacity Curves



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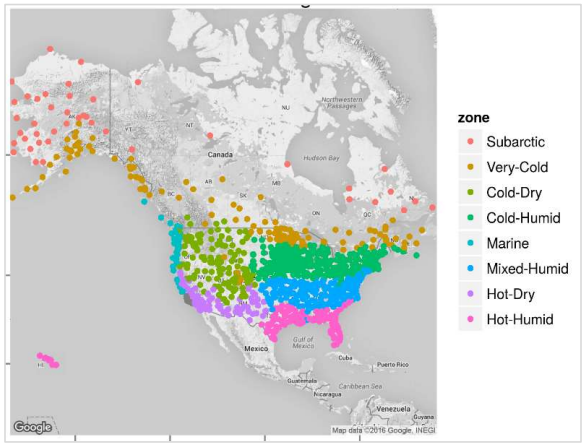
8 Climate Models
(bin-hour data)



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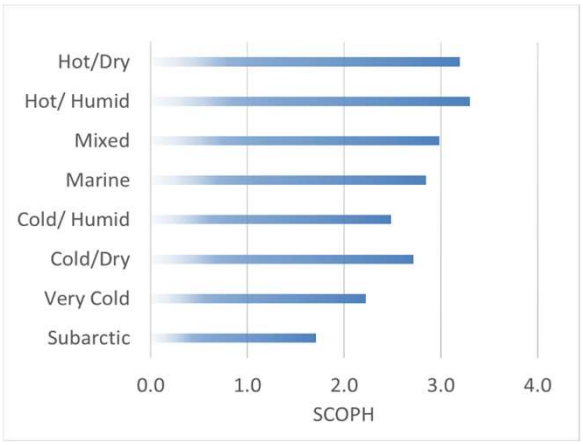
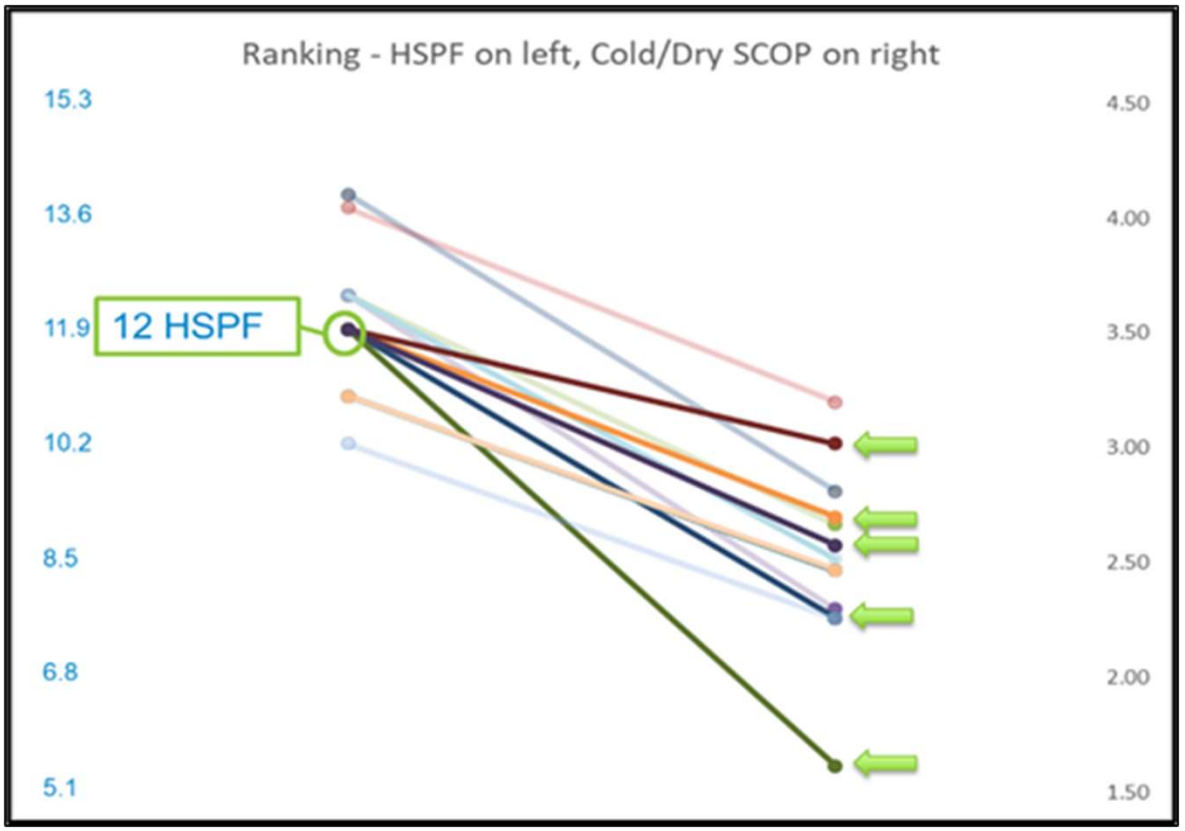
Climate Specific
Seasonal COP values



What we learned from testing 22 heat pumps in 2019-2021

Lab results, Heating: – HSPF and SCOP

AHRI rating



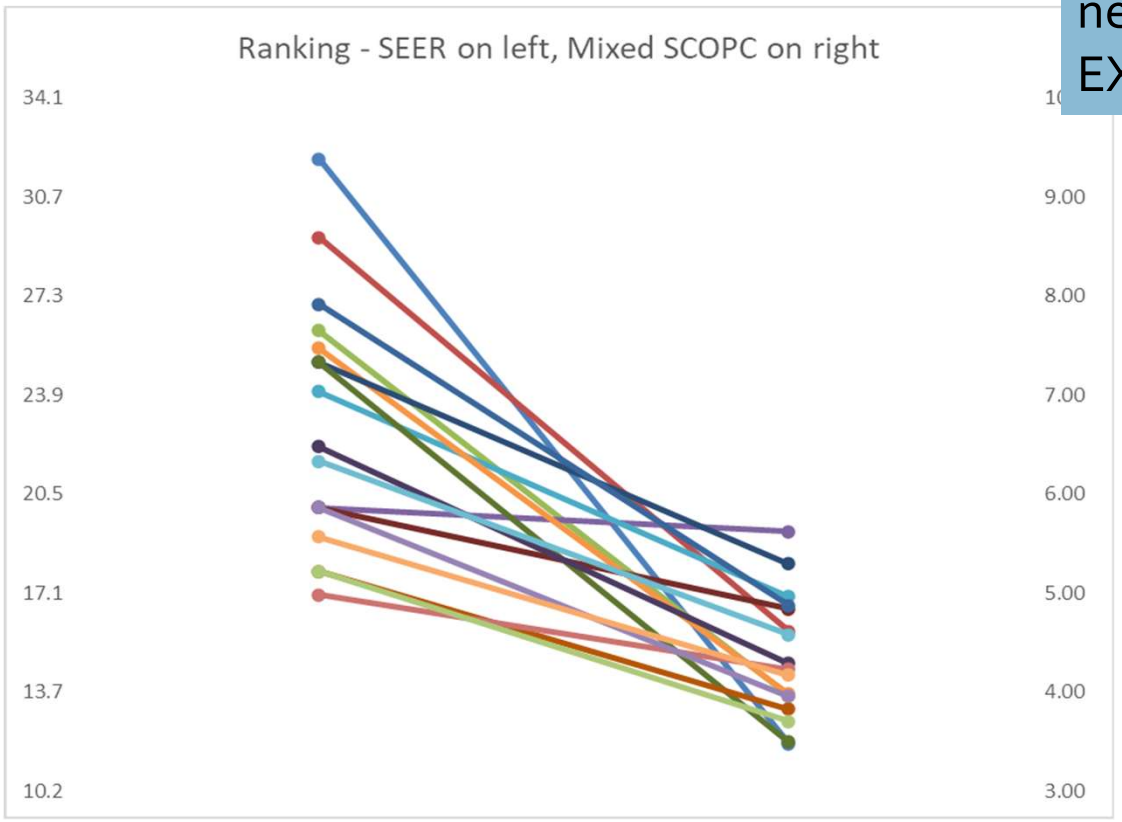
EXP07:19 SCOP

Five units with 12 HSPF are highlighted; EXP07 results vary widely

Cooling: SEER and SCOP

Results published in "interim report" neea.org search for EXP07

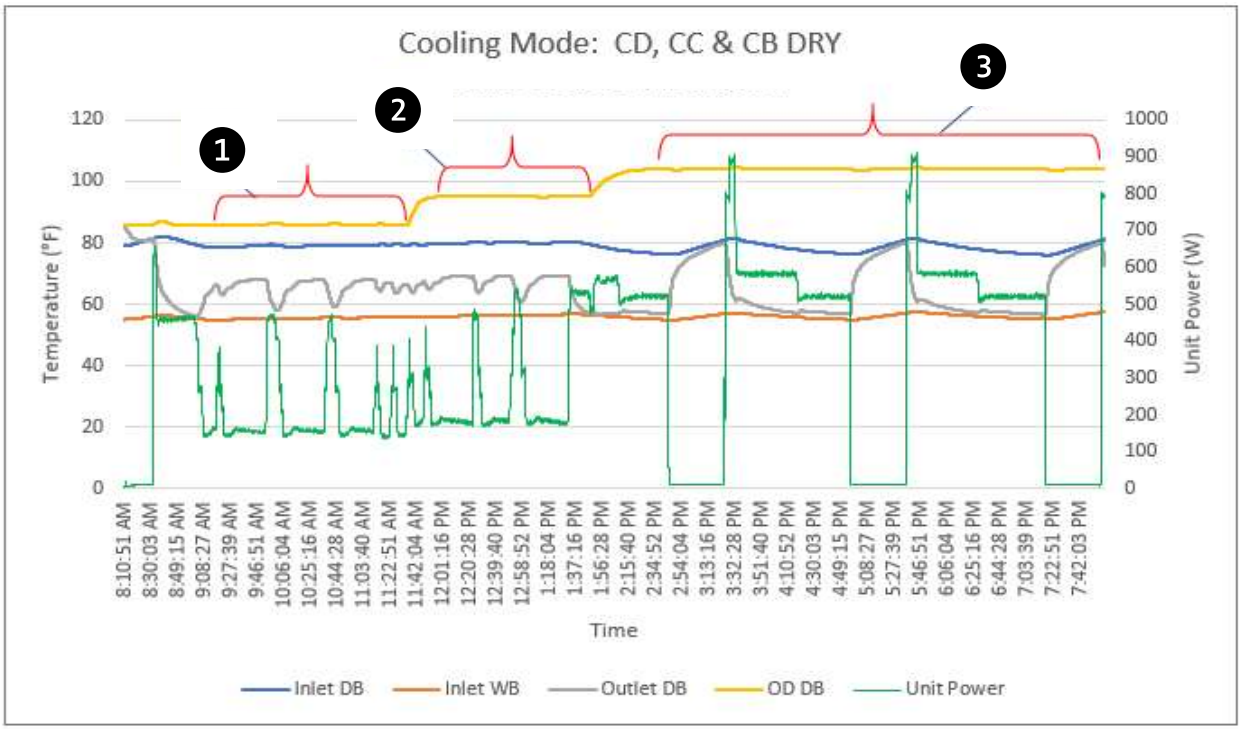
AHRI rating



EXP07:19 SCOP

Rank order varies even more than for heating

Anomalies during load-based testing:



❶ & ❷ show Modulating/ cycling

❸ has higher load, presumably should modulate but cycles **off** repeatedly

Cooling convergence is typically rapid

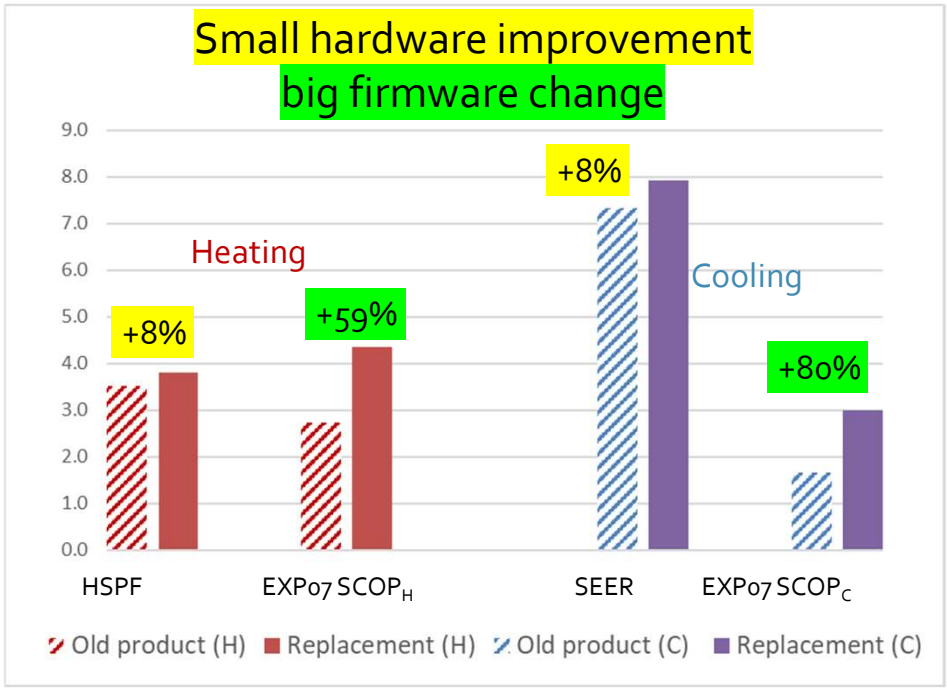
Heating convergence complicated by defrost cycles

Impact of a Product Update

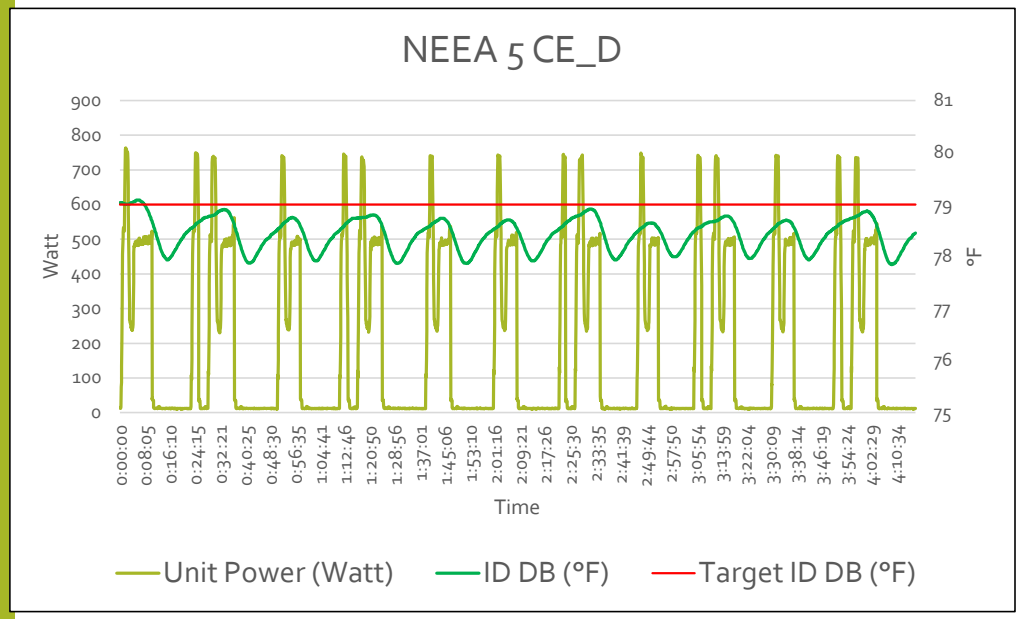
Lab test of same manufacturer - newer version of same product sent for testing

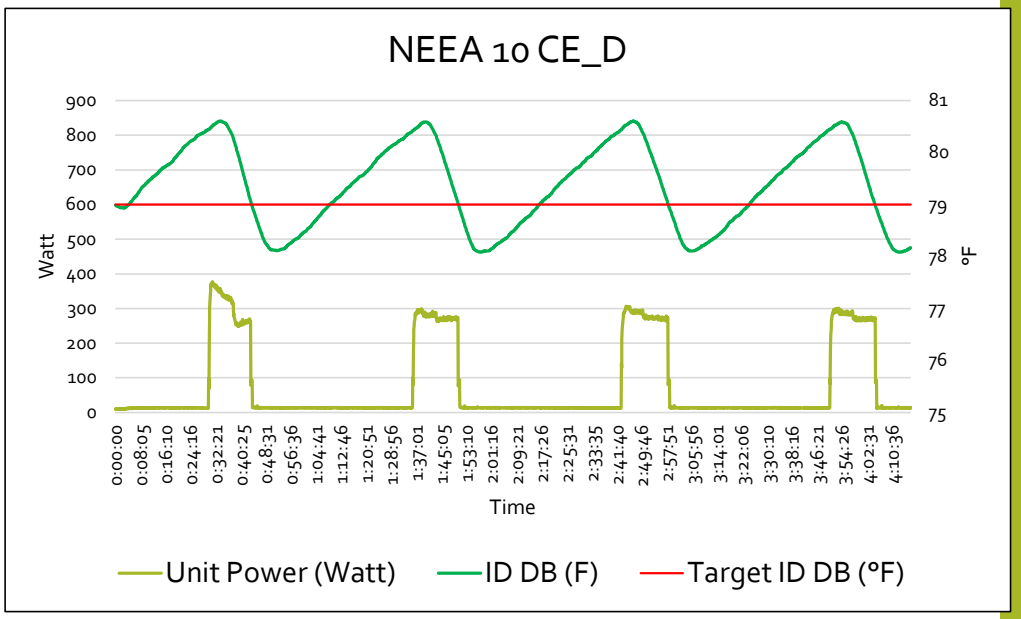
- HSPF and SEER ratings show moderate mechanical improvements (8%)
- EXP07 SCOP ratings reveals dramatic change in controls firmware

This example shows the importance of testing machines under their own control algorithm(s).



- **NEEA 5 and NEEA 10 Comparison**
- Test Interval: Dry Cooling (lowest load condition) THE SAME left and right





COP = 2.83
Rapid, high-power cycling

COP = 5.23
Low-power cycling, longer cycles

Conclusions about EXP07:19

- Very different rank order than HSPF and SEER
  - Suggests that HSPF/SEER are poor indicators of performance
  - Native controls / firmware significantly affects performance
  - Improvements should be reflected in SPE07 ratings and in field
- Load-based test appears to differentiate good performers
  - Provide better market signals, more realistic savings for programs
- Sources:
  - Interim report, plain language guide: neea.org (Search "EXP07")
  - Herrick Conference 2022 docs.lib.purdue.edu/iracc/ search 2022 proceedings for "Harley" and "Dhillon" **and 2024 when posted**

But is load-based testing really better?

- And if so, how much?
- 3 R's for testing/rating: Repeatable, Reproducible, Representative
  - 2020 reproducibility and repeatability study on 2019 EXP07:
    - Pretty good repeatability; reproducibility needed work
    - http://docs.lib.purdue.edu/iracc/2477/
  - This was not a surprise, being a novel approach
  - Revisions leading to SPE07-23 included many improvements
  - No HP test method has had field tests of **representativeness**

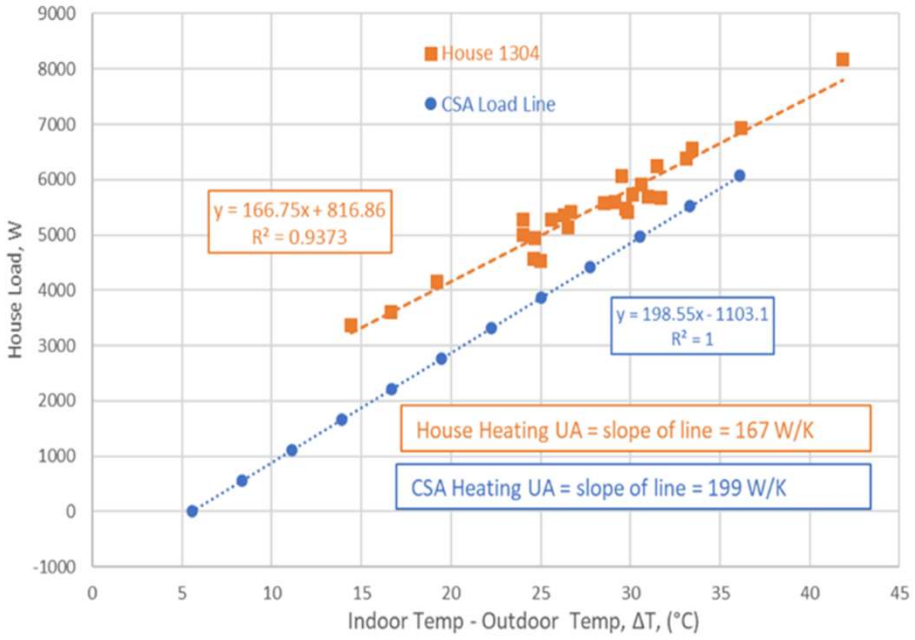
Representativeness Study (NEEP, DNV)

- This study is to validate rating methods with field performance
- Study objective: compare the measured data from field operation with two sets of lab tests:
  - *CSA SPE07-23 (load based)* vs *AHRI 210/240-2023 (2020) (fixed-speed)*
- Broadly speaking, we set out to test ***the test methods***
  - Not "test the products"

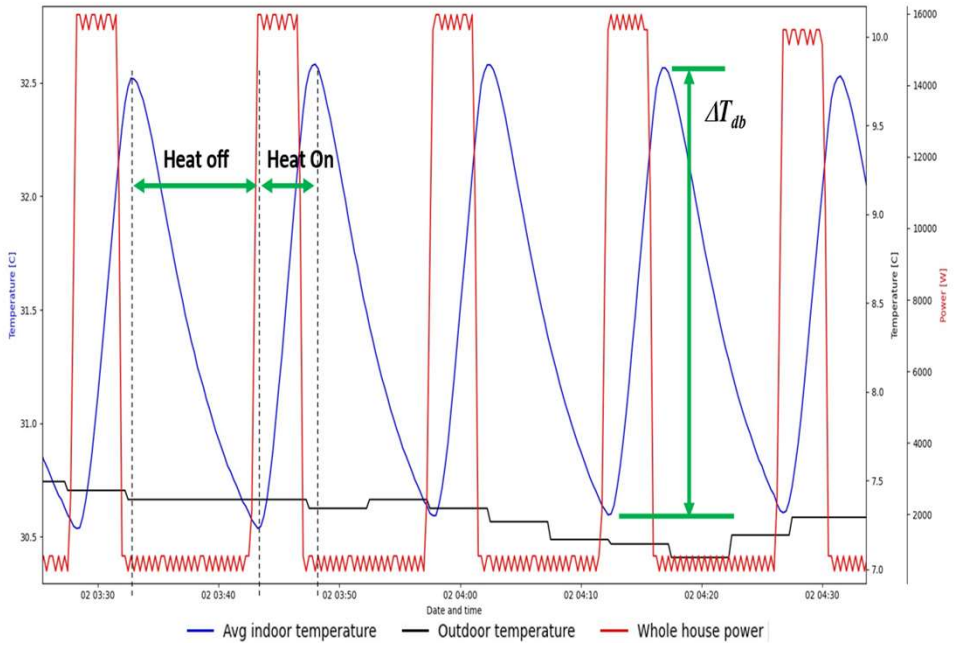
Phase 1 – Field study

- Lincoln, Nebraska Aug 2022 – March 2023
- 3 new, unoccupied mobile homes:
  - Same orientation
  - 1 ducted, 1 ductless in each house
  - Alternating units twice each week
  - Scheduled sensible / latent internal gains
- Prior to unit installation
  - Heating thermal load (UA) estimated using homes' electric furnaces
  - Shallow mass capacitance estimated using cycling rates of those electric furnaces

Load, thermal capacitance examples



Load vs. outdoor temperature



Cycling time constant and deadband

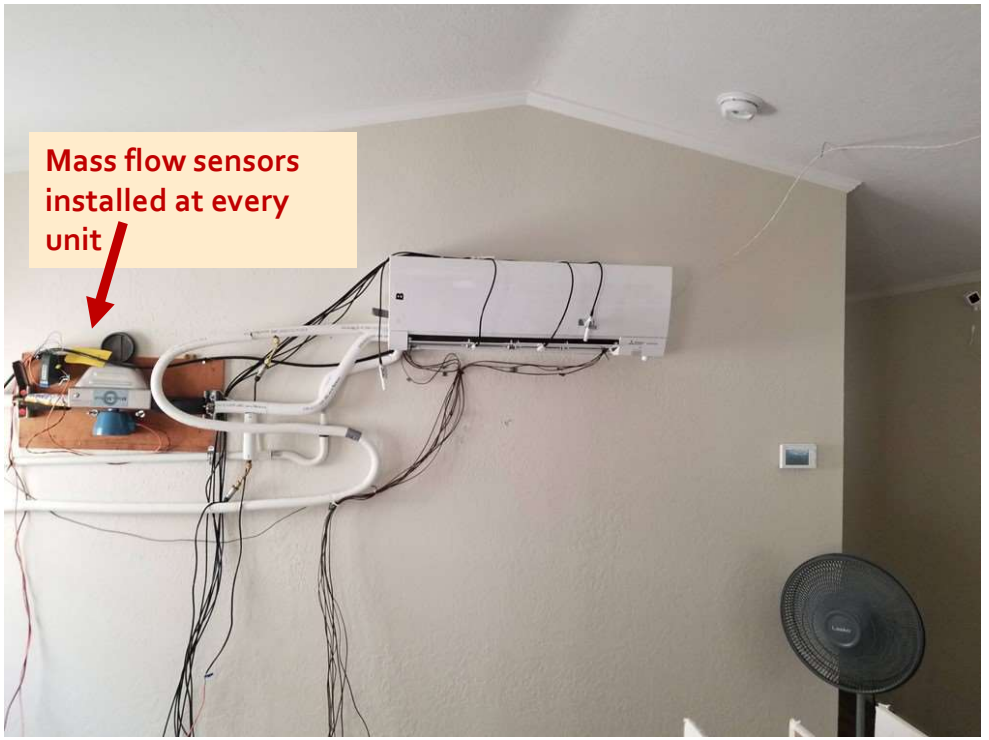
Adjustments made to homes

Steel window panels replaced some windows to increase load

Added drywall to increase mass capacitance

Instrumentation

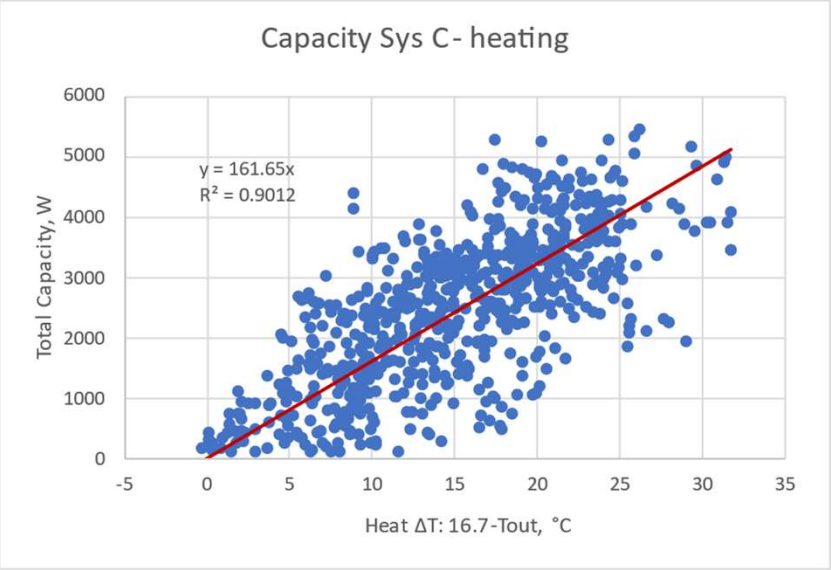
~100 measurement points/home

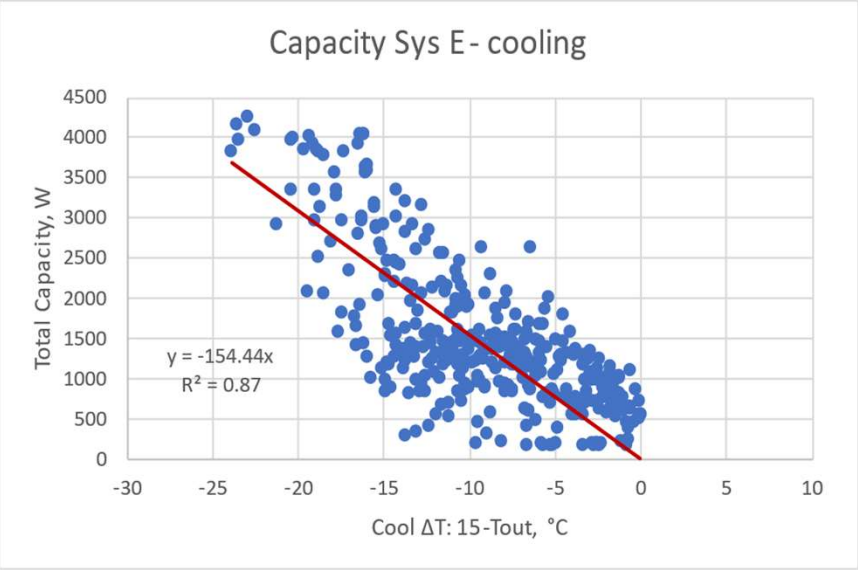


Ducted (L) and ductless (R) units installed

Load lines from field data to use in lab

To match field and lab conditions, load lines for SPE-07 testing were estimated using field data rather than "standard" SPE-07

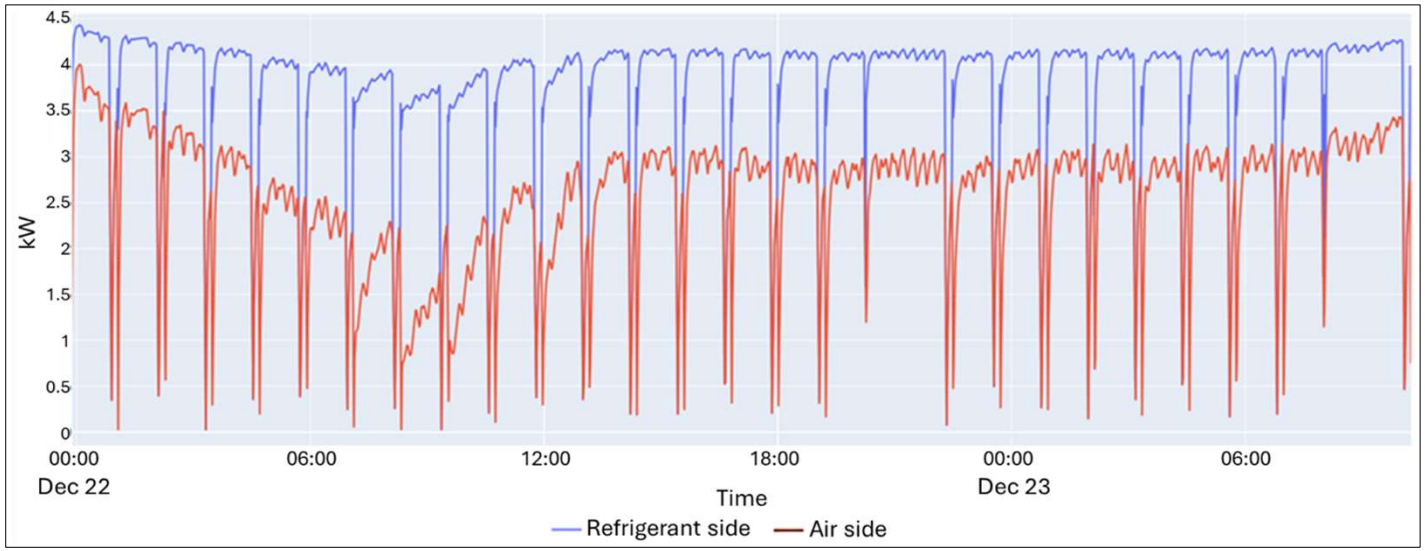




(AHRI 210-240 does not use load lines in testing)

Analysis process

- Air side measurements had low bias (common in field)
  - Used refrigerant-side capacity measurements where possible
  - Where not, air-side measurements adjusted based on regressions of good refrigerant periods to air side measurements).

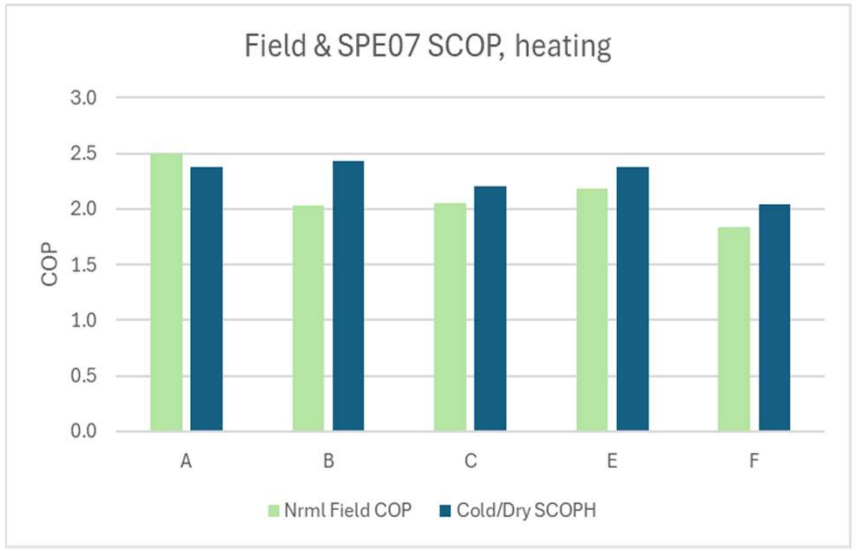


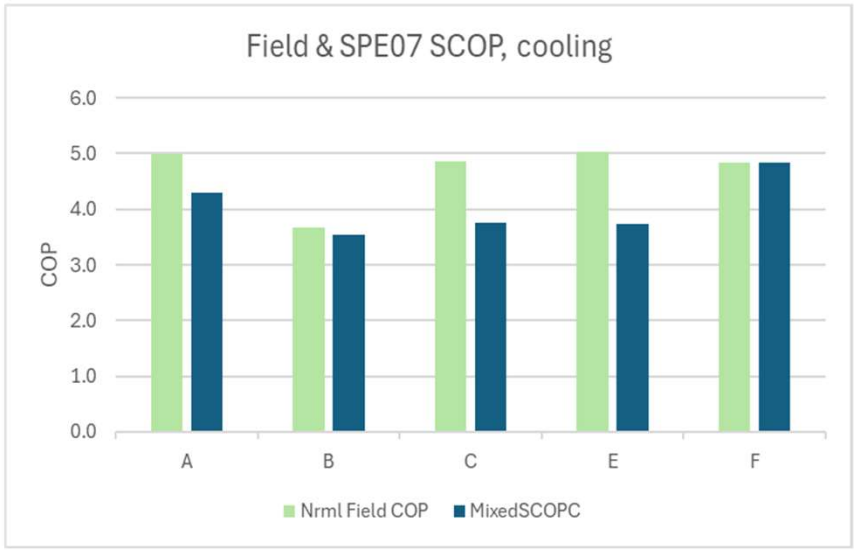
CSA ?

AHRI ?

Field vs. SPE07 results

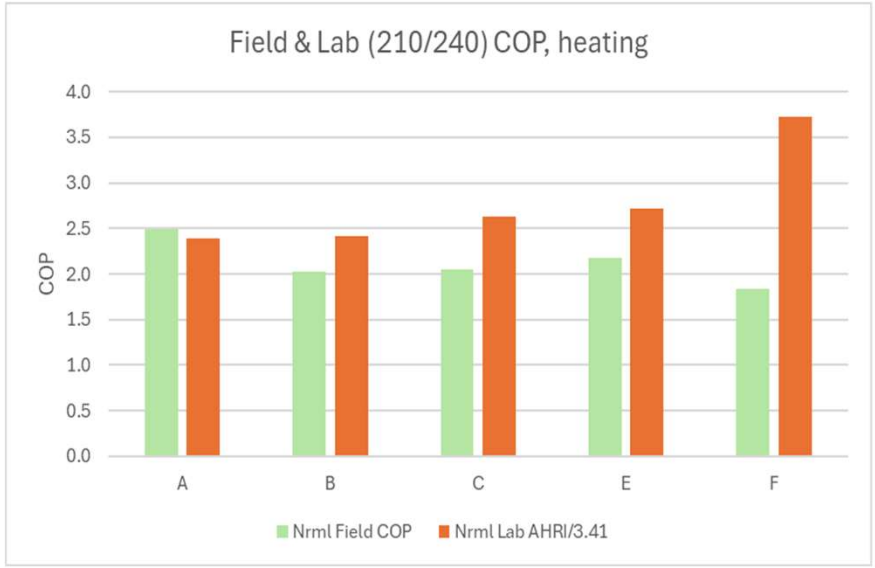
- Field data: normalized to SPE07 climates for comparison
- Heating: SPE07 Cold-Dry, Cooling: SPE07 Mixed-Humid
  - These are closest to the AHRI rating climate models
  - Heating: slight high bias, cooling: more noticeable low bias

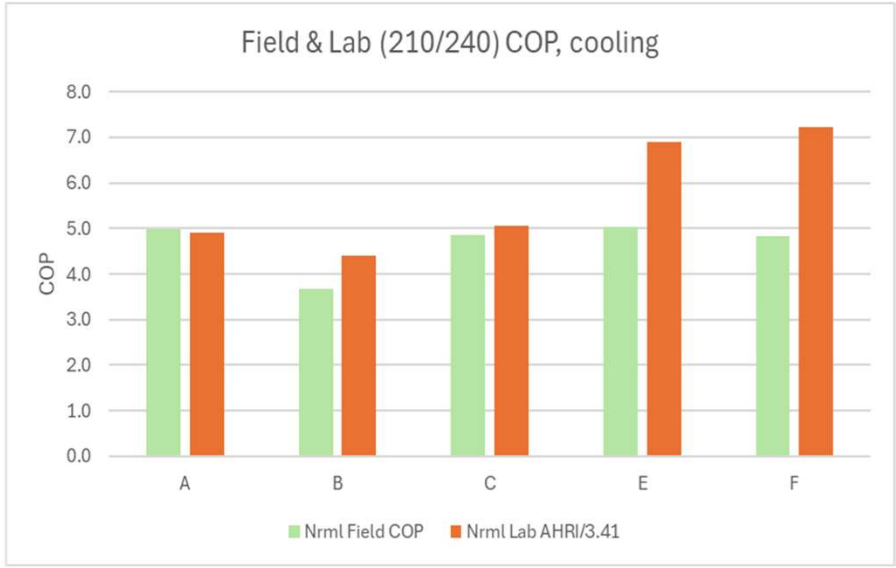




Field vs. AHRI test results

- AHRI test results were also normalized to the same two climates for fair comparison
- Mostly consistent high bias (except for unit A)

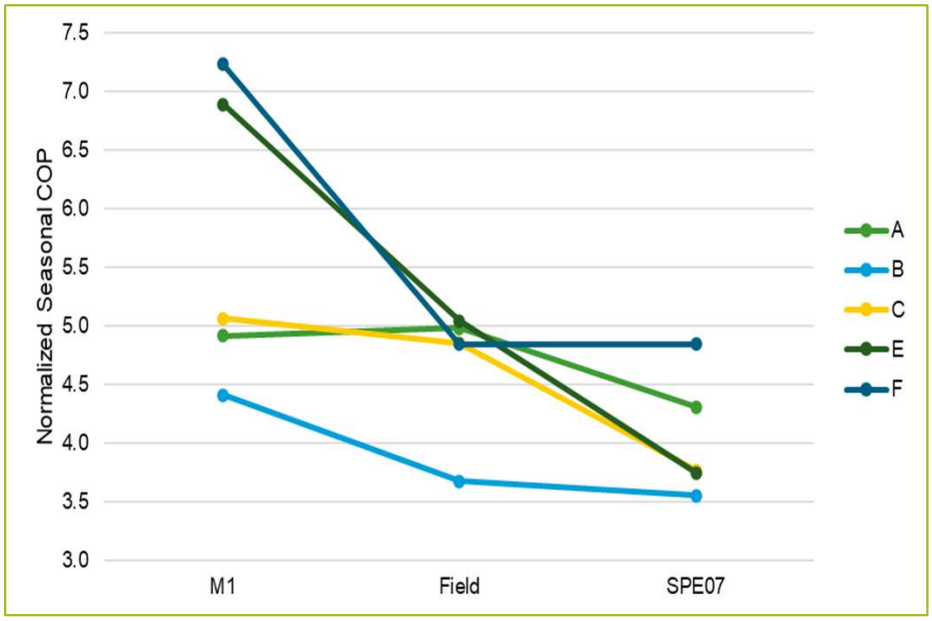




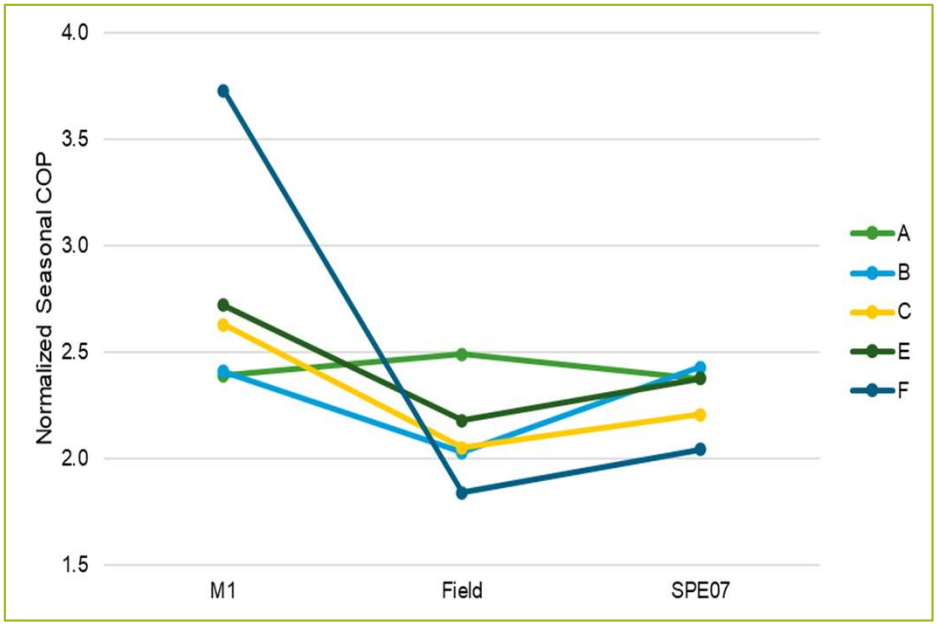
Visual of normalized values

- Rank order comparison

Cooling



Heating



Summary

- Valid data for 5 units (1 had multiple issues)
- Statistical summary of errors, but small sample size
  - Ducted vs. ductless differences (?)
- For all units: errors of M1 > than SPE07 (only < is ducted/cooling)

	Cooling RMSE		Heating RMSE		Cooling MAPE		Heating MAPE	
	SPE07	M1	SPE07	M1	SPE07	M1	SPE07	M1
Ducted n=3	0.74	0.45	0.26	0.40	13%	9%	11%	17%
Ductless n=2	0.92	2.14	0.20	1.39	13%	43%	10%	64%
Combined n=5	**0.82**	**1.40**	**0.24**	**0.93**	**13%**	**22%**	**10%**	**36%**

RMSE = root mean square error; MAPE = mean absolute percentage error

Policy context

AHRI/DOE 2023-present:

- Jan 2023 DOE issued RFI for proposed rule
  - Included several questions of interest on load-based testing
- By late spring, AHRI embarked on a project to update 210/240
  - 210/240 202x "short term"
    - Harmonize with Appendix M1, introduce some optional features
    - Introduce "controls verification procedure" (CVP)
  - AHRI 1600 "longer term"
    - Changes to metrics: "SCORE" and "SHORE" to include off-cycle energy
    - Other: defrost adjustments, airflow limits, bin model shift
    - Same CVP
- Draft standards were **completed by Sept 2023**, cited in **NOPR Feb '24**

New CVP-cooling

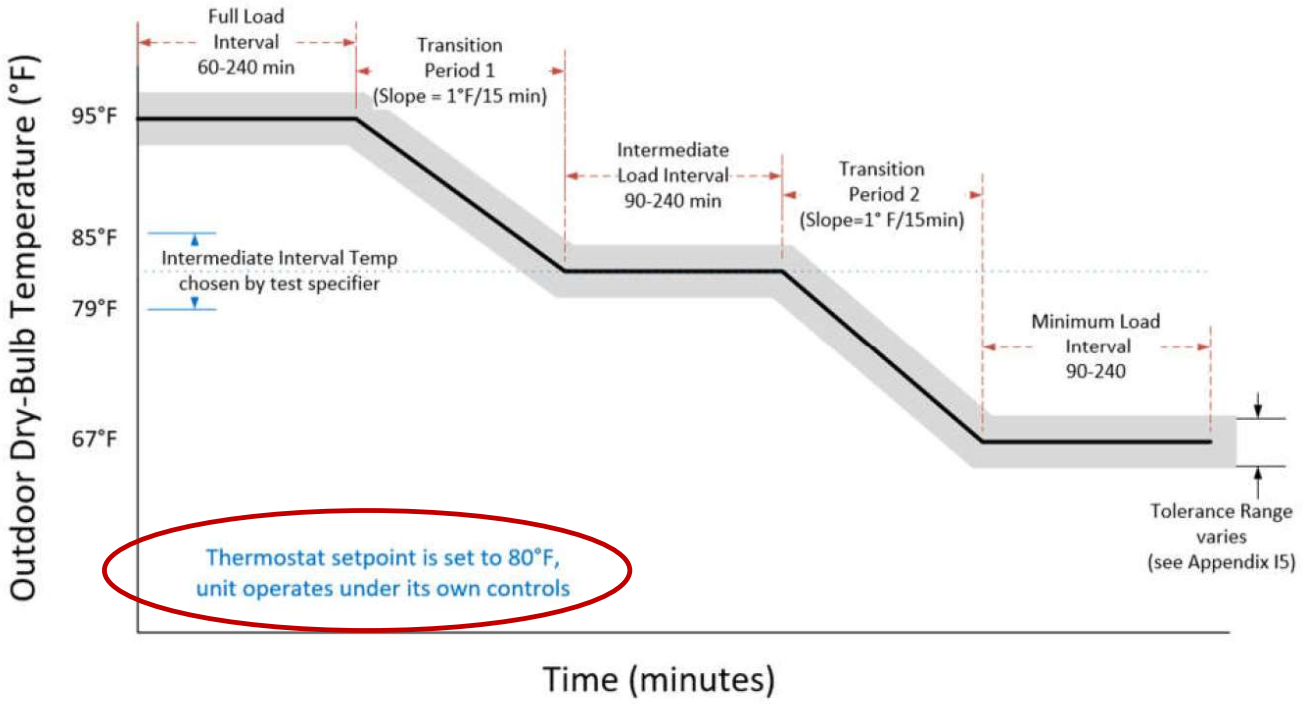


Figure I2 (Informative). Graphical representation of CVP

I4.1.6 *Cooling virtual sensible loads*. For the system under test, the sensible cooling portion of the VL, $VLs(T_j)$ (in Btu/hr), shall be simulated in the indoor room as defined by Equation I1:

$$VLs(T_j) = VLs(95) - \left[\frac{VLs(95) - VLs(67)}{95 - 67}\right] * (95 - Tj) \qquad \text{Equation I1}$$

New CVP-heating

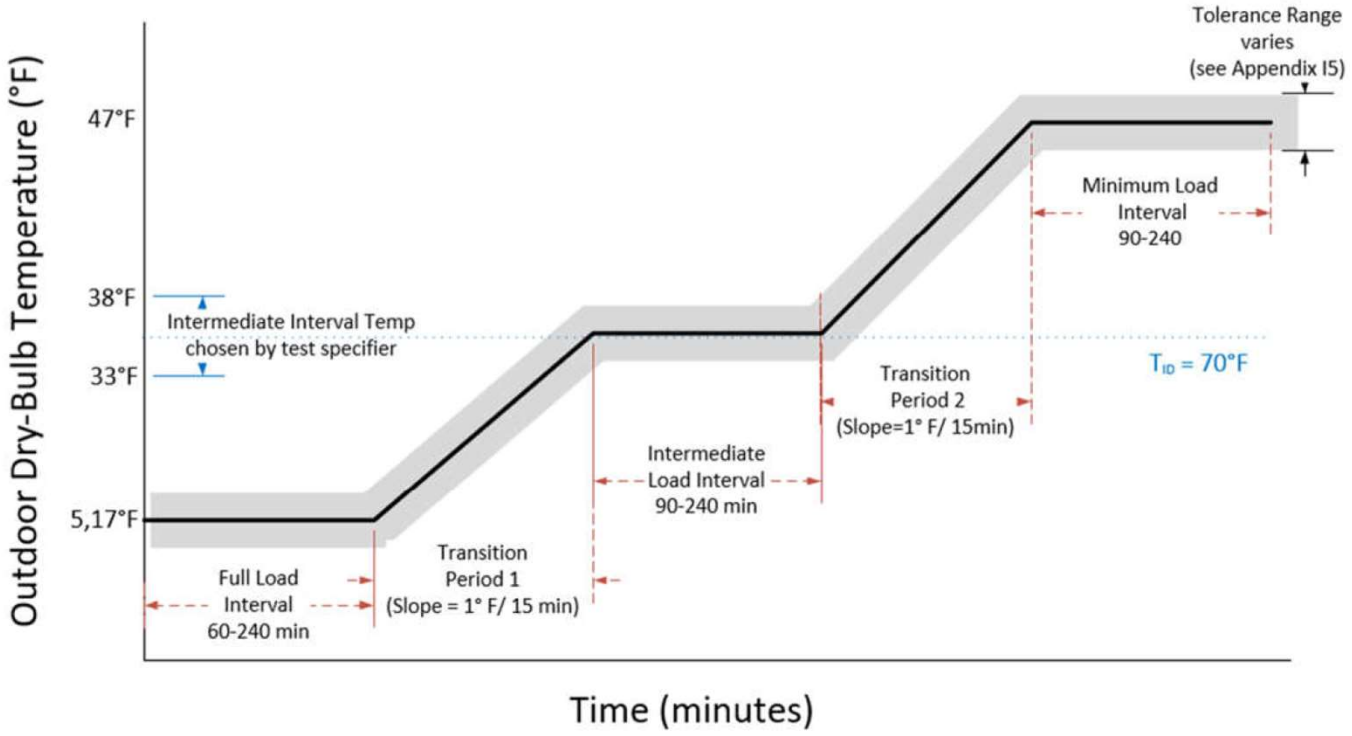


Figure I2. Informative Graphical Representation of Heating CVP

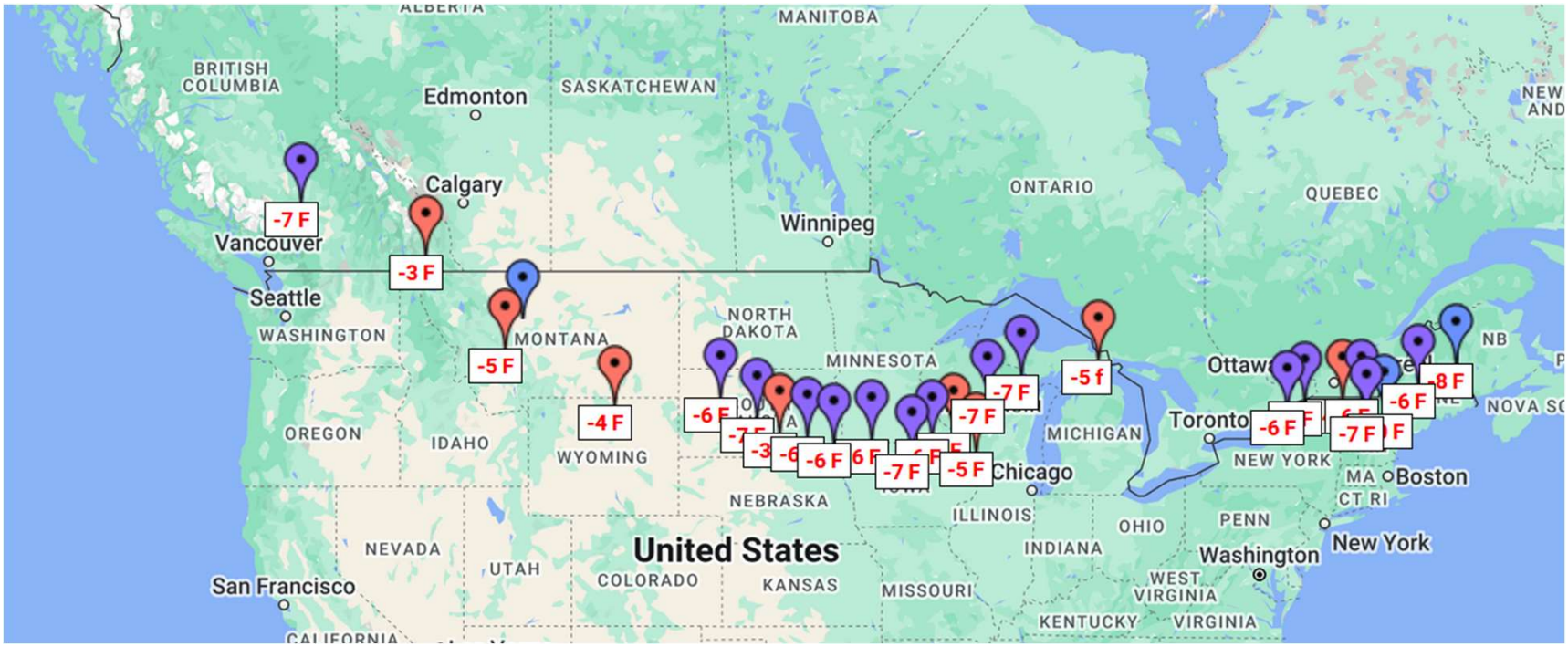
Future work

- Dig into data to learn more about:
  - Investigate apparent low bias of SPE07 cooling ratings
  - Impact of scattered load line on efficiency
  - Cycling / low-load behavior, defrost behavior
  - Could combine data with other studies' to further explore
- Repeatability: SPE07 testing on 2 units x 3 times each in this study
  - Repeatability was good (<3% at 95% confidence)
- Reproducibility (2nd lab is testing 2 of these units now)
  - More lab-to-lab testing will be needed
- Low load efficiency: 47 °F low-speed efficiency appears to have significant impact on seasonal performance
  - Doing lab tests on 6 units now (NEEA)

Avoiding trouble with HPs: quick summary

- Avoid oversizing, esp. multi-zone systems (120% good, 150% OK)
  - Use careful load calculations and trust them
  - Even if you look at capacity at more extreme design temps, focus on ASHRAE design conditions
  - If extremes (or design condition) are much below -5 °F, consider small amount of auxiliary heat *to make up the difference*
- Avoid single outdoor unit (except for passive/low-load):
  - Single zone 1:1 for main body of house
- No third-party wired thermostats (Nest, Ecobee, etc)
  - Use wall control for bigger rooms/spaces
  - Or wifi-enabled units that spoof the IR control

The Edge: ASHRAE 99% design ~ -5 °F



Thank you!

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