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EXP07:19 Load-based and Climate-Specific Testing and Rating Procedures for Heat Pumps and Air Conditioners

Interim Lab Testing and Rating Results

Prepared for NEEA, in partnership with:
BC Hydro
Natural Resources Canada
Northeast Energy Efficiency Partnerships
Pacific Gas and Electric

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Abstract
This report contains the results and analysis from initial testing done using the 2019 "technical review" version of CSA EXP07 load based test procedure and rating of heat pumps on. This test procedure and rating was designed to better characterize variable capacity heat pumps with capacity not larger than = 65,000 Btuh. These preliminary results suggest EXP07 provides valuable insight into heat pump performance operating under their own controls and responding to part load and defrost conditions. Appendix A contains graphs of capacity and performance from testing of 13 heat pumps. Appendix B contains a "plain language guide" of the test procedure for non-technical audiences.

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Executive Summary

In 2015 the Canadian Standards Association (CSA) formed a standards development work group charged with developing test and rating procedures that would better represent installed performance of variable capacity heat pumps (VCHPs). While heating seasonal performance factor (HSPF) and the seasonal energy efficiency ratio (SEER) appear to be effective at testing the performance of the hardware (i.e. the compressor, metering devices, fans and coils) these standard tests never employ the on-board control algorithms that are such an integral component of variable-speed systems' in-field operation.

The workgroup established a test procedure that includes both the effects of on-board control algorithms and a wider range of outdoor conditions than the current rating tests. Other objectives included standardized performance curves that could inform performance-based code compliance modeling or voluntary ratings, and the desire to differentiate performance across a wider range of climates. After several years of committee and exploratory lab work, the Canadian Standards Association (CSA) published EXP07:19, *Load-based and climate-specific testing and rating procedures for heat pumps and air conditioners*,[1] on March 29, 2019 (referred to herein as EXP07) for technical review.

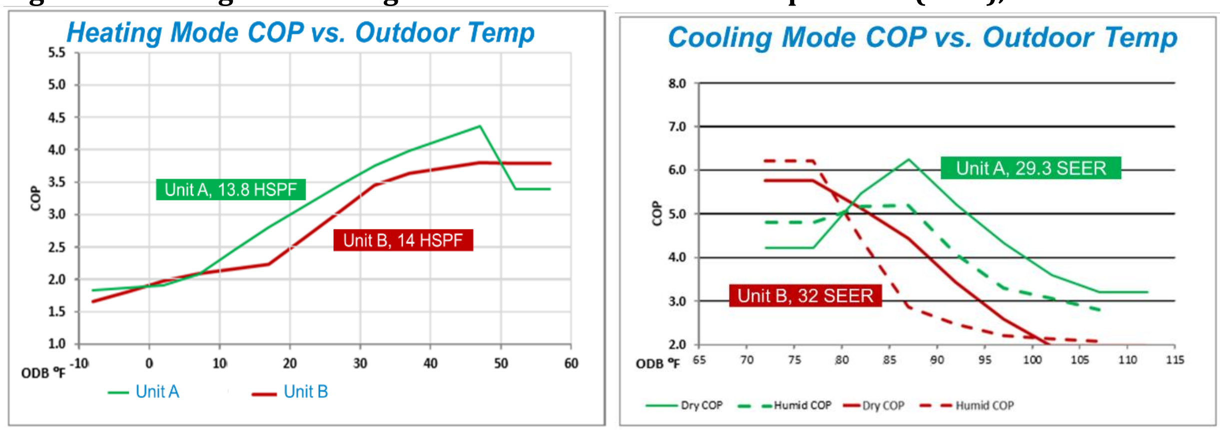
The procedure details a test method by which a sequence of simulated heating and cooling loads are imposed on the indoor room—commensurate with outdoor conditions that vary with each step in the sequence—and the equipment is allowed to heat or cool the indoor room in response to each simulated load, under its own controls, while its performance (primarily capacity and power input) are measured. To simulate a load, the delivered air flow and temperature are measured in real time, and the indoor chamber reconditioning equipment adjusts so that the indoor temperature reflects what a (simulated) house response would be. The indoor unit thus responds to conditions based on heat losses or gains typical of a home with a heat pump sized to meet that the design load of that home. The load based test condition closely simulates the thermal response, including thermal capacitance, as if it were in a house exposed to the outdoor conditions experienced by the heat pump outdoor unit. Although the test method is novel, the laboratory equipment setups and measurement techniques were adopted almost entirely from Appendix M1 of 10CFR 430, Subpart B,[2] with the intention that maintaining consistent laboratory setups – to the extent possible with the load-based test process – would benefit all users of these lab test procedures.

Using the EXP07 procedure, testing has been conducted by Underwriters Laboratories (UL) lab facility in their Plano, TX. This report covers the first 13 air source heat pump (ASHP) units tested between November 2018 and November 2019. The heat pumps were purchased directly from local distributors without coordination with the manufacturers.

[1] store.csagroup.org/ccrz__ProductDetails?viewState=DetailView&cartID=&portalUser=&store=&cclcl=en_US&sku=CSA%20EXP07%3A19 or go to store.csagroup.org/ and search for EXP07. The document is available at no cost.
[2] www.energy.gov/sites/prod/files/2016/11/f34/CAC_TP_Final_Rule.pdf

Responses to specific load and outdoor conditions varied from unit to unit, sometimes quite dramatically, even when comparing units with similar HSPF and SEER ratings. The apparent explanation for the wide variability in response and performance is the embedded control algorithms. For example, two 1-ton ductless units, with similar HSPF ratings of 13.8 and 14.0, (units A and B, respectively), and similar SEER ratings of 29.3 and 32, respectively, had very different coefficient of performance (COP) profiles with varying outdoor temperature. As a result, the units have very different seasonal COPs (SCOPs, calculated according to EXP07) in both heating and cooling modes. Figure 1 illustrates the considerably lower efficiency of Unit B under most test conditions for both heating and cooling, and Figure 2 shows the range in SCOP across the eight climates defined in the standard. The difference in SCOP is more dramatic for cooling performance, with a difference of more than 30% in some climates; in all cases Unit A, with the lower HSPF and SEER ratings, actually has higher SCOP ratings than Unit B.

Figure 1. Heating and Cooling COPs vs. Outdoor Room Temperature (ODB), Units A and B



Note: ODB = Outdoor dry bulb (temperature)

Figure 2. Heating and Cooling SCOPs by Climate, Units A and B

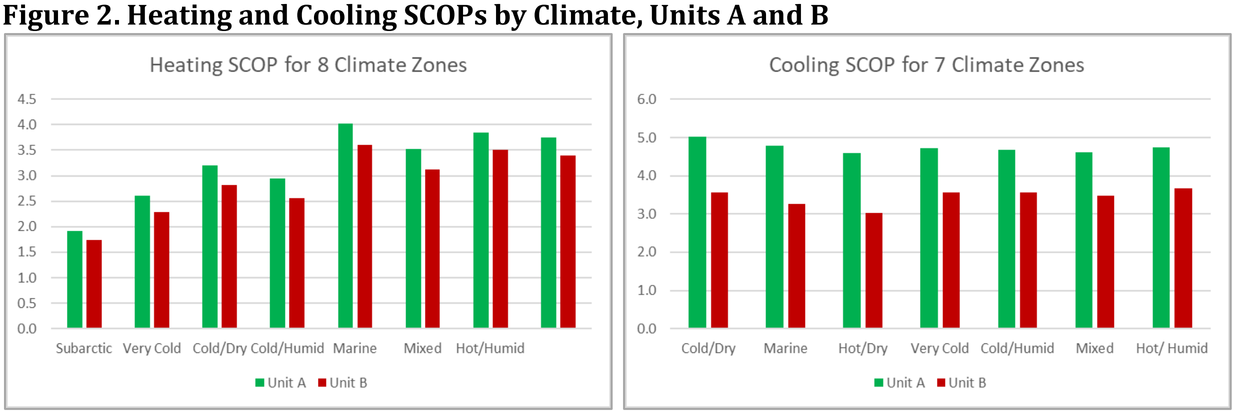
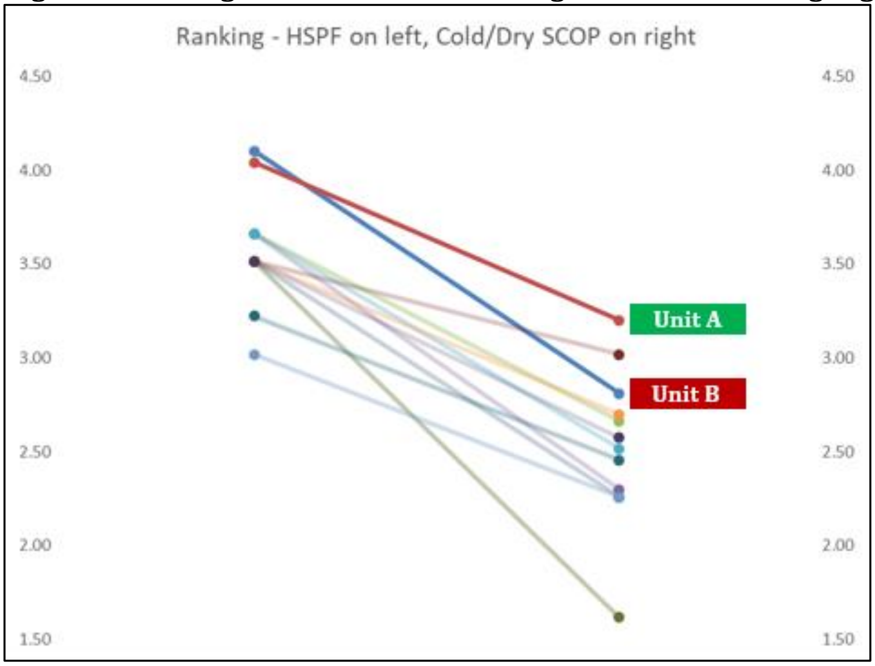


Figure 3 shows Units A and B, among all the units tested, with relative rankings of HSPF on the left and SCOP (Cold/Dry) on the right. In addition to the difference between units A and B, the relative ranking of heating SCOPs among all tested units varied considerably from the ranking of HSPF ratings.

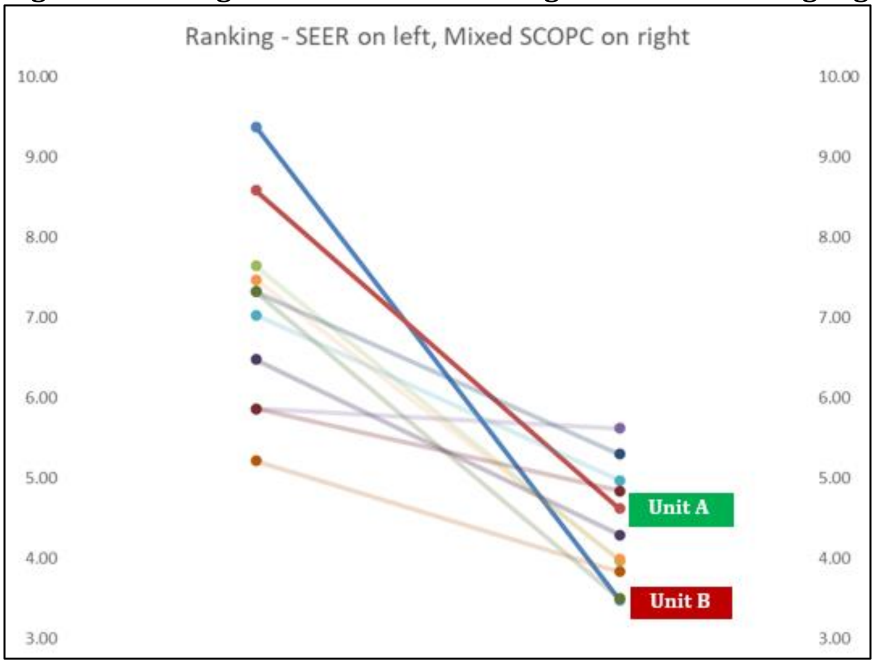
Figure 3. Heating HSPF and SCOP Rankings, Units A and B Highlighted



The cooling SCOPs varied even more widely than the heating SCOPs, when compared by rank order with the SEER ratings. Figure 4 shows the results of all 13 tests, with Units A (maroon) and B (blue) from the example highlighted. The significant degree of inversion in efficiency ranking[3] from one scale to the other is clear, with some cases exhibiting inversions even more dramatic than the example pair.

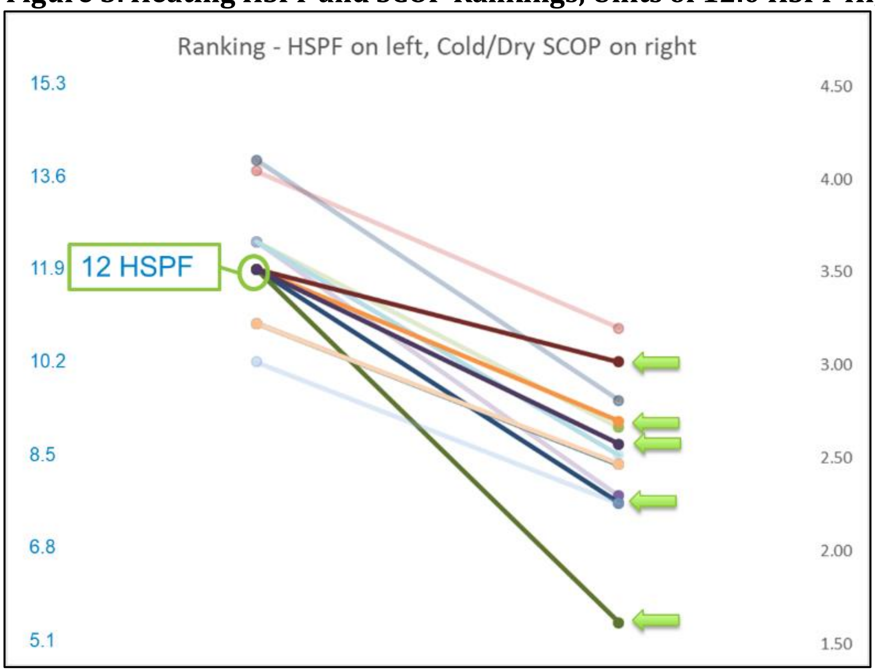
[3] Relative rank order of equipment by efficiency rating.

Figure 4. Cooling SEER and SCOP Rankings, Units A and B Highlighted



The example above was not the most significant ranking discrepancy, especially for the heating tests. Of the five tested ductless units with HSPF ratings of 12.0, the SCOP results using EXP07 (again, using the Cold/Dry climate for comparison) ranged from the second-highest to the lowest, as shown in Figure 5.

Figure 5. Heating HSPF and SCOP Rankings, Units of 12.0 HSPF Highlighted



The sample of products tested is too small to form any broad conclusions about a relationship, if any, between HSPF or SEER and SCOP. In addition, direct comparisons are not relevant or practical, because the EXP07 test inherently measures something different than does AHRI 210/240. However, measured performance using EXP07 yields results that clearly differ—substantially in some cases—from those observed with HSPF and SEER ratings. The ranking of heating or cooling SCOPs among different models using EXP07 would suggest very different conclusions about their performance, or savings, relative to each other than would be estimated by comparing HSPF or SEER rankings for the same models.

Some parties have suggested that cold- or very hot-climate ratings using AHRI 210/240 could be enhanced for predicting savings potential by including an additional requirement or adjustment using a standardized test result at 5°F[4] for heating performance in cold climates, and/or EER95 for cooling performance in hot climates. However, the results of the EXP07 testing so far do not appear to support the usefulness of those metrics in improving understanding of the operation of equipment as installed for more extreme climates.

Other high-level findings include:

- The units' response to the lab testing process varied, and some models were more difficult to test than others. This report shows some examples of ways in which the units' controls and operation interacted with the dynamic test process.
- In general, for each individual unit, heating SCOPs vary with climate as expected, with the heating SCOP improving for less severe heating climates. The research found similar results for the dry cooling SCOPs, with higher values in the milder climates.
- In humid cooling ratings, the humid test efficiencies did not closely follow the dry test efficiencies. In addition, the units exhibited significant variability in the effectiveness of their humidity control, which the test is designed to reveal. In the humid cooling tests, many units had trouble managing the indoor humidity at lower load conditions, with a range of indoor humidity from 39% to 68% during the lower load test conditions. Dehumidification generally improved with increasing total cooling loads, presumably due to longer and more consistent run times.
- EXP07 is meeting the CSA working group goal of providing test data using as-shipped controls under dynamic load conditions that provides insight into the difference between VCHP systems that are not apparent in the AHRI ratings.

[4] Which is included as an optional test in Appendix M1 of 10 CFR 430 Subpart B.

Introduct ion

Background

In 2015 the Canadian Standards Association (CSA) formed a standards development work group charged with developing test and rating procedures that would better represent installed performance of variable capacity heat pumps (VCHPs). The relevance of the heating seasonal performance factor (HSPF) and the seasonal energy efficiency ratio (SEER) as realistic performance metrics to represent savings had been increasingly under question; climate differences and in-field monitoring suggested fairly significant shortcomings in the ability of these ratings to predict installed efficiency. With utility and state/provincial efficiency programs generally increasing funding for efficient HVAC installations, program managers have increased motivation to reduce risk and find more suitable metrics to inform incentive budgets and improve evaluation results.

The work group focus began with variable-speed split-system equipment withnon-ducted or ducted indoor units, which depends heavily on on-board firmware to operate in-field, and for which installed performance varied considerably from standard ratings. While HSPF and SEER appear to be effective at testing the performance of the hardware—the compressor, metering devices, fans and coils—these standard tests never employ the on-board control algorithms that are such an integral component of variable-speed systems' in-field operation.

The workgroup established a test procedure that includes both the effects of on-board control algorithms and a wider range of outdoor conditions than the current rating tests. Other objectives included standardized performance curves that could inform performance-based code compliance modeling or voluntary ratings, and the desire to differentiate performance across a wider range of climates. The work was chaired by Gary Hamer of BC Hydro, with co-vice chairs Marshall Hunt (then) of Pacific Gas & Electric (PG&E), and Rob Andrushuk of Manitoba Hydro. Initial lab research was led by Robert Davis at the PG&E lab and by Dr. Jim Braun and his team from Herrick Lab at Purdue University. Primary technical writing of the test procedure was led by Charlie Stephens (NEEA). After several years of committee and exploratory lab work, the Canadian Standards Association (CSA) published a technical review version of EXP07:19, *Load-based and climate-specific testing and rating procedures for heat pumps and air conditioners*,[5] on March 29, 2019 (referred to herein as EXP07).

The procedure details a test method by which a sequence of simulated heating and cooling loads are imposed on the indoor room—commensurate with outdoor conditions that vary with each step in the sequence—and the equipment is allowed to heat or cool the indoor room in response to each simulated load, under its own controls, while its performance metrics (primarily capacity and power input) are measured. The results are then used to calculate seasonal coefficient of performance (SCOP) ratings for eight climate zones defined

[5] store.csagroup.org/ccrz__ProductDetails?viewState=DetailView&cartID=&portalUser=&store=&cclcl=en_US&sku=CSA%20EXP07%3A19 or go to store.csagroup.org/ and search for EXP07. The document is available at no cost.

in the procedure. Although the test method is novel, the laboratory equipment setups and measurement techniques were adopted almost entirely from Appendix M1 of 10CFR 430, Subpart B,[6] with the intention that maintaining consistent laboratory setups – to the extent possible with the load-based test process – would benefit all users of these lab test procedures.

Once the test procedure technical details had been finalized in late 2018, a new phase of lab testing began. The purpose of this testing phase was to operationalize the test procedure at a production lab and establish preliminary findings from multiple manufacturers in several different equipment configurations. The results of these preliminary tests are presented in this report. Funding for these tests were provided by the Northwest Energy Efficiency Alliance (NEEA) and Natural Resources Canada (NRCan). Testing was conducted by Underwriters Laboratories (UL) lab facility in their Plano, TX on 13 air source heat pump (ASHP) units between November 2018 and November 2019.

The 13 ASHP units tested at the UL laboratory for this study were purchased independently from local distributors without coordination with the manufacturers. They are identified throughout this report by the following labels, based on the organization funding each unit's testing, as follows:

- NEEA1 through NEEA7: funded by the Northwest Energy Efficiency Alliance
- NRCan1 through NRCan6: funded by Natural Resources Canada

Several labs had conducted a range of tests, using different types of load-based testing concepts, prior to publication of EXP07. In addition to the PG&E and Herrick labs, other early tests were conducted by CanMet Energy, the Natural Gas Technology Center (funded by NRCan), at NRCan's own labs, and by the Electric Power Research Institute (EPRI). These early tests were essential to establish and refine the basic approach to load-based testing of heat pumps and air conditioners; the Herrick labs in particular, funded largely by NEEA, helped to refine the details of the approach used in EXP07. All the lab tests through mid-2018 were essentially part of a research and development phase. While they were essential to understanding and improving the load-based test method, the results were preliminary and could not be compared to one another due to the evolving test methodologies.

The UL Plano lab tested 13 heat pump models made by nine manufacturers using EXP07. Two were initially only tested in the heating mode and eleven were tested in both heating and cooling modes to generate a complete set of SCOP ratings. Twelve of the units tested were ductless, single-zone systems between 12,000 and 18,000 Btu/h rated cooling capacity (1-1.5 tons). The last unit was a ducted, three-ton nominal system. All the tested models have HSPF ratings between 10 and 14, and eight are within the range of 12–12.5. All tested models have SEER ratings between 17 and 33, with six (of the 12 models tested

[6] www.energy.gov/sites/prod/files/2016/11/f34/CAC_TP_Final_Rule.pdf

for cooling) rated less than 23, and four between 23 and 26. All are listed in the NEEP cold-climate heat pump product list.[7]

A separate test at the heating temperature operation limit (TOL), which is optional in the test procedure, was conducted only for one model (NEEA2). The impact of this omission on the ratings is relatively small, as it only affects the heating ratings in the climates with significant heating hours with temperatures below -10°F (-23°C). This means the TOL test mostly affects the ratings for the Subarctic and Very Cold climates, with a much smaller impact in Cold/Dry and Cold/Humid climates, where those hours are minimal, and essentially no impact in the other, milder climates. The standby power tests in Clause B.3.6 in EXP07 have not been conducted on any of the units to date, so the SCOPs in this report strictly represent the seasonal heating and cooling ratings, and do not represent annual performance ratings.

Objectives

The objectives of the testing, which is ongoing and continues to expand, focus on three main points:

1. To begin compiling a data set on performance of a range of products using the load-based test, and the resulting ratings for the range of climates addressed by EXP07.
2. To evaluate the test procedure itself and to find areas to improve/optimize, as well as opportunities to save time and effort or lab time and expense.
3. To provide a baseline from which to begin establishing the degree of repeatability (within a lab), reproducibility (from lab to lab), and representativeness (relative to in-field performance) of the EXP07 procedure.

This report specifically addresses the first objective and includes some exploration of the second. The third objective is currently being developed and supported by a program of additional testing at UL Plano and in other labs. Future repeatability, reproducibility and representativeness testing will include some of the units tested so far, as well as others. That work will involve conducting back-to-back and round-robin tests at multiple labs, and deploying the same units in field tests to allow analysis of representativeness.

It is important to understand that the results of EXP07 ***are not*** directly comparable to those of the AHRI 210/240 test procedure and rating. The indoor and outdoor conditions (temperature and humidity) are not the same, the load lines used in the seasonal rating computations differ slightly, and most importantly, in EXP07 the unit under test (UUT) is not forced to operate at fixed fan and compressor speeds. Even though the EXP07 "full load" tests are used when the unit's capacity has been exceeded, the unit's compressor is still allowed to operate under its normal firmware algorithms; some units seem to load up beyond the speed at which they would run during the AHRI 210/240 test, at similar temperature conditions, and some units seem to operate at a level that is actually less than that at which they operate under dynamic testing, at the lower load conditions. The objective of EXP07 is to mimic as closely as possible the operating conditions a unit would

[7] The NEEP ccASHP listing is found at: ashp.neep.org

encounter during a real-world installation, and the behavior is a characteristic of the unit's firmware.

EXP07 Test Description

Load-Based Testing Approach

The EXP07 test procedure uses 11 heating conditions and 10 cooling conditions, replicated in a lab setting. The cooling conditions are divided into two climate regimes, humid and dry, shown in Table 1 (Table B.3 in EXP07). Heating conditions are divided into continental and marine, as shown in Table 2 (Table B.5 in EXP07).

Table 1. Cooling Indoor and Outdoor Test Conditions

	Humid test conditions §			Dry test conditions		
	Outdoor dry-bulb tempera-ture, °F	Indoor dry-bulb tempera-ture,† °F	Indoor wet-bulb tempera-ture,‡ °F	Outdoor dry-bulb tempera-ture, °F	Indoor dry-bulb tempera-ture,† °F	Indoor wet-bulb tempera-ture, ‡ °F
CA*	N/A	74	63	113	79	56 (maximum)
CB	104			104		
CC	95			95		
CD	86			86		
CE	77			77		

** Temperature "CA" conditions are required only for a "Hot/Dry" climate rating.*
† Indoor room conditions at start of testing, target for equipment to meet during dynamic test intervals, and indoor room test temperature for full-load test intervals.
‡ Indoor room conditions at start of testing, and indoor room test condition for full-load test intervals.
§ Outdoor wet-bulb temperature during wet coil cooling mode tests where the unit rejects condensate to the outdoor coil shall be selected to maintain an indoor relative humidity of 40%.

Table 2. Heating Indoor and Outdoor Test Conditions

	Continental outdoor conditions		Marine outdoor conditions		Indoor conditions	
	Dry-bulb tempera-ture, °F	Wet-bulb tempera-ture, °F	Dry-bulb tempera-ture, °F	Wet-bulb tempera-ture, °F	Dry-bulb tempera-ture, °F‡	Wet-bulb tempera-ture,§ °F
HA*	-10	-11.4			70	60 (maximum)
HB*	5	4				
HC	17	14.5	17	15.5		
HD	34	31	34	32		
HE	47	41	47	45		
HF	54	45	54	49		
HL*,†	TOL	TOL-1	TOL	TOL-1		

** Temperatures "HA" (-10°F) and "HB" (5°F) may be omitted for the "Marine", "Hot/Humid", and "Hot/Dry" climate ratings.*
*† TOL as a unique test condition may be omitted if it is lower than -10F, or if it corresponds to one of the other required test temperatures in accordance with footnote *.*
‡ Indoor conditions at start of testing, target for equipment to meet during dynamic test intervals, and indoor room test temperature for full-load test intervals.

The use of 95°F as one of the cooling outdoor temperatures, and the use of 5, 17 and 47°F as heating outdoor temperatures, are meant to anchor the general profile of the test procedure to well-established outdoor conditions used for many of the AHRI 210/240 tests. Besides the obvious point that EXP07 includes tests at a number of additional outdoor temperature conditions, it is important to remember that the performance results at those common outdoor temperatures are *not* comparable to those in AHRI 210/240, because they are testing unit performance under very different operating conditions.

To simulate the load in the indoor room, EXP07 uses a dynamic updating model that calculates temperature conditions in the indoor room, based the capacity of the equipment under test in real time, and compares it to the specified *load* to be imposed. The lab control software updates the indoor room conditions based on the difference between the load and the capacity measurement, rather than by holding a fixed indoor condition throughout each test. Thus, the equipment under test is allowed to respond to those varying indoor room conditions under its own internal logic and controls as it tries to maintain the target indoor temperature setpoint. Each outdoor temperature condition corresponds to a specified load condition for the indoor room. At each outdoor temperature, the load that is simulated in the indoor room is appropriate for the outdoor temperature at which the equipment is tested, for a typical residential application. The basic load equation for cooling (Equation B.3 in EXP07) is:

$$BL\left(T_j\right) = \frac{1}{1.2} \times SHR_{building} \times \dot{Q}_c(95) \times \left[\frac{T_j - T_{bal}}{T_{OD} - T_{zl}}\right] \quad \text{(Eq. B.3)}$$

Where:

$BL(T_j)$ = the sensible building load to be simulated in the indoor room at the test interval outdoor ambient dry-bulb temperature T_j

$SHR_{building}$ = the target sensible heat ratio (0.8 for the humid and 1.0 for the dry test condition)

$\dot{Q}_c(95)$ = the maximum total cooling capacity of the heat pump at an outdoor ambient dry-bulb temperature of 95°F as determined in the A or A2 Test (as applicable); $BL(T_j)$ and $\dot{Q}_c$(95) are in Btu/hr

T_{OD} = the outdoor design temperature = 95°F (Humid cooling test) or 105°F (Dry cooling test)

T_{zl} = the zero-load temperature (67°F for the humid and 72°F for the dry test condition)

T_{bal} = the balance point temperature based on the current indoor room setpoint. (Note: Tbal would normally be the same as Tzl for a fixed-condition test, but for the dynamic test it is adjusted by the difference between the current indoor room temperature and the target indoor room temperature.)

In addition, for the humid cooling tests, a dynamic humidity load is applied to the space in a manner very similar to that of the sensible cooling loads. Its magnitude is calculated from the total load in equation B.3, and the sensible heat ratio of 0.8 used in the equation.

For heating, the building load (Equation B.9 in EXP07) is:

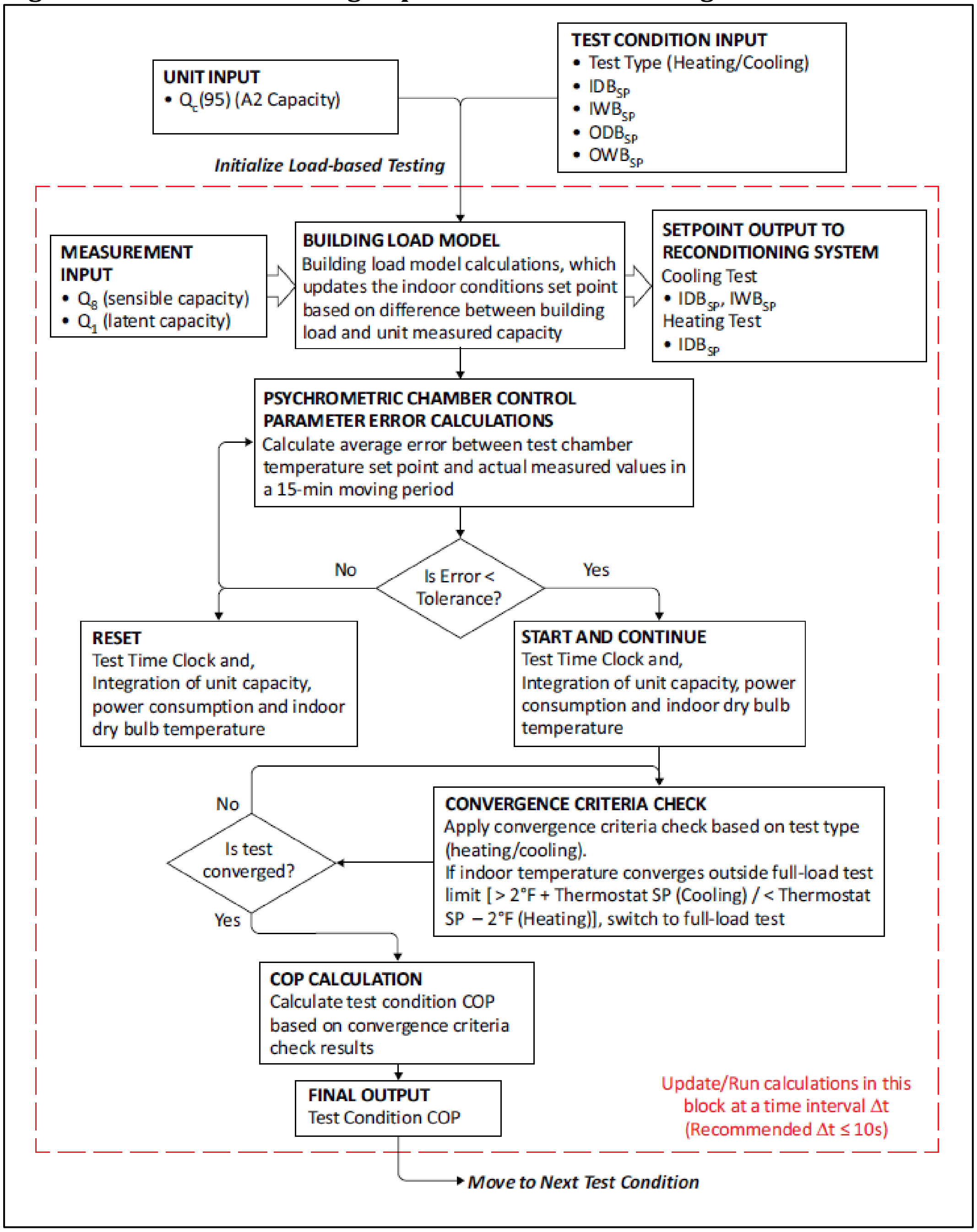
$$BL(T_j) = 1.15 \times \dot{Q}_c(95) \times \left[\frac{T_{bal} - T_j}{T_{zl} - T_{ref}}\right] \quad \text{(Eq. B.9)}$$

Where:

- $BL(T_j)$ = the building load at the test interval outdoor ambient dry-bulb temperature T_j
- $\dot{Q}_c(95)$ = the maximum total capacity of the heat pump at an outdoor ambient dry-bulb temperature of 95°F as determined in the A or A2 test (as applicable); $BL(T_j)$ and $\dot{Q}_c(95)$ are in Btu/hr
- T_{zl} = the zero-load or design balance point temperature (60°F)
- T_{ref} = an outdoor load reference temperature = 5°F
- T_{bal} = the balance point temperature based on the current indoor room setpoint. (This is also adjusted dynamically based on the difference between the current indoor room temperature and the target indoor room temperature, as in cooling).

The test is run at each condition until the system under test achieves a stable COP value ("convergence"), or until it reaches the end of the test period, at which point the capacity and input power are integrated over the defined test period. The detailed steps used to determine convergence during this process are found in EXP07, clauses B.3.2.2.3.6 (cooling) and B.3.3.2.3.6 (heating). The steps required to implement the dynamic load simulation, collect the data, and to determine convergence are detailed in the informative Annex D of the procedure as pseudo-code. Figure 6 (Figure D.1 in EXP07) shows a high-level flow chart of the process.

Figure 6. Load-Based Testing Implementation – Flow Diagram



Efficiency Metrics (Ratings)

Once the test results have been measured and recorded, seasonal efficiency values are calculated based on the values measured in the tests. Seasonal efficiencies are calculated using a bin model, consistent with other rating and HVAC (heating, ventilation and air-conditioning) analysis methods. For each climate, the model defines a specific number of hours that are considered as heating (or cooling) hours at each temperature "bin" throughout the heating and cooling seasons. (The bin hours are statistically derived for each of the eight prototypical climates based on current "typical" weather data for the US and Canada, as detailed in Annex G clauses G.2 and G.3 of EXP07). The temperature bins are in increments of 5°F, and the procedure specifies that the unit's heating or cooling output, and energy input, is applied at each bin for the number of hours in that bin. Table 3 (a portion of Table B.12 from EXP07) shows an example of heating bin hours for the Cold/Dry heating climate:

Table 3. Heating Bin Temperatures and Fractions for Cold/Dry Climate

j	T_j (°F)	n_j/N
1	-23	-
2	-18	0.001
3	-13	0.002
4	-8	0.004
5	-3	0.005
6	2	0.010
7	7	0.014
8	12	0.025
9	17	0.047
10	22	0.064
11	27	0.120
12	32	0.162
13	37	0.171
14	42	0.125
15	47	0.123
16	52	0.079
17	57	0.047

Notes: Cold/Dry N = 5,017

For each temperature bin *j*, the temperature given as T_j is considered to represent the center temperature in degrees Fahrenheit; for example, the range for bin 16 is between 49.5°F and 54.5°F, and is represented in the model by the measured performance of the heat pump at 52°F. The bin method is essentially the same method used by AHRI 210/240, although the prototypical climates are different (and thus none of the climates exactly match the US Department of Energy (DOE) Region IV used for the HSPF rating). Also, because EXP07 uses a zero-load point of 60°F, it has no temperature bin for 62°F.

Example Calculation

For an example calculation of Cold/Dry $SCOP_H$, using the test unit NRCan2, start with the test results of the unit for the continental heating test consisting of 6 test points (HA through HF). The results of these test points are used to generate the Cold/Dry climate rating, as shown in Table 4:

Table 4. Continental Heating Test Results, Unit NRCan2

Test Point	Target ODB,°F	Actual ODB,°F	$C_{HP}(T_j)$, Btu/h	$COP(T_j)$
HA	-10	-9.8	11436	1.81
HB	5	5.0	15377	2.07
HC	17	17.0	13057	2.74
HD	34	35.1	7979	4.10
HE	47	47.0	3947	5.58
HF	54	54.0	1657	3.20

Note: ODB = Outdoor dry bulb (temperature)

The equation used to calculate the overall SCOP is as follows (Equation B.20 in EXP07):

$$\mathrm{SCOP_H} = \frac{\sum_{j=1}^{n}\left(\mathrm{DHR}\left(T_j\right) \times \frac{n_j}{N}\right)}{\sum_{j=1}^{n}\left[\left(\frac{\left(\mathrm{DHR}\left(T_j\right) - \mathrm{RH}\left(T_j\right)\right)}{\mathrm{COP_H}\left(T_j\right)} + \mathrm{RH}\left(T_j\right)\right) \times \frac{n_j}{N}\right] + P_{HNA}}$$

where

j = the bin number

T_j = the bin temperature, outdoor dry bulb in degrees F

n_j/N = the ratio of the number of hours during the heating season when the outdoor temperature fell within the range represented by bin temperature T_j to the total number of heating hours

DHR(T_j) = the heating demand of the building for the corresponding temperature bin T_j in Btu/h

RH(T_j) = the incremental electrical power required for auxiliary space heating at temperature T_j

COP(T_j) = the COP value of the unit at the corresponding temperature T_j

P_{HNA} is a term used for the standby power, which will be set to 0 in this example. The procedure states that the $\mathrm{SCOP_H}$ shall be calculated using P_{HNA} = 0 for the active mode only, which is the only mode this report addresses.

Further, DHR(T_j) is defined in Equation B.21 of EXP07 as:

$$\mathrm{DHR}\left(T_j\right) = \dot{Q}_c(95) \times 1.15 \times \left(\frac{60 - T_j}{60 - 5}\right)$$

This is the same as the heating load equation used during the testing, with the exception that T_{bal} = T_{zl} = 60 (there is no dynamic updating for the bin model), T_{ref} = 5, and Tj represents the bin temperature rather than the outdoor test temperature. For both the heating and cooling ratings, the magnitude of the building loads used for the bin model are the same as those used during the testing process at the same temperatures.

Using the bin data from Table 3 and filling in other key values provides the set of results in Figure 7 for the individual bins, that is one row for each step of the sums used in the $SCOP_H$ equation:

Figure 7. Bin Calculation Results for Unit NRCan2 in the Cold/Dry Heating Climate[a]

Units:	Deg F	-	Btu/h	Btu/h	-	Partial	Partial
J	**T_j**	**n_j/N**	**$DHR(T_j)$**	**RH(Tj)[b]**	**$COP_H(T_j)$**	**numerator[c]**	**denominator[d]**
1	-23	-	20825	20825	N/A	0	0
2	-18	0.001	19571	19571	N/A	20	20
3	-13	0.002	18316	18316	N/A	37	37
4	-8	0.004	17062	5158	1.84	68	46
5	-3	0.005	15807	2571	1.93	79	47
6	2	0.010	14553	0	2.02	146	72
7	7	0.014	13298	0	2.18	186	85
8	12	0.025	12044	0	2.46	301	122
9	17	0.047	10789	0	2.74	507	185
10	22	0.064	9535	0	3.11	610	196
11	27	0.120	8280	0	3.49	994	285
12	32	0.162	7025	0	3.87	1138	294
13	37	0.171	5771	0	4.34	987	227
14	42	0.125	4516	0	4.96	565	114
15	47	0.123	3262	0	5.57	401	72
16	52	0.079	2007	0	3.87	159	41
17	57	0.047	753	0	3.87	35	9
∑ of bins = numerator and denominator:						**6232**	**1853**

Cold/Dry n = 5,017

Notes:

a. For all values of T_j that are not equal to one of the test conditions, e.g., those shown in Table 4 for this example, interpolation is used to determine COP and heat pump capacity. This is a typical approach for such a model, and because there are more test points than in other procedures, these estimates are likely to be reasonably representative over the wide range of outdoor conditions used for testing.

b. *RH(Tj)* is calculated as the difference between the measured capacity of the heat pump for the temperature and the load $DHR(T_j)$. For any bin for which heat pump capacity does not meet the building load, the difference is assumed to be made up by auxiliary resistance heat at a COP of 1. This method is identical to AHRI 210/240. Heat pump capacity is deemed to be zero at temperatures below the lowest temperature tested (which is not the case for AHRI 210/240, where extrapolation is used). For this example, no additional test was conducted at TOL, even though the tested model is rated to operate below -10°F, so values below the bin of -8 are 100% of the load $DHR(T_j)$.

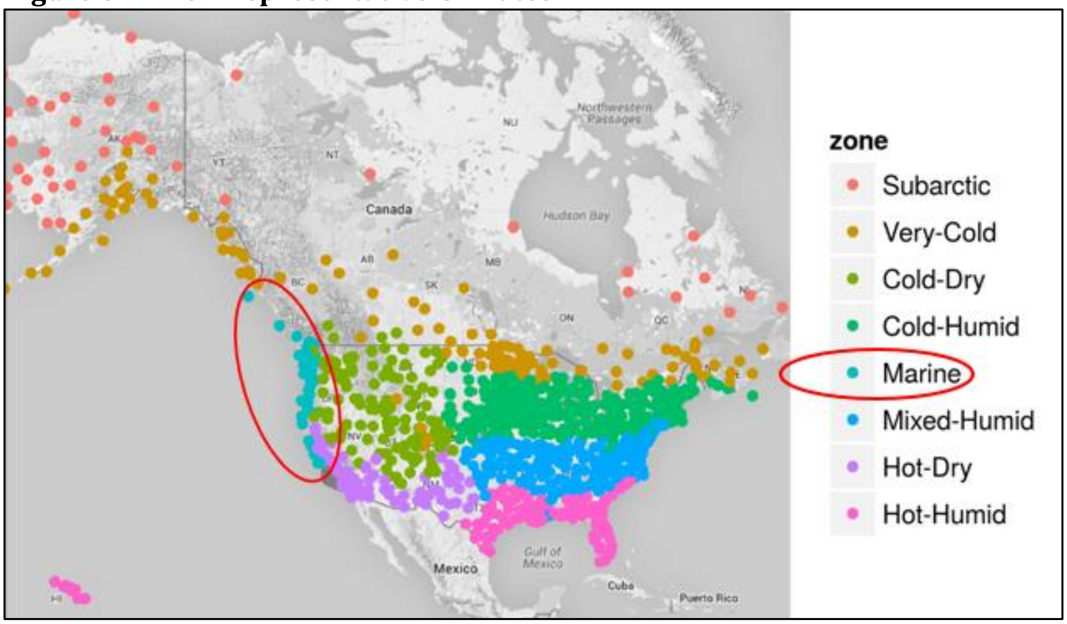
c. For each bin: $DHR(T_j) \times N_j/n$

d. For each bin: $\{ [DHR(T_j) – RH(Tj)] / COP_H(Tj) + RH(Tj) \} \times N_j/n$

The final result is the quotient of the sums: 6232 / 1853 = 3.36 $SCOP_H$. This represents the total seasonal heating capacity divided by the total seasonal input energy (each is normalized to one hour, by dividing by the number of heating hours *N.* Multiplying each value by N=5017 for Cold/Dry gives the totals of 31.3 x 10^6 Btu delivered, and 9.2 x 10^6 Btu or 2709 kWh consumed, for the season).

The heating SCOP for other climates is calculated the same way, with each respective set of bin fractions n_j/N. The marine test data are used for the Marine climate rating and the continental test data for all other ratings. The cooling SCOP calculation is similar, except that there is no backup source (the RH(T_j) terms disappear) and the DCL(Tj) equation includes a term for sensible heat ratio (SHR). SHR, the balance point temperature T_{zl}, and the design temperature T_{ODC} all vary by climate zone (as detailed in equations B.16 and B.17 of EXP07).

Figure 8. EXP07 Representative Climates[8]



The weather data cities used to calculate each of the eight representative climate zones are shown in Figure 8. Table 5 shows which test sequence result is used for calculating each climate's heating and cooling SCOPs.

[8] The marine climate is circled only to differentiate it from other climates sown in similar colors

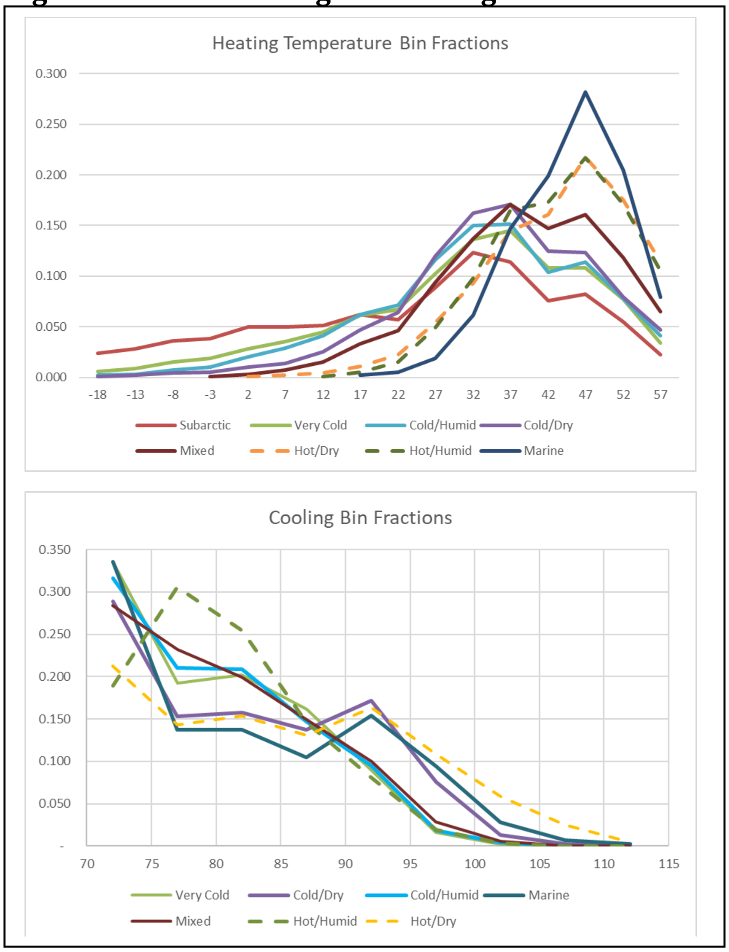
Table 5. EXP07 Test Results As Applied to Representative Climates

Rating Climate	Heating Test Used	Cooling Test Used
Subarctic	Standard	*No cooling rating*
Very Cold	Continental	Humid
Cold/Dry	Continental	Dry
Cold/Humid	Continental	Humid
Marine	Marine	Dry
Mixed	Continental	Humid
Hot/Humid	Continental	Humid
Hot/Dry	Continental	Dry

As one would expect, for a given unit, heating SCOPs are generally higher in warmer climates and lower in colder climates, and cooling SCOPs are generally lower in the hottest climates and increase as summer climates get cooler.

Figure 9 shows the heating and cooling bin fractions for each climate, for reference:

Figure 9. EXP07 Heating and Cooling Bin Fractions



Lab Testing Using EXP07

The tested units were set up in the lab in accordance with EXP07, Clauses B.2.1–B.2.3 and B.2.5–B.2.10. These sections cite relevant ASHRAE standards (23, 37, 41.1, 41.2, 41.6, 41.9, and 51) extensively and are consistent, to the degree possible considering the load-based testing process, with Appendix M1. The general requirements of B.3.1 were followed as applicable throughout; the cooling tests were conducted according to B.3.2 and the heating tests according to B.3.3. Clause B.3.6, the clause regarding standby testing, was omitted for this round of tests. Figure 10 and Figure 11 show examples of typical outdoor and indoor test setups, respectively.

Figure 10. Example of Outdoor Unit Setup in Lab

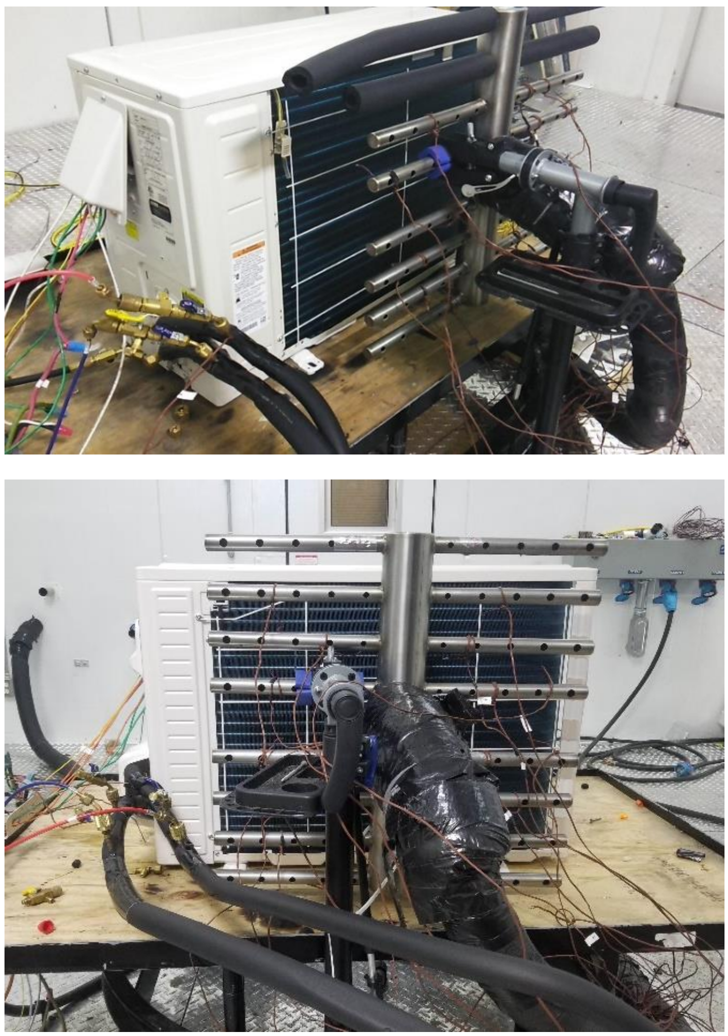


Figure 11. Example of Indoor Unit Setup in Lab

Figure 11 shows the indoor head of a ductless minisplit setup in the lab. The ducted connection shown here, typical of lab setups for other tests such as AHRI 210/240, has a flow measurement that imposes zero static pressure at the outlet of the minisplt so the delievered air flow is unaffected.

Unit Designations

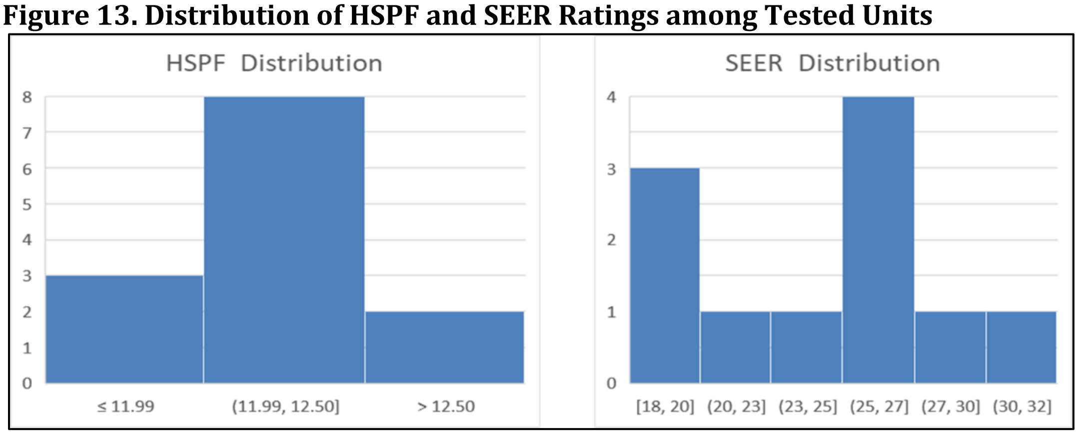
Figure 12 shows the tested units with their respective test designations, the nominal size in tons, and which tests were completed. It also shows the approximate HSPF and SEER ratings of the units. Exact values are not shown, in the interest of anonymity.

Figure 12. EXP07 Test Sequence Overview

Test Designation	Nominal Capacity (Tons)	HSPF (range)	SEER (range)	Notes
NEEA 1	0.9	12-12.5	23-26	Ductless Heat Pump (DHP)
NEEA 2	1.0	12-12.5	>26	DHP
NEEA 3	1.0	12-12.5	23-26	DHP
NEEA 4	0.9	12-12.5	<23	DHP
NEEA 5	1.0	12-12.5	23-26	DHP
NEEA 6	1.0	>12.5	>26	DHP
NEEA 7	2.8	<12	<23	Ducted central forced air system
NRCan1	1.4	<12	<23	did not include marine or cooling
NRCan2	1.0	>12.5	>26	DHP
NRCan3	1.0	<12	<23	DHP
NRCan4	1.3	12-12.5	<23	DHP
NRCan5	1.3	12-12.5	23-26	DHP
NRCan6	1.3	12-12.5	<23	DHP

Figure 13 shows the distribution of HSPF and SEER among the tested units. Most of the HSPF ratings are clustered fairly tightly in a range between 12 and 12.5. The SEER ratings are more evenly distributed with the largest number between 25 and 27; all but two are less than 27.

Figure 13. Distribution of HSPF and SEER Ratings among Tested Units



Unit Behavior During Lab Tests

Testing to EXP07 uncovered a number of anomalies and unexpected behavior for some of the equipment under test (subsequently: unit under test, or UUT) at certain test points or certain conditions. Because in many cases the tested units' behavior was more predictable, illustrating some of the anomalies can be best achieved by first considering a more typical instance.

Typical "Expected" Behavior

Figure 14 illustrates a typical behavior mode under low load conditions, from a cooling test at 77°F outdoor dry bulb (test condition CE humid conditions – see Table 1). The time segment shown includes three on/off cycles, during which the outdoor room is kept within the accepted tolerance, and the indoor room temperature fluctuates as the UUT responds. As the UUT begins cooling, the room temperature decreases, and the unit power maintains nearly steady until the internal controls tell it that the indoor room is cool enough, at which point the unit stops cooling and the room air temperature increases until the next cycle begins.

Figure 14. Cooling Test CE-H Example: Indoor/Outdoor Room Temperature and Power (Cycling)

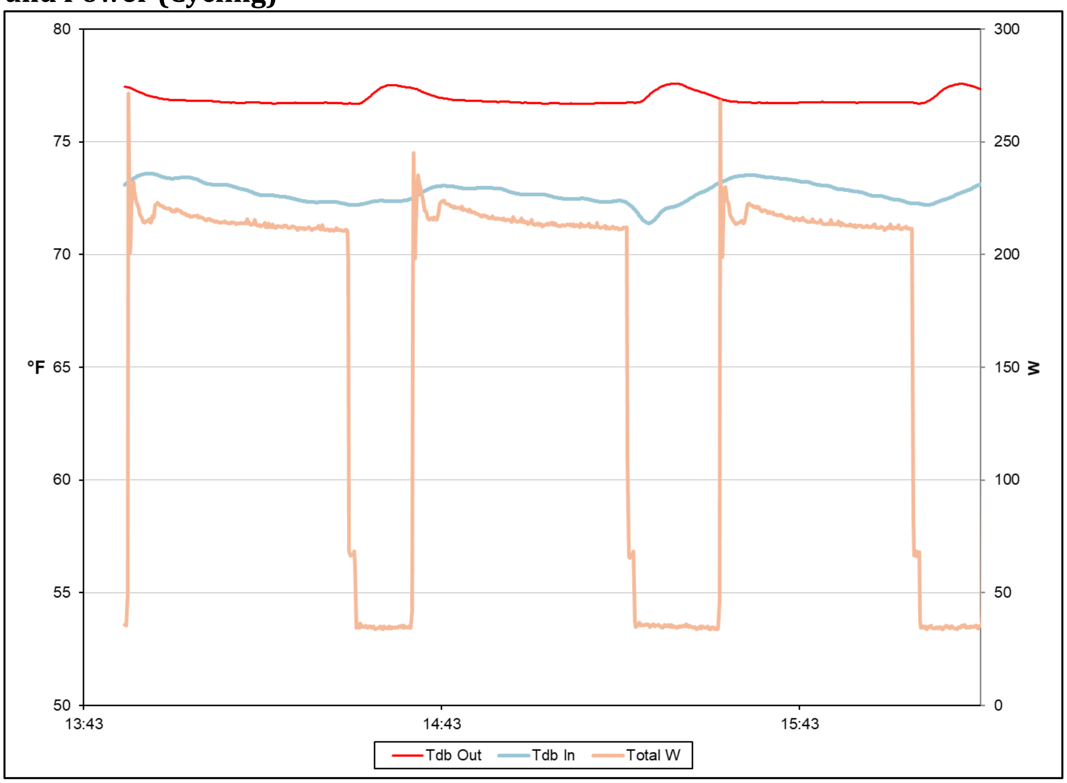
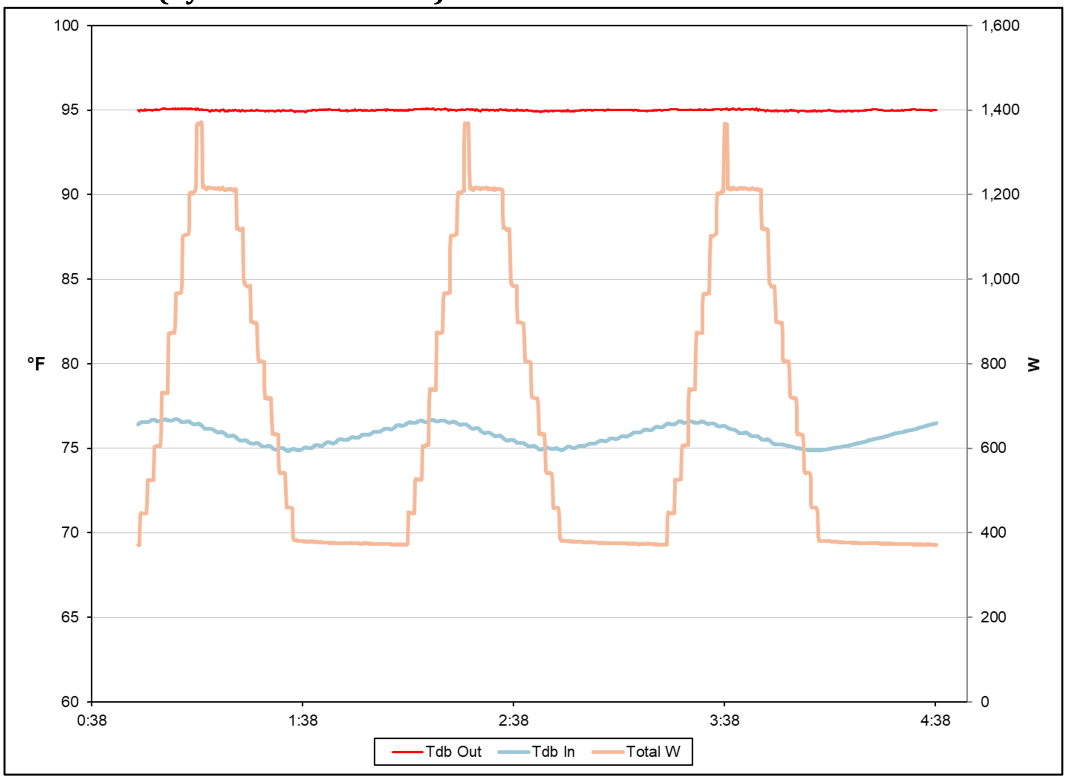


Figure 15 shows the behavior of the same UUT from a cooling test at 95°F outdoor dry bulb (test condition CC humid conditions – see Table 1), a more significant loading condition. In this case the UUT is "cyclically modulating": the compressor never shuts down, but modulates between roughly 380W and 1,200W, while the room temperature swings up and down in a regular pattern according to the simulated load program.

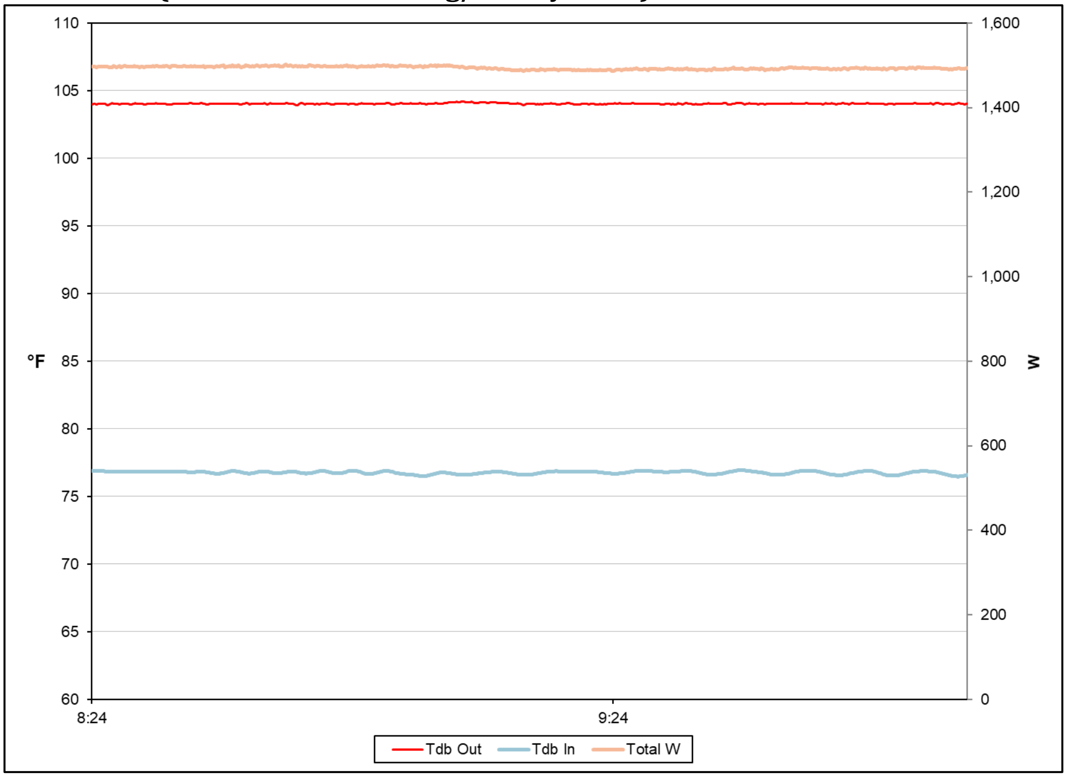
Figure 15. Cooling Test CC-H Example: Indoor/Outdoor Room Temperature and Power (Cyclical Modulation)



The third example, shown in Figure 16, is a full-load cooling test at 104°F outdoor dry bulb (test condition CB humid climate). This is an example of steady-state operation during a full-load test. Because the target load is higher than the UUT maximum capacity, the unit controls are set at their maximum temperature setting (in this case, minimum indoor room temperature setting) and the indoor room is held constant at the target temperature by the reconditioning equipment; there is no dynamic load but the UUT is still operating in its normal installed configuration with no special test mode settings.

Similar behavior under low-load, part-load, and full-load conditions are seen in many of the test runs across many of the tested units.

Figure 16. Cooling Test CB-H Example: Indoor/Outdoor Room Temperature and Power (Full Load, Modulating/Steady State)



Anomalous Behavior

UUT behavior is less predictable in a many cases. For example, Figure 17 shows a different UUT than previous figures during a heating test at 34°F outdoor dry bulb (test condition HD marine climate) During this test the UUT begins each cycle running at about 1200W, then modulates down to about 800W as the room temperature increases toward the setpoint. The room temperature continues to increase more slowly, and the compressor shuts off. The atypical behavior in this exampleis that at the end of each off-cycle, the next on-cycle begins with a defrost operation while the indoor room temperature continues to drop. After each defrost, a similar cycle begins. The irregular cycles slow convergence of the measurements, which is the most challenging any time the UUT is in a mode of repeating defrosts as well as cycling on heating capacity. In addition, `the indoor temperature swings of roughly 10°F over each cycle represent a significant comfort concern. A swing of 2°F is normal; if anything, variable-speed equipment promises more consistent indoor temperature control than conventional systems.

Figure 17. Heating Test HD-M Example

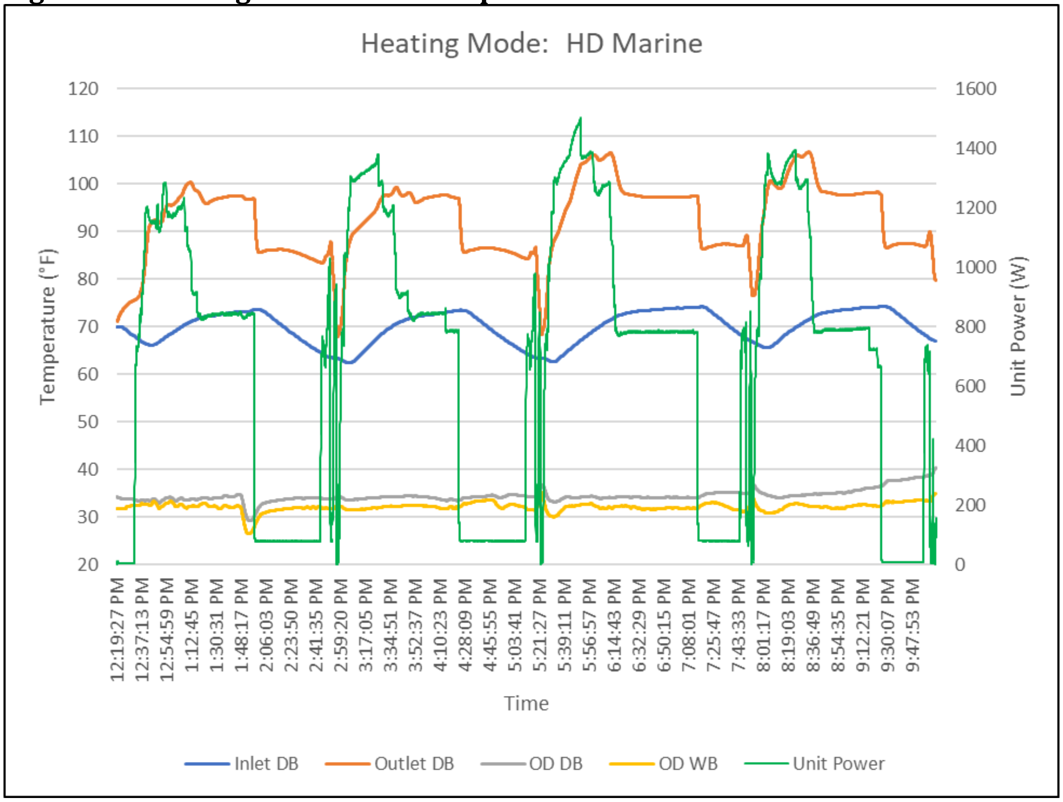


Figure 18 shows a dry-climate cooling test that spans three sequential test conditions over about a 9½ hour period. The first test condition shown (the 84°F outdoor condition indicated by the bracket labeled "1") shows a cyclically modulating mode during which the indoor room is kept at a fairly steady temperature while the input power modulates between 150 and 400W. During the second test condition (the 95°F outdoor condition shown in bracket "2"), the unit continues similar operation with somewhat higher input power levels. However, once the 104°F test has stabilized, the UUT seems to be unable to modulate even though it clearly has more than enough capacity to meet the load. Rather, it cycles the compressor on and off periodically at a much higher input level, while still maintaining the indoor temperature in a cyclical pattern rather than at a steady temperature. As with the previous example, this is an illustration of equipment algorithms that do not seem to be optimized, rather than an issue with the particular measurements or procedure; it also increases the test time, because cyclical operation nearly always requires longer to reach convergence than does a steady-state or smoothly modulating mode.

Figure 18. Cooling Test CD, CC, CB-D Example

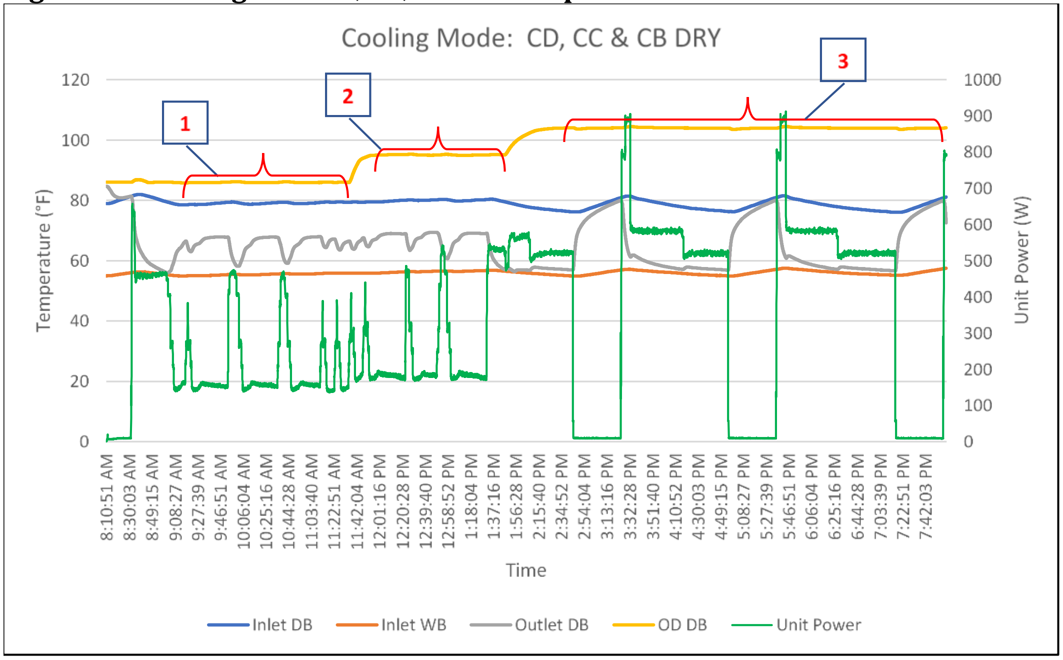
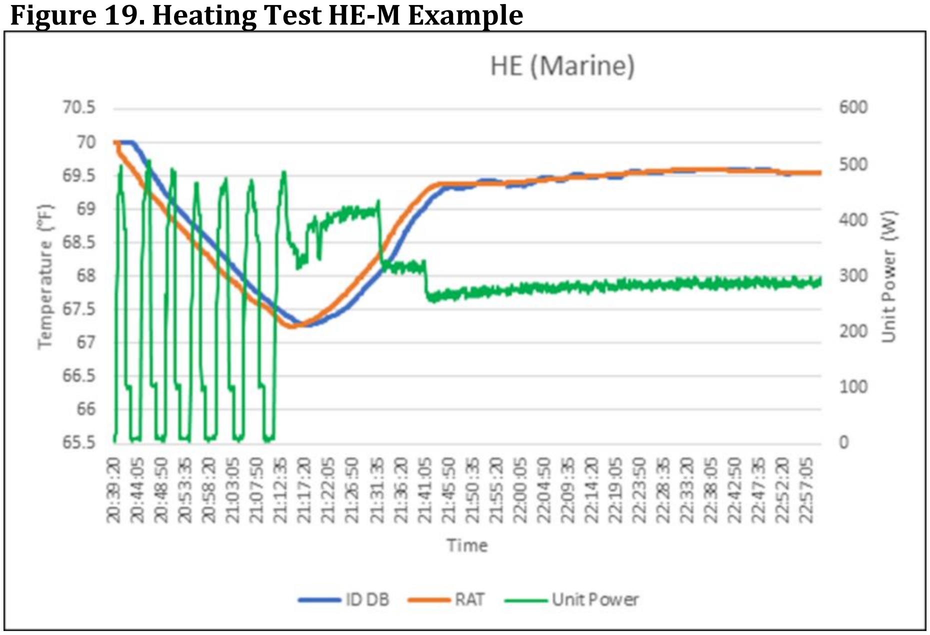


Figure 19 shows a heating test at 47°F marine conditions. This unit begins cycling, as the indoor room temperature drops significantly below the target of 70°F. After more than half an hour, it begins to run steadily, initially at a higher level of about 400W, and then modulating in two steps to about 300W as the room temperature stabilizes. Again, this does not present a problem for convergence once the unit is running in a stable manner, but it does extend the test time, seemingly unnecessarily, and suggests that the unit may not be operating optimally for real-life load conditions in that it allows for a significant temperature drop before adapting to the conditions and modulating.

Figure 19. Heating Test HE-M Example



Implications of Erratic Behavior

The instances of anomalous or erratic behavior in equipment under test were both frequent and varied enough to be worth noting, although no broad pattern or trends emerged that could be easily quantified. Some salient points regarding behavior clearly merit more investigation:

- Thermostat settings and offsets[9] are inconsistent, not only from model to model, but in some cases even for a given UUT under differing test conditions. Thermostat offsets present a challenge, both in finding the right setting to allow the UUT to reach the target indoor conditions within the allowed tolerances, and also by taking up significant lab time with the need to re-calibrate the thermostat target multiple times during a sequence of test segments.
- Irregular modulation and irregular responses of UUTs to load conditions lead to longer test times and increased uncertainty in the results at some test conditions. Some units were tested multiple times at the same conditions in order to obtain reasonable results, and in many cases the convergence criteria were not met, requiring the results to be integrated over the maximum prescribed test time, before moving on to the next test condition.
- Anecdotally, these irregular operating modes and erratic behavior are similar to observed behavior during field monitoring, and in general they seem to be associated with poorer overall performance in both maintaining comfort and field-measured efficiency.

If manufacturers were able to adjust their control algorithms to provide more consistent response to indoor and outdoor conditions, better calibration to indoor temperature, and to encourage modulation over cycling at lower load conditions, it is likely that test times could be shortened, and that both lab and in-field performance could be improved at the same time. Alternately, for the sake of consistency and repeatability, it may be necessary to determine a criteria under which some UUT fail the EXP07 test; currently no failure criteria exists.

Test Summary Results

Plots of Test Data

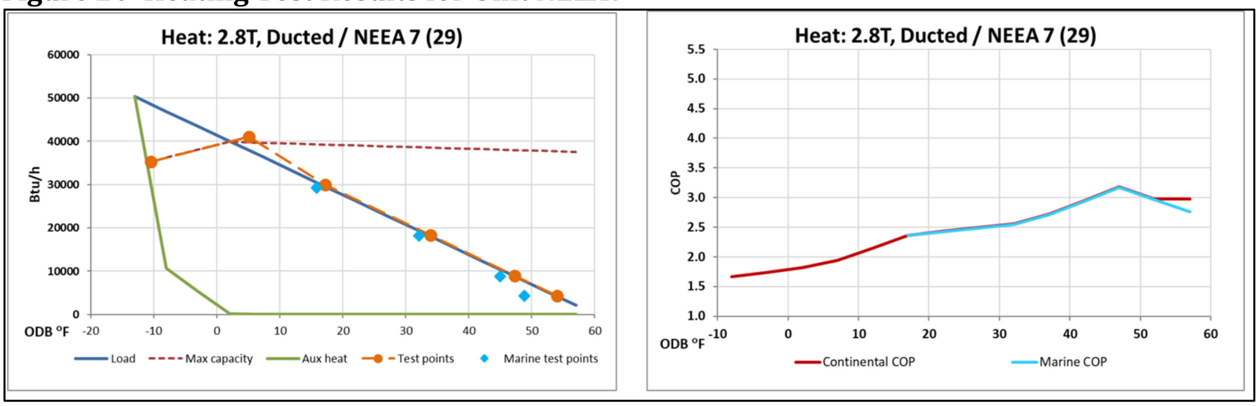
Every test sequence conducted yields two key data sets that can be plotted to understand the test results – capacity vs. outdoor temperature at the specific test points, and COPs across the entire range of outdoor test temperatures. The following section presents the results from the NEEA7 unit to illustrate this. Figure 20 shows the capacity plots on the left for the two heating test sequences: the orange points are the continental test points, and the blue diamonds are the marine test points. The solid blue line represents the load line; in

[9] That is, differences between control settings made by the user and the actual indoor room temperature maintained by the UUT as a result. Indoor room temperatures are evaluated in the test process by the actual temperature in the room, not the control settings, so any offset outside the allowed tolerance needs to be determined in order to conduct the test.

this case it's apparent that the unit capacity was only exceeded at the coldest outdoor temperature (-10°F, point HA-C), so that test was conducted as a full-load test.

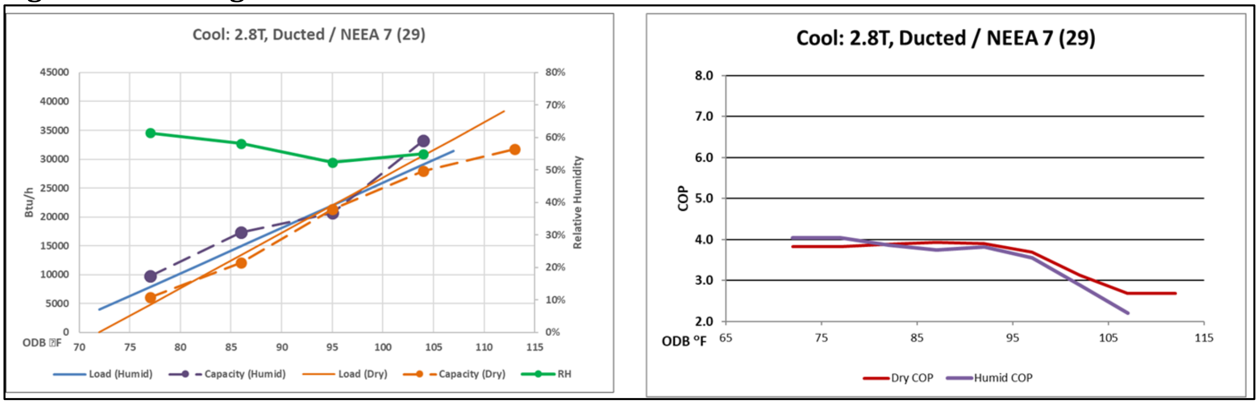
On the right-hand side, the COPs are plotted (red for continental, blue for marine); in accordance with the procedure, these COPs are interpolated for other temperatures used in the bin analysis. The COPs overlap between 17°F and 54°F. The green line on the capacity plot (left) represents the assumed electric resistance heat that would be needed once the UUT capacity is exceeded. Note that the COPs shown on the right are *not* adjusted to include the effect of the (assumed) resistance heat; that is added during the bin calculation for SCOP (e.g., footnote d of Figure 7). In this case, as one would expect, the COP is generally highest at the mildest outdoor temperatures.

Figure 20. Heating Test Results for Unit NEEA7



Similarly, the cooling capacity plot for the same unit (Figure 21) shows capacity measurements at the test points: orange for dry, purple for humid. The orange and blue solid lines represent the load lines for dry and humid respectively, which are similar – but not identical – in accordance with the procedure. Also, the relative humidity for the humid test is plotted in green (using the right-hand axis). In this case, the humidity control is moderate, at 61% R.H. at the lowest-load point and staying at or below 55% at the two highest points. In the COP chart on the right the dry and tumid traces are close together until temperatures reach 100ºF. As expected, the COPs are also lower with increasing outdoor temperature.

Figure 21. Cooling Test Results for Unit NEEA7



A full set of heating and cooling test plots is found in Appendix A.

Heating Seasonal COP Ratings

The full set of heating ratings for each unit and climate are shown in Table 6. The two highest-performing units in the Cold/Dry climate are highlighted in green, and also in the colder climates in light green. The same units are the top performers in all three climates, except for an additional tie for second place in the Subarctic climate. Cold/Dry is highlighted because it is the climate zone in EXP07 that has the most similar temperature bins to the Region IV bin data used in AHRI 210/240. The colder climates are also of particular interest because the tested units are all listed in the NEEP cold-climate directory, and because they represent the extremes of the heating rating process.

Table 6. Heating SCOP Results for All Climates

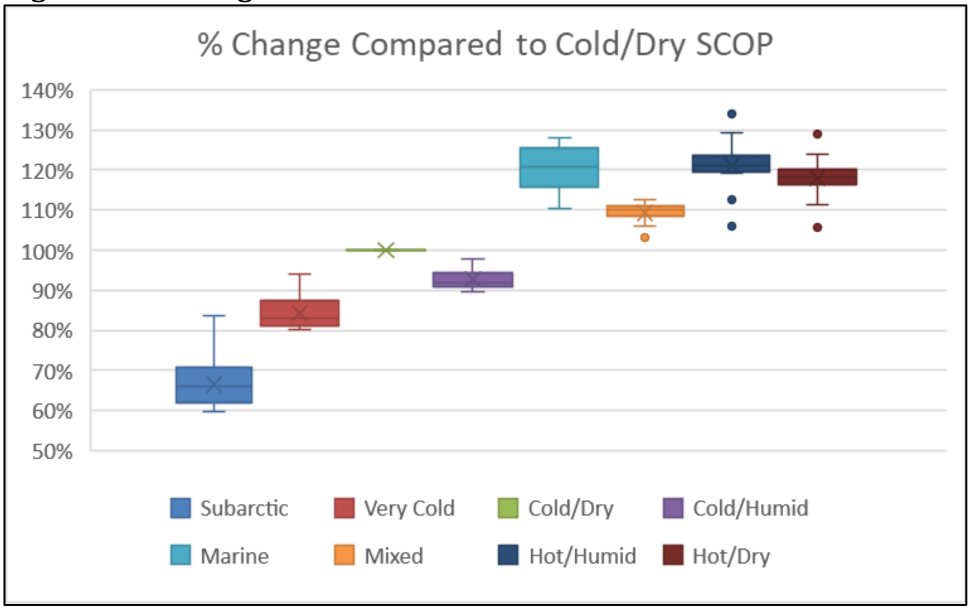
	Subarctic	Very Cold	Cold/Dry	Cold/Humid	Marine	Mixed	Hot/Humid	Hot/Dry
NEEA 1	1.68	2.19	2.70	2.45	3.31	2.98	3.29	3.19
NEEA2*	**1.80**	2.29	2.66	2.50	3.20	2.90	3.26	3.18
NEEA 3	1.60	1.97	2.26	2.13	N/A	2.45	2.74	2.68
NEEA 4	**1.80**	**2.42**	**3.02**	2.75	3.49	3.33	3.61	3.51
NEEA 5	1.35	1.52	1.62	1.58	1.78	1.67	1.71	1.71
NEEA 6	1.74	2.29	2.81	2.56	3.60	3.12	3.51	3.40
NEEA 7	1.74	2.18	2.47	2.36	2.85	2.62	2.78	2.74
NRCan1	** 1.55	2.01	2.47	2.26	N/A	2.73	2.98	2.91
NRCan2	**1.92**	**2.60**	**3.20**	2.94	4.02	3.52	3.84	3.74
NRCan3	1.49	1.88	2.26	2.08	2.73	2.47	2.69	2.63
NRCan4	1.63	2.01	2.30	2.17	2.88	2.49	2.79	2.72
NRCan5	1.67	2.11	2.52	2.31	2.98	2.82	3.37	3.24
NRCan6	1.59	2.06	2.58	2.31	3.14	2.90	3.33	3.19

* **NEEA2** is the only unit in the group that was tested using the optional point TOL (heating temperature operation limit), which for that unit is at Tout = -15°F. The added test boosts its SCOP in the coldest climates. The benefit (compared with the results if the TOL test had not been conducted) is 2.1% of the SCOP in Subarctic, 1.1% in Very Cold, less than 0.4% in the two "cold" climate zones, and no change for the remaining climates. The ratings of any unit with a TOL less than -10°F would benefit to some degree by including a TOL test, perhaps a bit more or less than the benefit for NEEA2. The degree of benefit would depend on both the outdoor limit temperature, and the unit's performance at that temperature; but the magnitude would be relatively small in any case due to the limited bin fractions at those low outdoor temperatures.

****NRCan1** did not have the HA-continental test conducted (at -10°F), so electric resistance heat is assumed below 5°F (the lowest temperature tested) in the bin calculation of SCOP. An estimated performance curve was applied from another tested unit with a similar capacity and efficiency profile, to estimate the sensitivity to this omission. It is larger than the omission of TOL (unsurprisingly because less-cold temperatures are affected); The SCOPs for the four coldest climates in that scenario would have been 1.76, 2.23, 2.58, 2.44, a penalty of between 4% and 12%. The SCOPs in the warmest climates would be affected much less. The heating results for this unit were included in the report because the difference would not have affected the analysis or conclusions to a substantial degree.

As can be expected, the SCOP values are lowest in the coldest climates and highest for the mild/hot climates. Figure 22 shows the distribution for each climate of the percent change of SCOPs for each unit compared with the same unit's Cold/Dry SCOP. It is not surprising that the climates with the tightest distributions are Cold/Humid and Mixed, which also have the closest bin profiles to Cold/Dry. Subarctic has the widest spread (with no outliers), which also makes sense because of the fairly wide variation in both the drop-off of heating capacity (affecting the use of assumed resistance heat), and also the drop-off in COP, at the colder temperatures. Such information about performance in various climate regions could help stakeholders (such as electric utilities in Very Cold climates) promote products that have the best performance for their specific region.

Figure 22. Heating SCOP Variations across Climate Zones



Cooling Seasonal COP Ratings

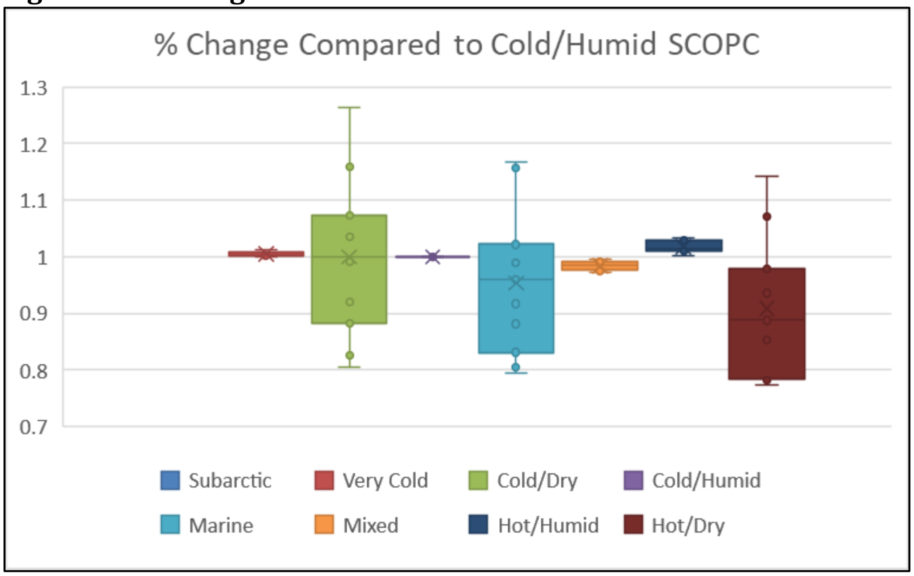
The full set of cooling ratings for each unit and climate are shown in Table 7. The two highest-performing units in the Cold/Humid climate are highlighted in green, and also in the hottest climates in light green. The same units are the top performers in all three climates. Cold/Humid is highlighted because it is the climate zone in EXP07 with temperature bins most similar to the cooling climate used in AHRI 210/240. The hotter climates are also of particular interest because they represent the extremes of the cooling rating process.

Table 7. Cooling SCOP Results for All Climates

	Very Cold	Cold/Dry	Cold/Humid	Marine	Mixed	Hot/Humid	Hot/Dry
NEEA 1	4.04	4.66	4.02	4.66	3.99	4.07	4.60
NEEA2*	4.01	3.68	4.00	3.53	3.97	4.06	3.42
NEEA 3	5.48	5.66	**5.43**	5.22	5.30	**5.60**	**4.83**
NEEA 4	5.04	4.39	4.97	4.13	4.84	5.07	3.90
NEEA 5	3.54	2.84	3.53	2.80	3.50	3.57	2.76
NEEA 6	3.57	3.56	3.56	3.26	3.48	3.68	3.04
NEEA 7	3.85	3.81	3.85	3.72	3.83	3.86	3.61
NRCan1	N/A						
NRCan2	4.73	5.03	4.68	4.79	4.62	4.73	4.58
NRCan3	N/A						
NRCan4	5.74	5.91	**5.71**	5.64	5.62	**5.79**	**5.34**
NRCan5	5.12	4.19	5.07	4.08	4.97	5.16	3.92
NRCan6	4.36	5.52	4.37	5.10	4.29	4.49	4.68

Figure 23 shows the distribution for each climate of the percent change of SCOPs for each unit compared with the same unit's Cold/Humid SCOP. Unlike the heating distribution by climate, the cooling distribution shows a pattern in which the dry climate ratings (Cold/Dry, Marine, and Hot/Dry) all vary quite substantially when compared to the humid SCOPs, while all the humid SCOPs form a very tight pattern with little variability. This means that the humid seasonal cooling performance is *not* a very good predictor of the dry seasonal cooling performance, and vice-versa.

Figure 23. Cooling SCOP Variations across Climate Zones



Indeed, during the humid cooling test, the various tested units exhibit a wide range of responses to the dynamic humidity load imposed by the indoor room dynamic model.

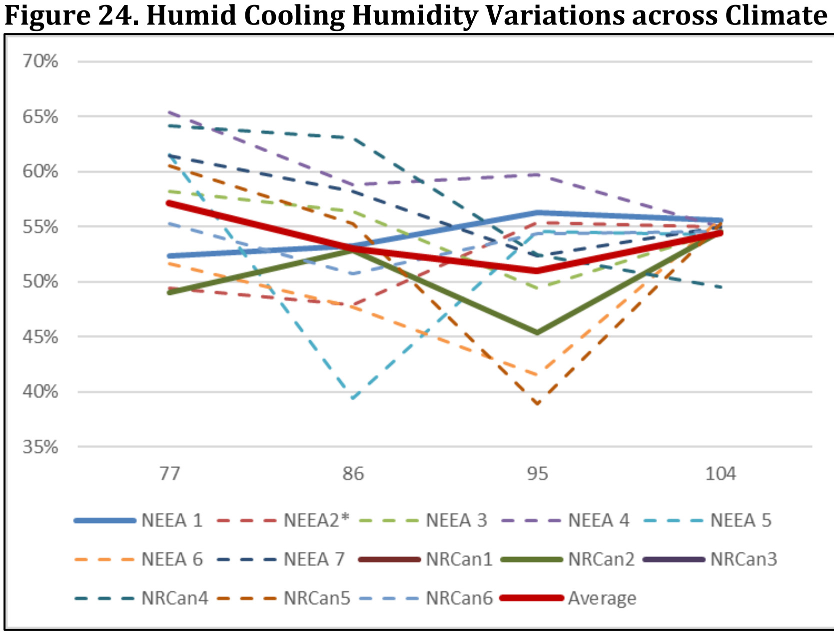
Before discussing humidity response in more detail, there is another observation about the overall test results from Table 6 and Table 7. NEEA5 tests showed poor performance, with heating SCOPs in the range of 10%– 35% lower than the next-lowest unit in heating mode (though its HSPF is 17% higher); in cooling, its SCOPs were much closer to the second-worst performing unit. It is highly unlikely that any test anomaly was responsible for these results, because the unit tested so poorly in all four test sequences (two each heating and cooling). It is notable that the unit was observed to operate in on/off cyclic modes at larger load conditions than most of its peers, suggesting that the poor performance could be due at least in part to the control algorithms. The unit was carefully setup and charged by a professional HVAC technician prior to testing., but it is possible that the machine purchased was defective and thus an anomaly. In the analysis presented below, this unit is either called out, or omitted from comparisons, in case that may be true.

Humidity Response

The range of response of the tested units to the dynamically-imposed humidity loads deserves mention. Unlike a standard full-load test used in other test procedures, the humidity in the indoor room is not held constant for each humid test interval. Rather, the target moisture *load* is determined as a percentage of the total load (SHR=0.8) and the moisture content in the indoor room air is updated in an identical manner to the sensible temperature for all the dynamic tests. The resulting humidity is measured and reported during the convergence period for each test interval. This is in contrast to the approach used in AHRI 210/240, where the humidity (as well as the temperature) of the indoor room is maintained by the room reconditioning equipment. The load-based humidity test employed by EXP07 requires the UUT to respond to a simulated humidity load and thus the UUT is solely responsible for removing the moisture. Some systems will be more effective at removing humidity than others under the same load conditions, and the EXP07 test reveals that. Figure 24 shows the responses of all 11 units tested in cooling mode, with the relative humidity on the y-axis and the four humid test outdoor temperatures reported on the x-axis.

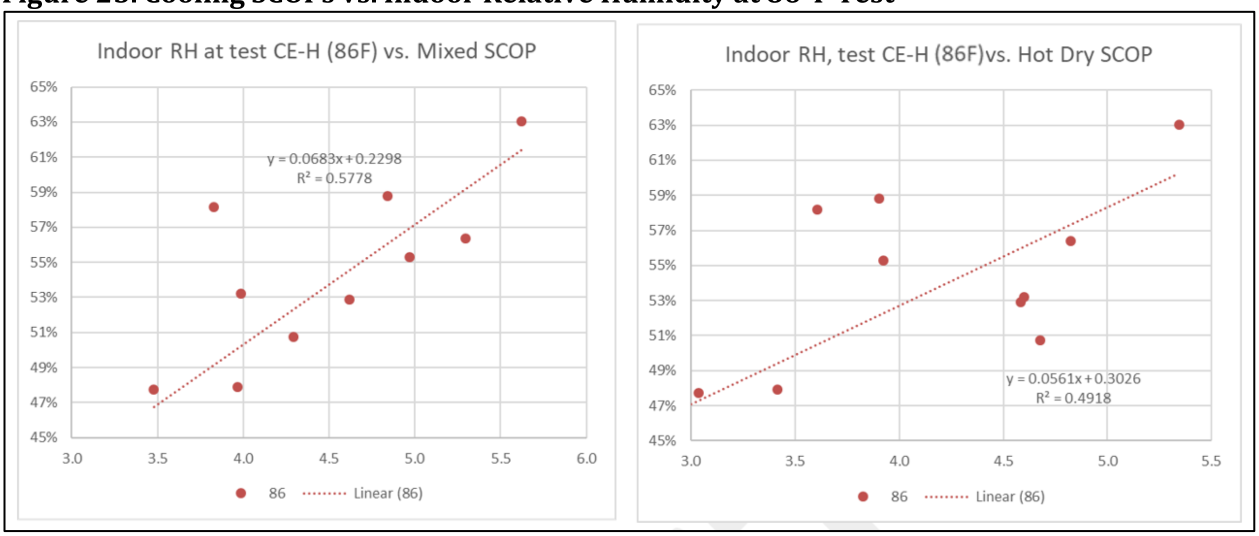
In general, the humidity control improves at higher loads, fairly steadily though there are some individual anomalies. This trend is not surprising because humidity control would be more difficult when the units are cycling on and off, which is common under the lower load conditions. Some are of the opinion that VCHP do not have this behavior since they can theoretically modulate to lower capacities and not cycle on and off, however in many cases they do cycle more than manufacturer's specifications would suggest. In all cases but one, the humidity is 55% at the 104°F test due to the units being converted to full-load tests; the one case represents a unit that continued to operate in modulating mode with adequate capacity at that temperature. A fair degree of variation appears to exist among the humidity control capabilities at the lower temperatures, with about a 15% spread between 50% and 65% relative humidity at the lowest-load point and a similar spread (though at somewhat lower humidities) at each of the next two points.

Figure 24. Humid Cooling Humidity Variations across Climate Zones



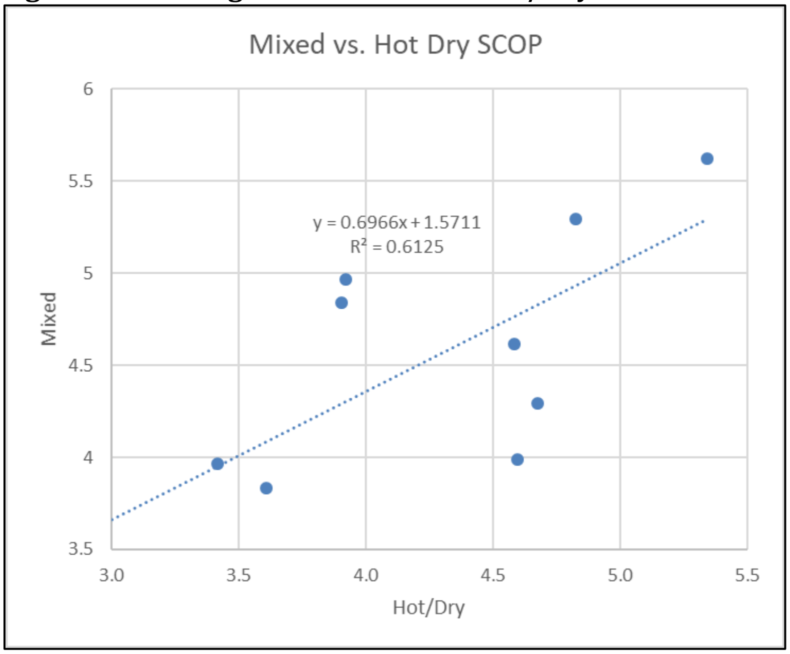
When considering the varying humidity response of the units, and the fact previously noted that the dry climate SCOPs vary widely relative to the (same units') humid climate SCOPs, it seemed possible that perhaps better humidity control under low load would be related to efficiency. When the humidity at the 86°F test is plotted against both Mixed and Hot/Dry SCOPs (Figure 25), there is a modestly strong relationship, especially for the Mixed climate comparison. The temperature bins from 77°F to 87°F represent the largest share of total cooling hours (60%–70% in both the Mixed and Hot/Humid climates), so the dehumidification performance at those conditions affects a unit's SCOP the most. It makes sense that the relationship would be inverse: it requires energy to dehumidify, so the units that are more "efficient" may not actually provide as much humidity control or comfort in humid cooling climates. If test results of EXP07 were widely available, this type of information could be used by individual regions to help stakeholders to target products that best meet both consumer needs and stakeholder (e.g., electric utility) interests. Because the SCOP includes the energy used to provide both sensible and latent cooling during those tests, a unit with a higher SCOP and lower reported relative humidities would provide a significant advantage for those climates. It may be worth finding a way to combining the SCOP and humidity removal into a single metric for humid cooling ratings.

Figure 25. Cooling SCOPs vs. Indoor Relative Humidity at 86°F Test



While some modest exceptions exist, the trend is fairly strong between the Mixed and Hot/Dry SCOPs (Figure 26). While it is plausible that some individual products may be better optimized "out of the box" for either a dry or a humid climate, this doesn't generally seem to be the case with the units tested in this project.

Figure 26. Cooling SCOPs: Mixed vs. Hot/Dry



Analysis of EXP07 and AHRI Ratings

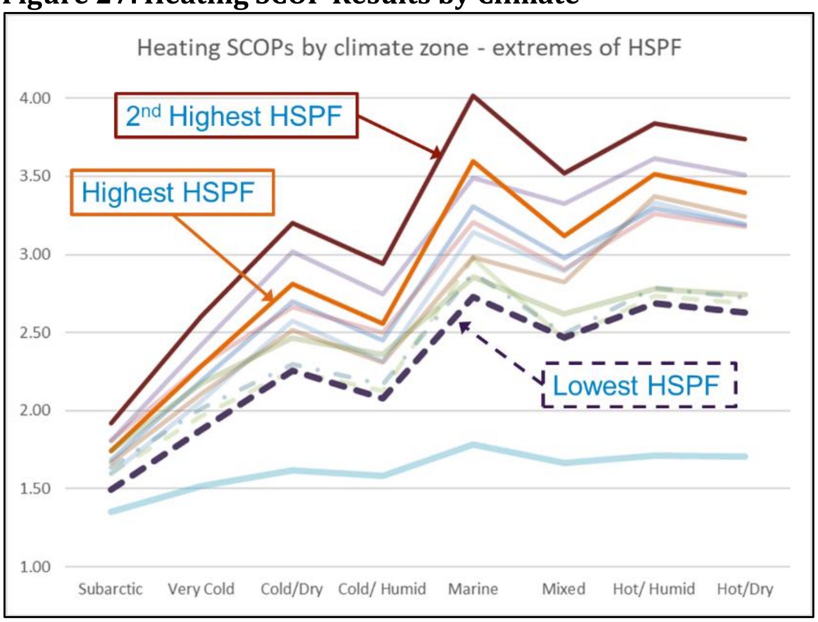
Because the sample size is small, and some details of the test procedure was still being adjusted over the course of the year these tests were being conducted, no sweeping conclusions are possible based on the test results. This is one reason this study team has not reported on or analyzed the specific relationship between heating SCOP and HSPF or cooling SCOP and SEER. (Another reason is that these are two different metrics based on very different measurements, as has been discussed above).

Heating Performance by Climate

One way to visualize the results of the heating tests is to plot the SCOP result for each tested unit, by climate. Figure 27 shows the eight heating climate zones along the x-axis, and the calculated SCOP on the y-axis. Each tested unit is shown as a different line so that the SCOP of each is easy to see, relative to the others and across the climates. The climates are ranked generally by severity of temperature with coldest on the left and warmest on the right; the Marine climate is the anomaly with much higher SCOPs due to its unique climate profile.

Three units have been highlighted on this chart: the two with the highest HSPF ratings, and the one with the lowest HSPF. Setting aside the one unit with SCOPs that are far below all the others (in case it was an individual, defective product), the highest HSPF units generally performed well in the heating tests and the lowest HPSF unit had the lowest heating efficiency.

Figure 27. Heating SCOP Results by Climate



Heating Rank Order

Another way to visualize the collective data from the tests is to compare the rank order of the SCOP ratings using EXP07 with the rank order of the HSPF ratings from AHRI 210/240 (aka "ranking"). It might be reasonable to expect that if the AHRI 210/240 ratings were representative of as-installed performance, that in general the load-based test in EXP07 would rank the efficiency of a group of tested units in roughly the same order as the ranking of their AHRI ratings. This is not the case.

For the heating tests, Figure 28 shows the ranking of the 13 units' HSPF ratings on the left y-axis, and that of their Cold/Dry SCOP values on the right y-axis. (Cold/Dry was chosen because the bin profile is the closest match to that of the Region IV that is used in the HSPF rating). What is immediately apparent is that the rank order differ- substantially. Although the two top-rated HSPF units are among the top three SCOP values, and the two with the lowest HSPF ratings are among the lowest five SCOP results, the overall order is significantly mixed. The best explanation for these extremely varied results is that the control algorithms in some cases don't allow the equipment to perform as well as the equipment hardware components are capable of, or as well as fixed-condition tests (and in many cases, extended engineering performance tables) would indicate.

Figure 28. Ranking of HSPF and SCOP

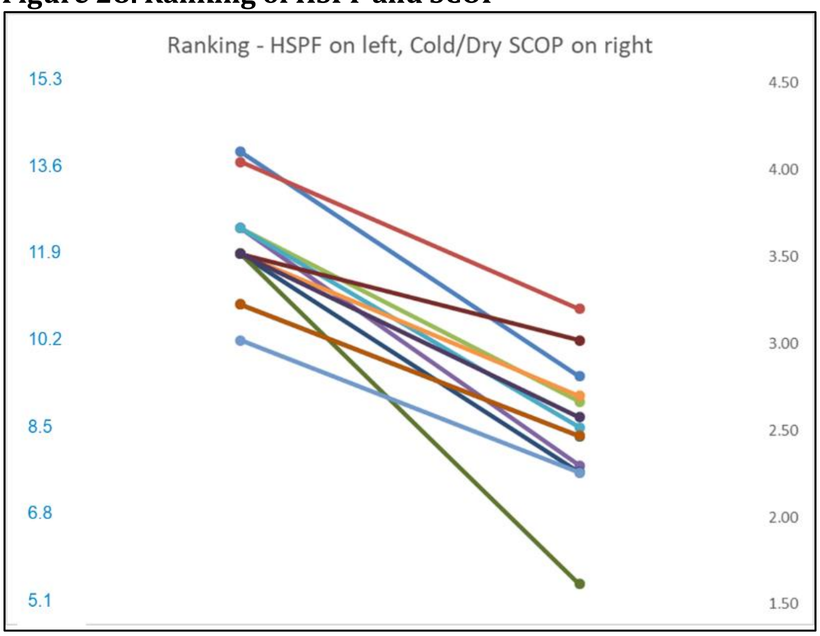
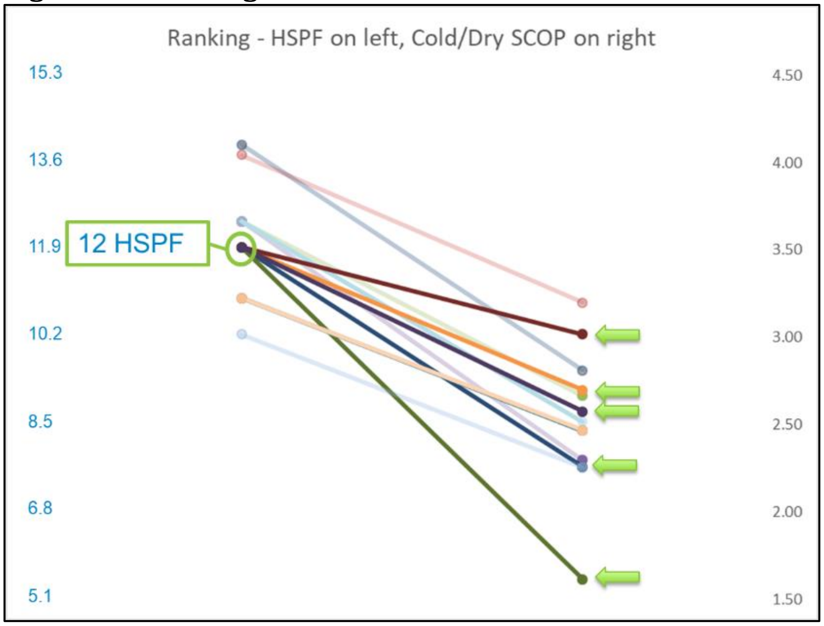


Figure 29 shows the same data, but with the focus on the five units with an HSPF of 12. Though the AHRI rating is the same for all five, the SCOP results cover a range from the lowest to the second-highest in the group. These results, representing a range of nearly 2:1, are too large to be explained by minor inconsistencies that may linger in the test procedure. Even discounting the one outstanding poor performer as before, the highest SCOP of the 12 HSPF units is 34% higher than the lowest SCOP, and the SCOP results still span almost the full range of those units tested. This is not surprising, considering that the use of units' internal controls results in a wide range of behaviors during the load-based test, behaviors that are not apparent when conducting the AHRI 210/240 test and rating. Incentive programs and building standards based on HSPF are thus not capable of giving appropriate credit to the better performing units.

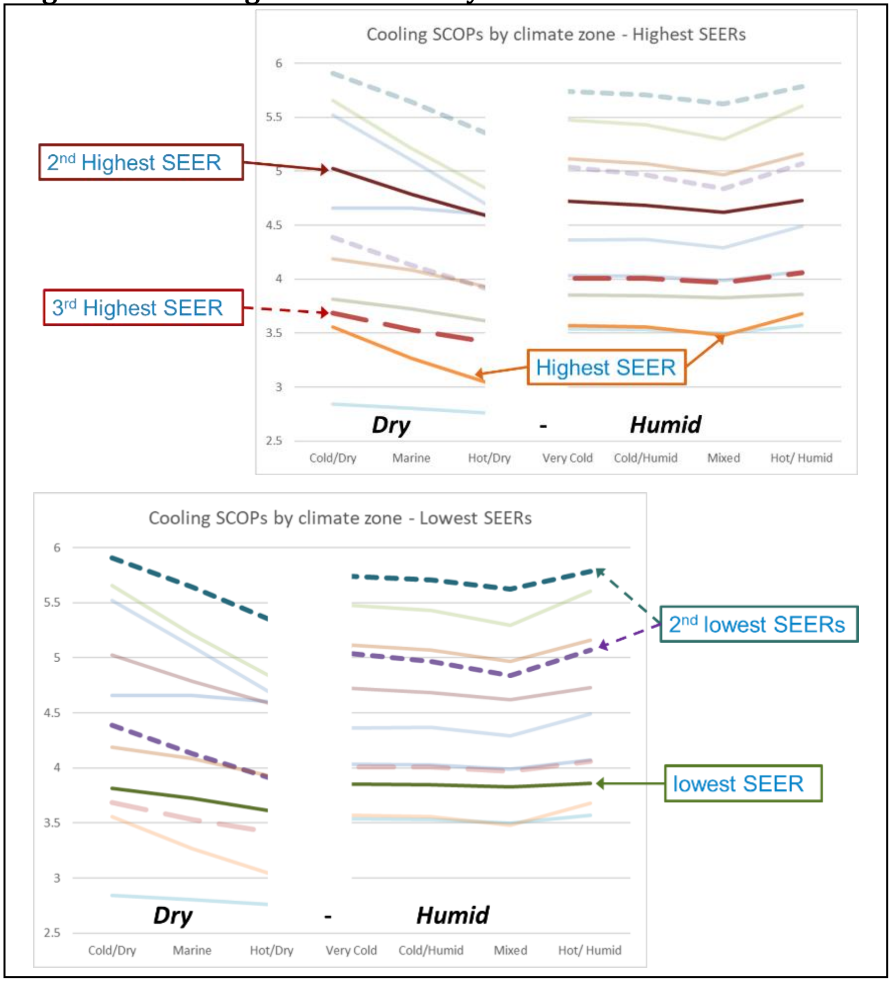
Figure 29. Ranking of HSPF and SCOP



Cooling Performance by Climate

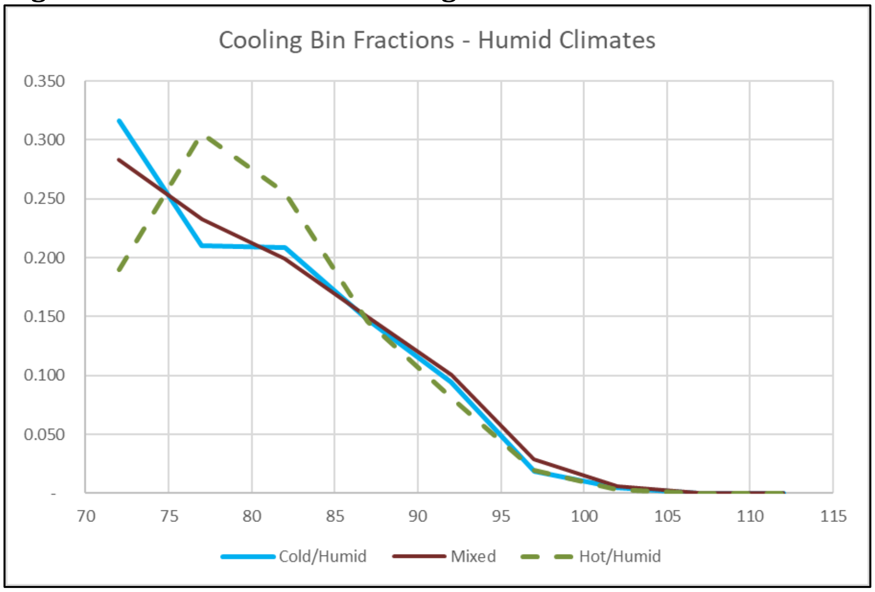
Figure 30 shows a pair of charts, each displaying the cooling SCOP results by climate. Like the heating chart in Figure 27, the x-axis shows climates arranged by temperature; however, for each chart the dry climates are shown on the left side (in order) and the humid climates on the right (also in order). In the dry climates, for each unit, cooling SCOP drops as the climate gets hotter; however, for the humid climates, the hottest climate generally has the highest SCOP. (This may seem counter-intuitive, but as shown in Figure 31, the Hot/Humid climate has much higher bin fractions at the 77.5- and 82.5-degree bins, where efficiencies are generally higher, than the other humid summer climates; their bin fractions are all similar at the higher temperatures where efficiencies are generally lower.)

Figure 30. Cooling SCOP Results by Climate



Within each chart, several units are highlighted. The top chart shows three highest SEER ratings; the unit with the highest SEER has the worst efficiency in all the cooling climates (excepting the one outlier, which also had the worst result in the heating tests). All three are in the lowest half of the group. On the bottom chart, the lower-SEER units are called out; they span most of the range of EXP07 cooling SCOPs. Notably, one of the units with the second-lowest SEER (two were tied for second) had the best cooling performance of the eleven.

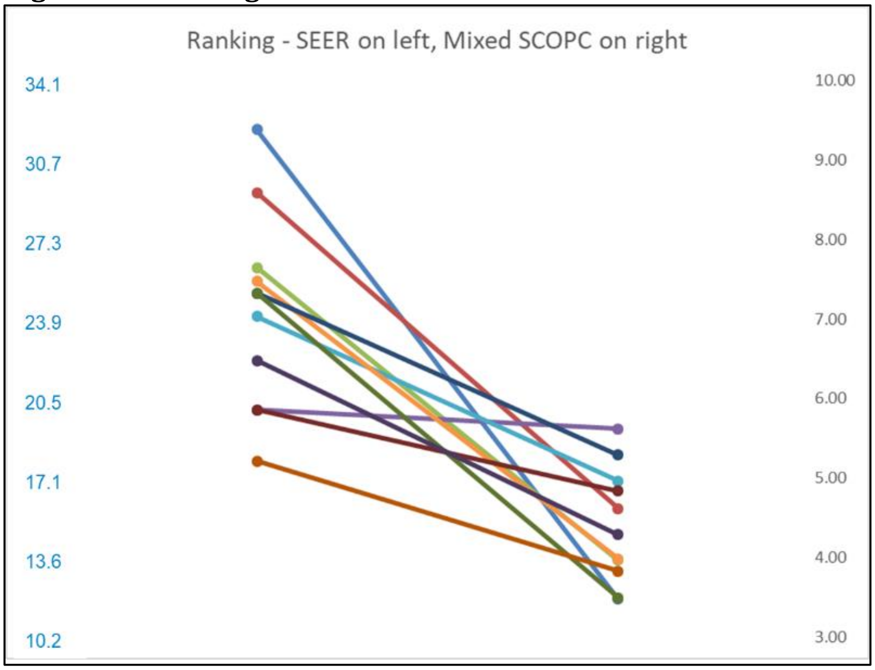
Figure 31. Humid Climate Cooling Bin Fractions



Cooling Ranking

Similar to the heating results, it's useful to visualize the rank order of cooling SCOP ratings using EXP07, side-by-side with the rank order of the SEER ratings using AHRI 210/240 (aka "ranking"). Figure 32 shows the rank order of SEER ratings on the left y-axis, with each corresponding units' Mixed/Humid-climate SCOP on the right. This chart has significantly more cross-over, with several units with higher SEER ratings showing low efficiency using EXP07, and some units on the lower end of the SEER ratings doing quite well with EXP07. The highest SEER unit has the lowest SCOP. A middle of SEERs unit has the highest SCOP.

Figure 32. Ranking of SEER and SCOP

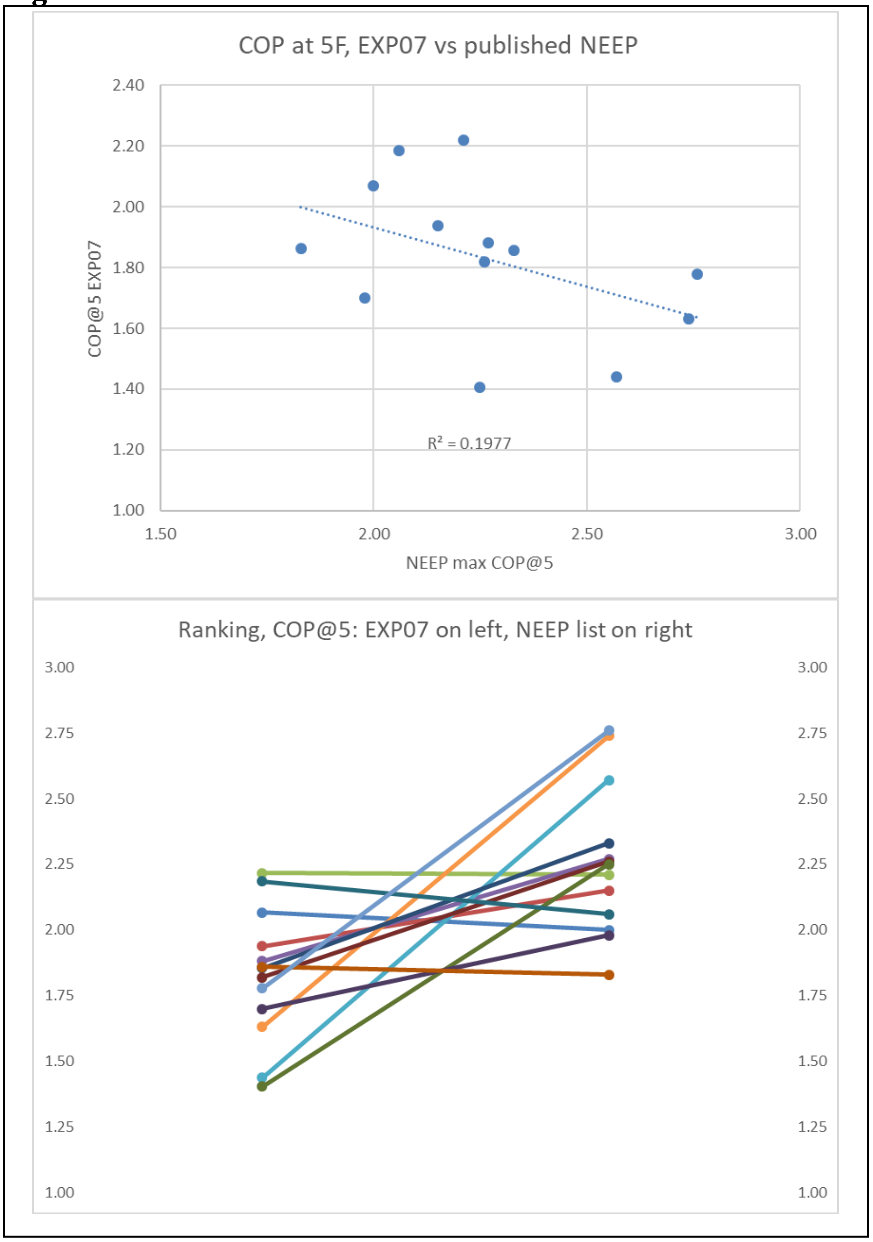


Alternates Using Existing Metrics versus EXP07 Tests

Some heat pump and AC stakeholders have suggested that supplementing traditional HSPF and SEER metrics with information gained from existing or soon-to-be standardized tests such as the COP at 5°F and EER at 95°F will improve the understanding of overall cold or hot weather performance, respectively. In fact, many programs have used EER at 95°F for many years, and more recently the NEEP cold climate listing criteria (and the proposed V6.0 Energy Star heat pump/AC product specification) include a minimum COP at 5°F for heating performance. Looking at the EXP07 test results may provide some insight into the relevance of such specifications. Before test results using Appendix M1 are available, the only available information on COP at 5°F to compare with EXP07 is from manufacturer self-reporting; generally, values reported in the NEEP listing tend to match closely with manufacturers' extended performance tables.

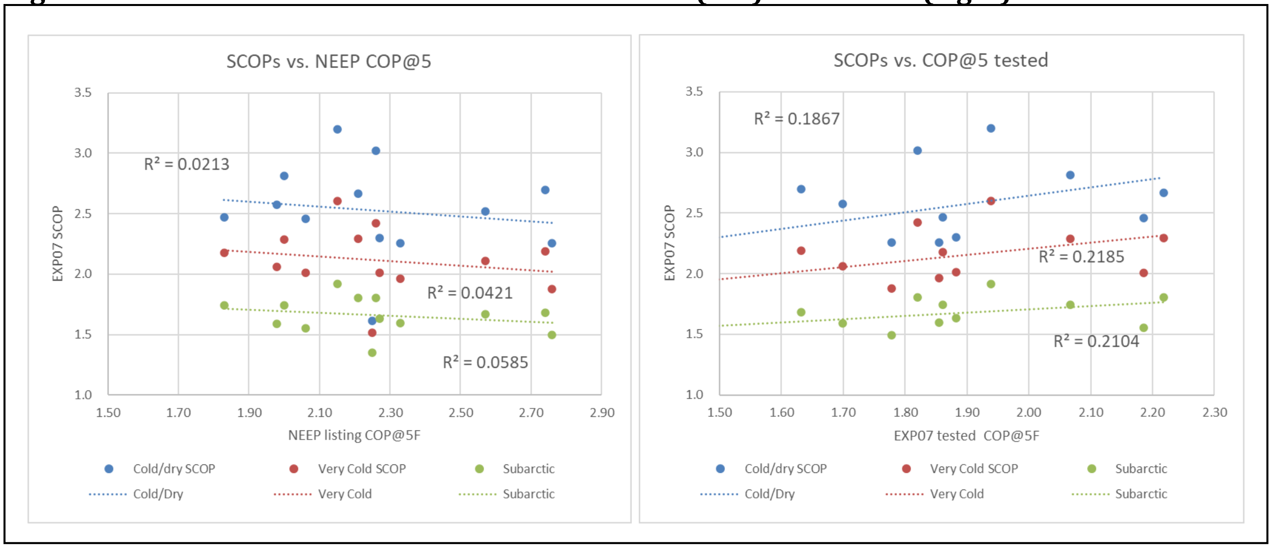
Figure 33 shows the COP relationship between the NEEP listed manufacturer's data and the EXP07 test results at 5°F in two ways: scatter plot with linear fit; and solid lines from EXP07 and NEEP reported COP at 5°F. There is a very poor correlation between the lab test results and manufacturers' data. Only three of the UUT have nearly the same COP as shown by nearly horizontal lines in the lower plot. Whether conducting tests at 5°F using Appendix M1 will yield results more in line with real operating performance remains to be seen.

Figure 33. COP at 5°F: EXP07 vs. NEEP



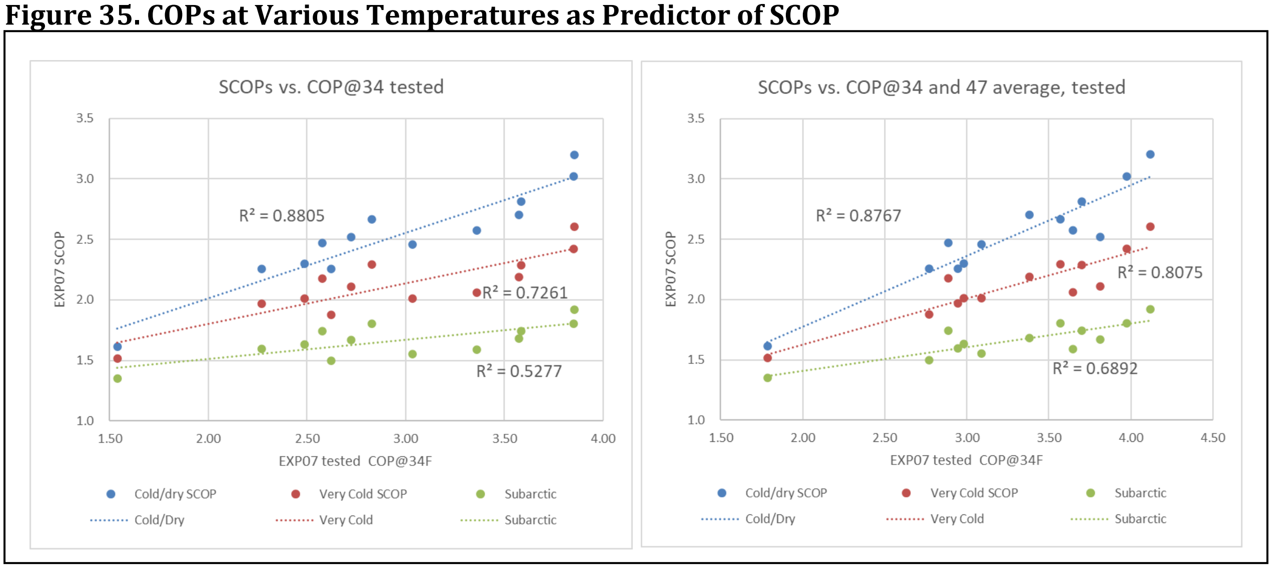
It's also useful to consider whether the 5°F performance is a good predictor of seasonal performance. Figure 34, left shows that the NEEP-reported COPs are extremely poor predictors of SCOP in three of the coldest climates (Subarctic in green, Very Cold in red, and Cold/Dry in blue), and in fact there seems to be a modest inverse relationship with a lot of scatter. The EXP07 tests (on the right) seem to be slightly more representative of realistic performance, still with poor correlations but with R squared values an order of magnitude higher and with a positive slope.

Figure 34. COP at 5°F as a Predictor of SCOP – NEEP (left) and EXP07 (right)



Of course, the coldest climates have many more hours at much lower temperatures than the more moderate climates, but even the Subarctic climate has only 20% of the bin hours below 5°F, with 70% between 5 and 47. Reviewing the data, it turns out that the individual test COP that correlates best with the Cold/Dry SCOP for this set of tests is the 34°F test (Figure 35, left). The 17°F test correlates slightly better in the Very Cold and Subarctic climate SCOPs (not shown). Averaging two or more of the individual COPs yielded even closer correlation, with 34°F and 47°F together being the most predictive (Figure 35, right).

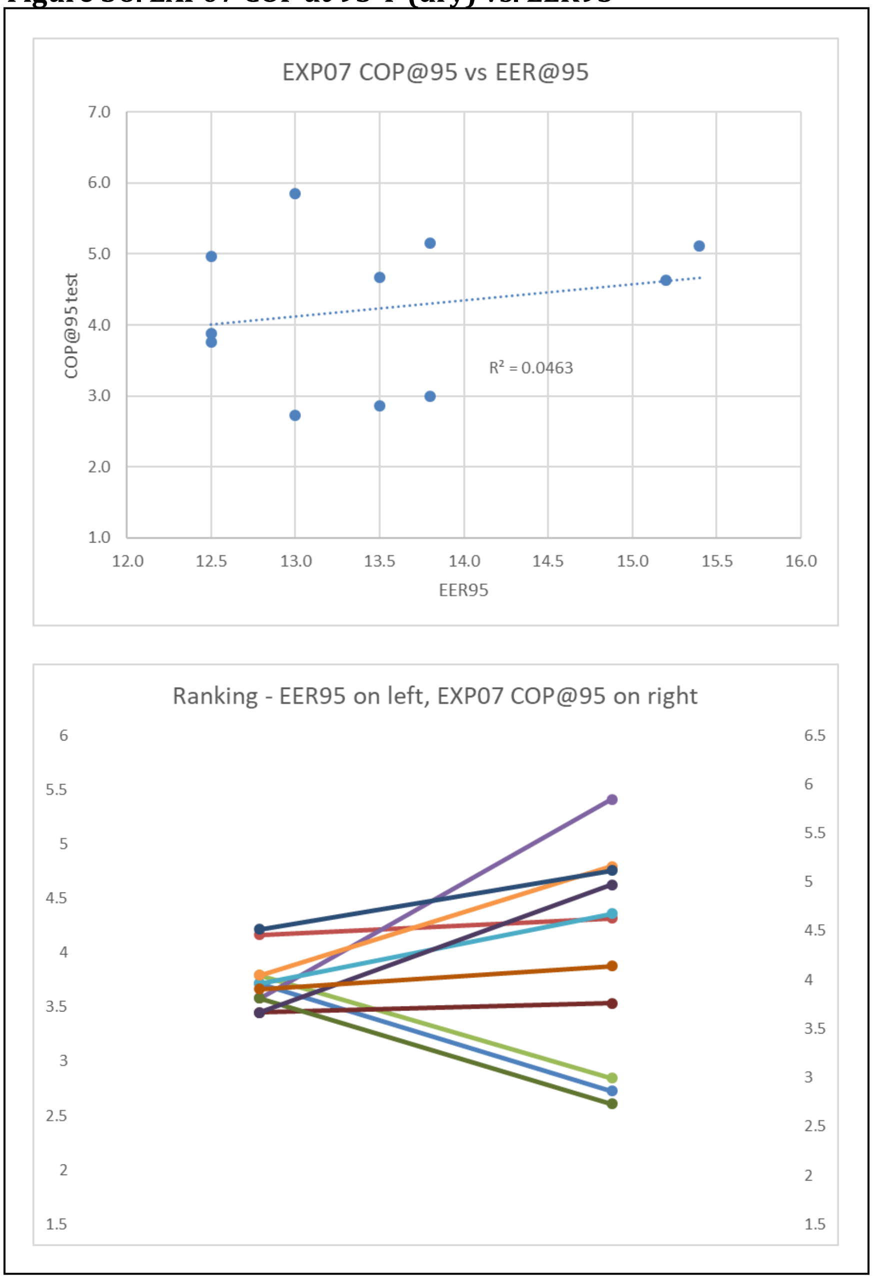
Figure 35. COPs at Various Temperatures as Predictor of SCOP



Unsurprisingly, averaging all four of the test points, equally-weighted, from 5°F to 47°F led to the highest correlations; however, that result gets so much closer to the bin-weighted result that is the SCOP calculation that there's not much advantage in averaging multiple test points. However, the idea that a single metric such as 5°F performance—even when measured under realistic performance conditions—is likely to provide a good proxy for overall cold-weather performance is not supported by this analysis.

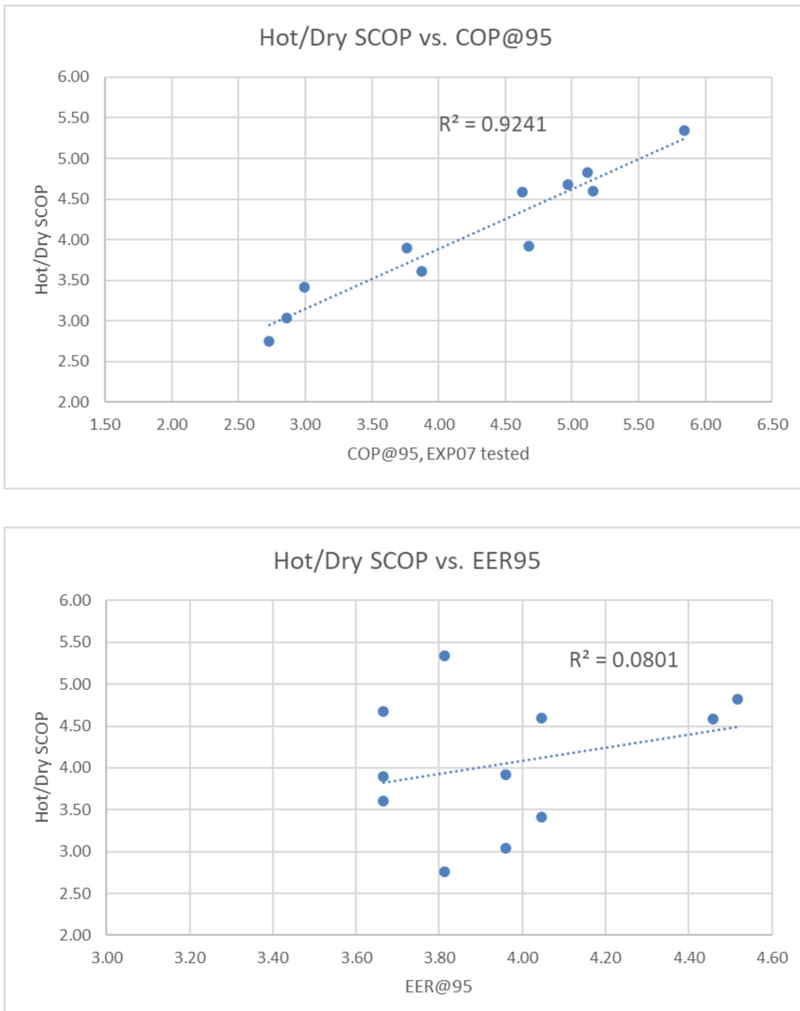
In terms of cooling performance, EER95 seems no better-suited. Figure 36 shows how little relationship the EER95 has to the EXP07 test results at the 95°F dry test regime; although the tests are not directly comparable, one might expect at least some correlation if the equipment performance under fixed conditions and locked equipment operation was representative of performance using native controls. As seen previously most UUT have major changes with four of the units having almost horizontal lines.

Figure 36. EXP07 COP at 95°F (dry) vs. EER95



As it turns out, the EXP07 dry COP at 95°F is actually a good predictor of the Hot/Dry SCOP, as shown in Figure 37 (top). Its correlation coefficient of 0.92 is an order of magnitude better than EER95, as shown in Figure 37 (bottom).

Figure 37. EXP07 COP at 95°F (dry) and EER95 as Predictors of Hot/Dry SCOP



Marine vs. Continental Testing

Because the test time is significant, especially for heating tests, one question is whether the separate marine heating test sequence is worth the extra test time. There are differences between the marine test and the continental test: in the marine testing the outdoor room humidities are higher, and the testing does not include any outdoor temperatures below 17°F (they are not needed in the bin profile of the Marine climate). The higher outdoor room humidities do present more of challenge for the outdoor room reconditioning equipment as well.

Figure 38 illustrates the relationship between the Marine SCOP when calculated using the marine test data (on the x-axis) and the calculated Marine SCOP using the continental test data. The average variance for this sample of 12 units is 2.3%; using the continental test results tends toward slightly higher ratings, which makes sense because the defrost energy is expected to be somewhat lower than it would be in the marine test results. The total range of results are less than +/-10% of the average, which is not trivial but is also not large. It may be fruitful to explore the possibility of eliminating the separate marine test sequence, which would save a significant amount of the lab test time needed for the heating tests.

Perhaps the best way to address this would be to allow the additional testing to be optional; for example, using a discount in the range of 5–10% if the continental test data are used to calculate the Marine SCOP, in lieu of conducting actual marine tests. This would allow manufacturers who employ significantly improved defrost capabilities to take credit for improved performance in the Marine climate and would also allow the option to forego the increased test burden by using a default.

Another option would be to repeat the higher outdoor humidity testing at only one test point (at 34°F). The difference is not very significant using the 34°F test point (red data points, Figure 38 top), but it does align the results somewhat more closely. The average deviation shrinks to 1.5%, and as shown in Figure 39, it does tighten the range of variation somewhat. More data collected from additional ongoing tests can be used to further this analysis and to evaluate the degree to which the additional marine tests could be omitted, or made optional, and the likely impact that would have on the rating results.

Figure 38. Marine SCOP as Tested vs. Marine SCOP Using Continental Test Data (Alt Marine)

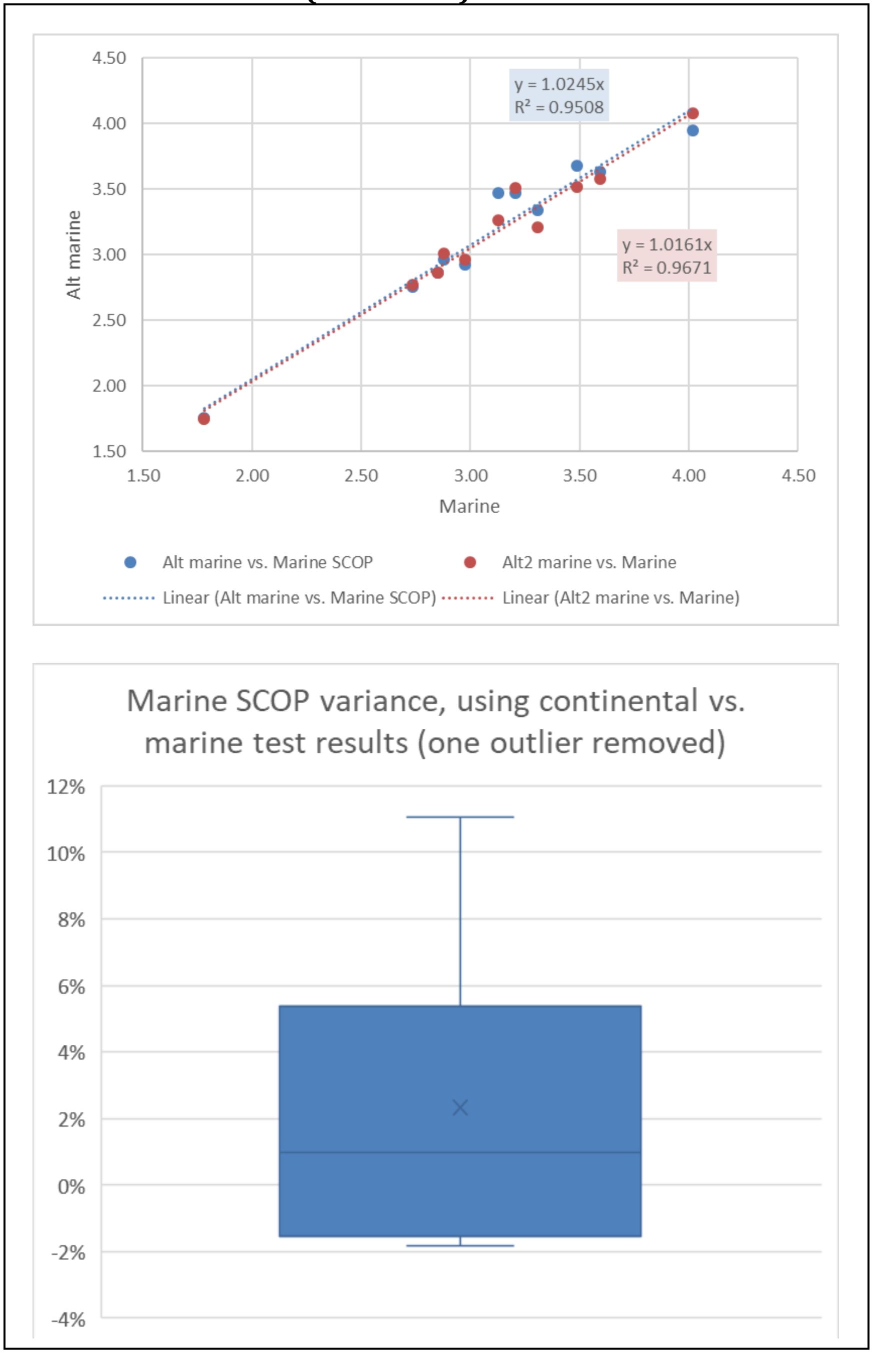
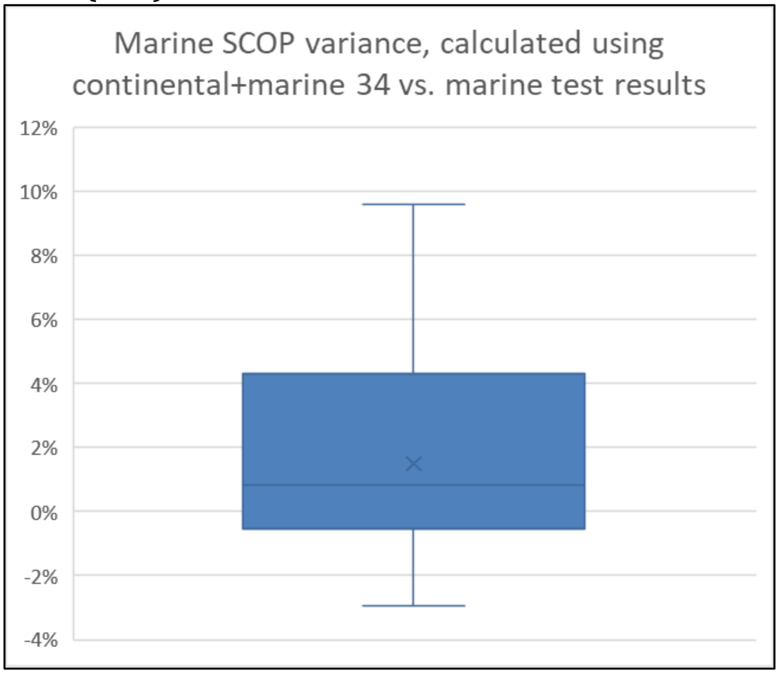


Figure 39. Marine SCOP as Tested, Variance from Marine SCOP Using Continental Test Data Plus One Marine Test Point (Alt2)



Summary and Conclusions

At this stage in the process of developing the EXP07 test procedure, the most significant conclusions are that the performance results of EXP07 would lead stakeholders to rather different conclusions about the relative efficiencies of various models, both in general and in specific climates, as compared with the current AHRI 210/240 test and rating results. The single largest reason for the variability appears to be in the firmware: the embedded control logic, which is not tested using current AHRI rating procedures. While some manufacturers may under-report their units' performance using AHRI tests for the purpose of publishing ratings, it's unlikely that this practice is widespread or explains the degree found in the comparisons shown in Figure 28, Figure 29, and Figure 32. The fact that a significant number of units perform much more poorly in the EXP07 test relative to their peers with the same, or lower, AHRI ratings calls into question the validity of using AHRI ratings to estimate energy consumption and savings for consumers, utilities, and government agencies.

Optimization of equipment firmware algorithms that would provide better performance and faster, less expensive lab tests under EXP07 would likely not only improve reliability of the test procedure results, but would also likely improve field performance and efficiency by reducing or eliminating erratic performance, irregular temperature sensing, and low-load short-cycling. One of the things worth future consideration is that changes in firmware should be tracked so that labs, consumers, incentive programs, and building standards know what performance to expect. It is possible to have the same model but different controls that make a large difference in performance. It is also possible with internet connectivity that unit controls can be updated/changed. If so this needs to be tracked.

More testing using EXP07, including the current phase of research that focuses on repeatability and reproducibility of the test, will add valuable insight into the test procedure and will likely yield suggestions for improvement of the procedure. Representativeness testing will also be critical—validating EXP07 with comparisons to field performance testing of the same units will reinforce the value and relevance of load-based testing. Comparison of EXP07 results with field monitoring, will help ascertain the degree to which load-based testing represents of real-world performance. Field data will not match exactly estimated data from lab results, but it will show relevant performance trends and comparative performance between models.

Even before the results of this ongoing and future research are available, the current findings clearly indicate that operational performance is not always well-predicted by the current standard AHRI ratings. AHRI ratings are effective at measuring the *potential* performance of equipment, but leaving the operational control "brains" entirely out of test and rating procedures omits a critical component of real system operation. Using load-based testing that includes these "brains" provides very different rankings of performance across units for both heating and cooling operation; because many of the same anomalies observed in the EXP07 lab testing have also been observed in field monitoring, it is reasonable to expect that the EXP07 results will be validated to a significant extent by a more focused model-by-model comparison with real in-field data.

Appendix A: Test Plots

The following pages show the test plots of all 13 units. On the left are the load line and capacity curves; on the right are the COP profiles (as explained in the narrative surrounding Figure 20 and Figure 21). Heating charts are on top and cooling charts are on the bottom, for each set (except for two units that did not have cooling tests).

Figure 40. Test Plots for NEEA 1

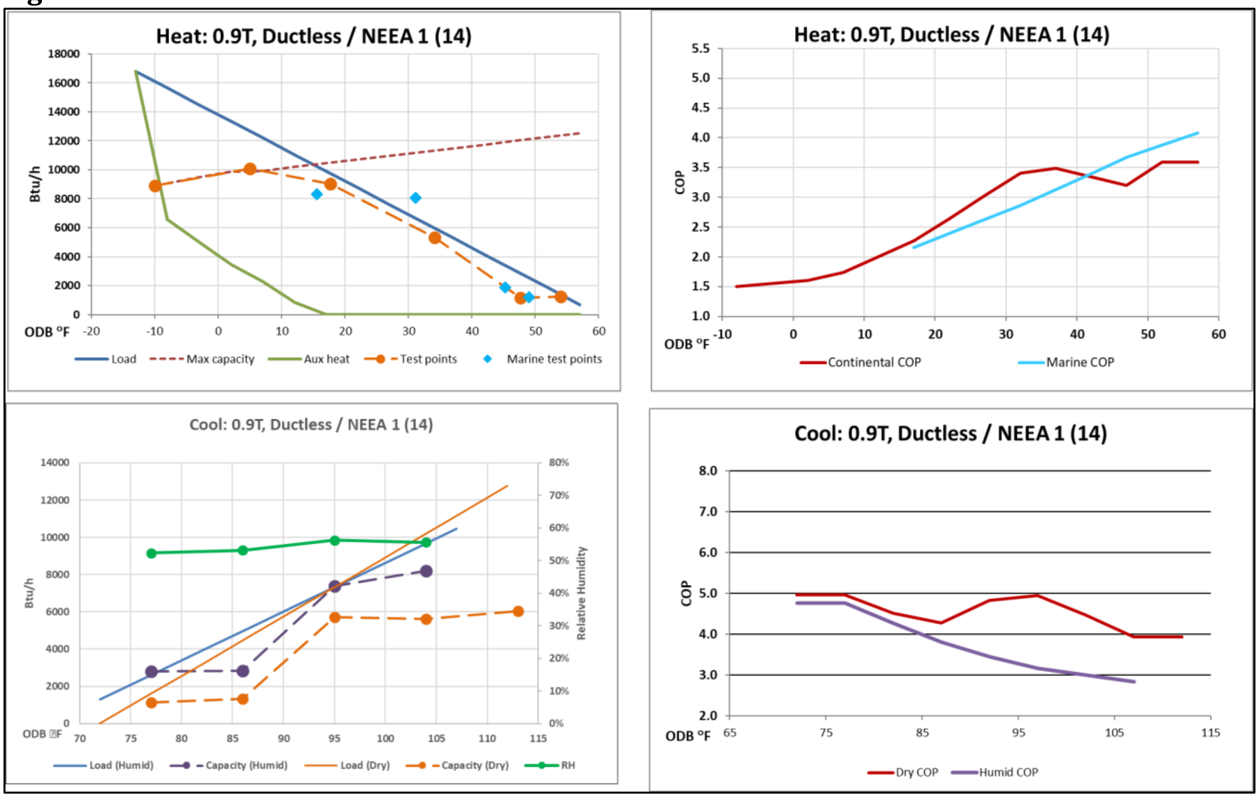


Figure 41. Test Plots for NEEA 2

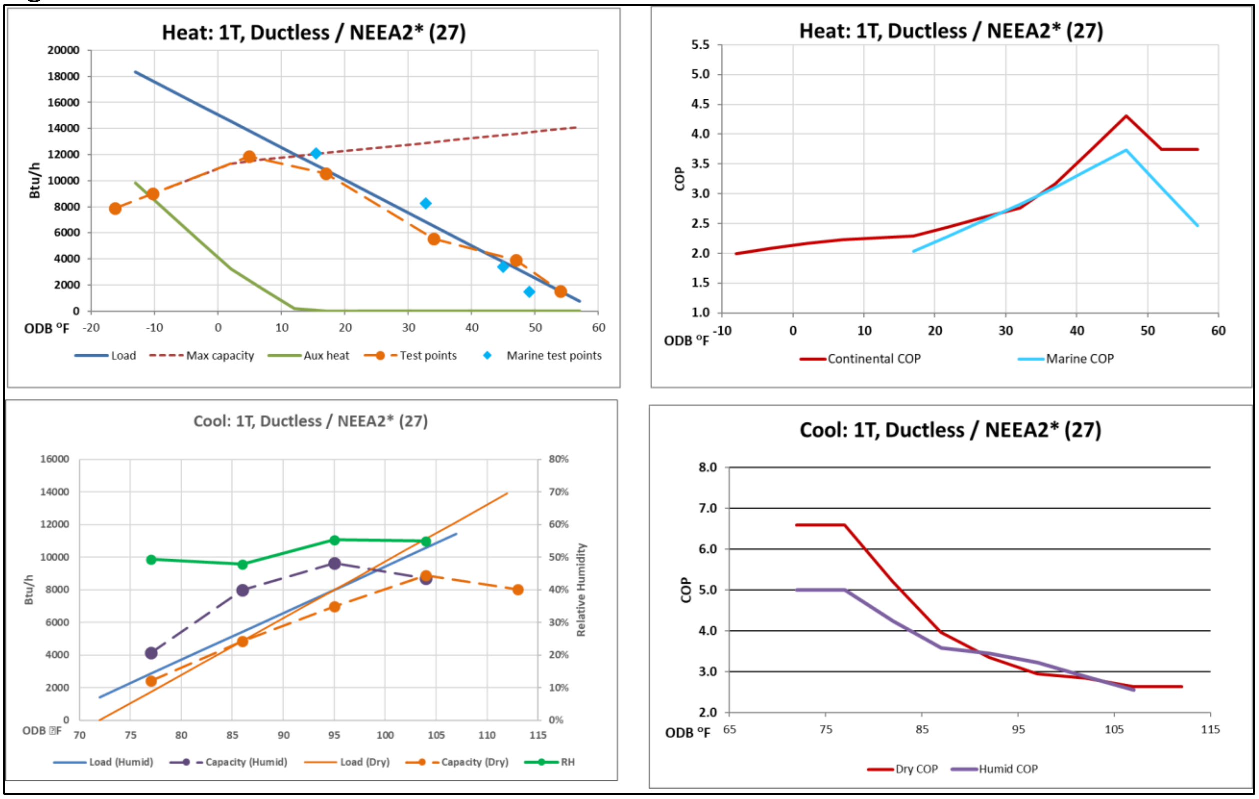


Figure 42. Test Plots for NEEA 3

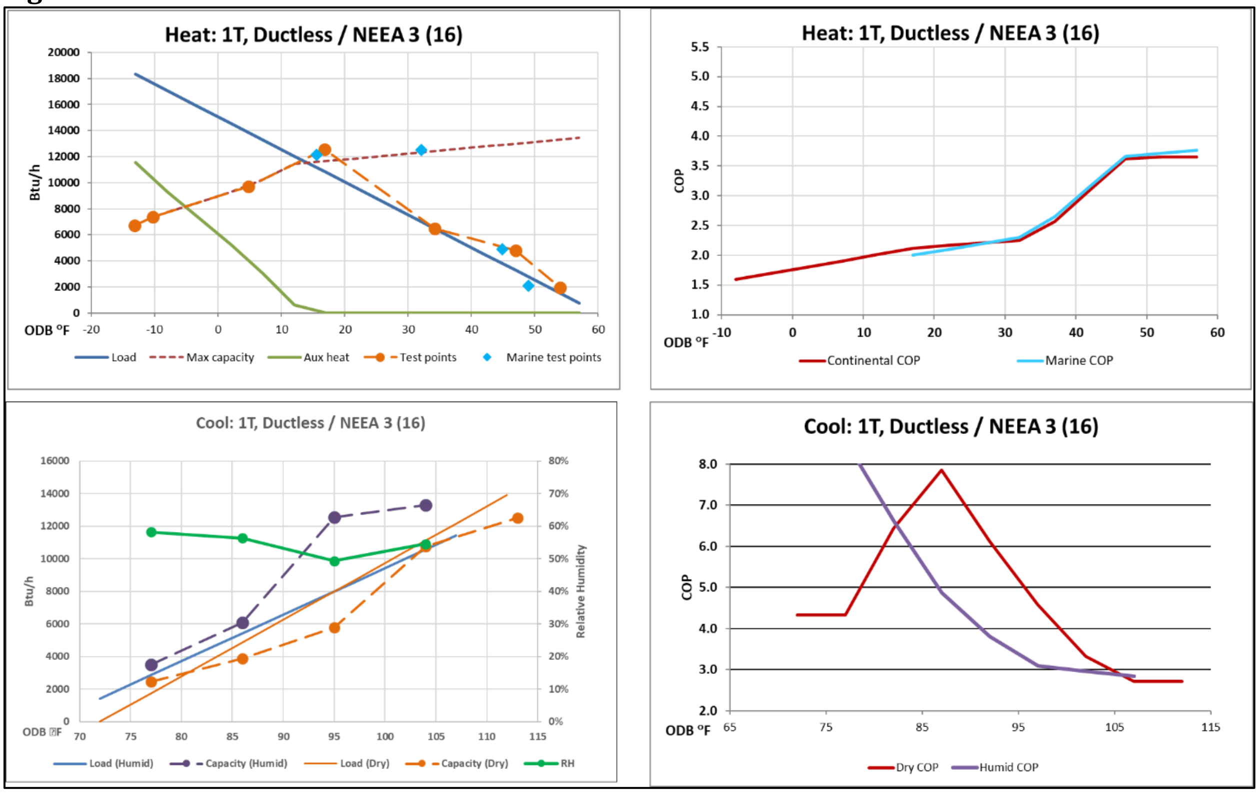


Figure 43. Test Plots for NEEA 4

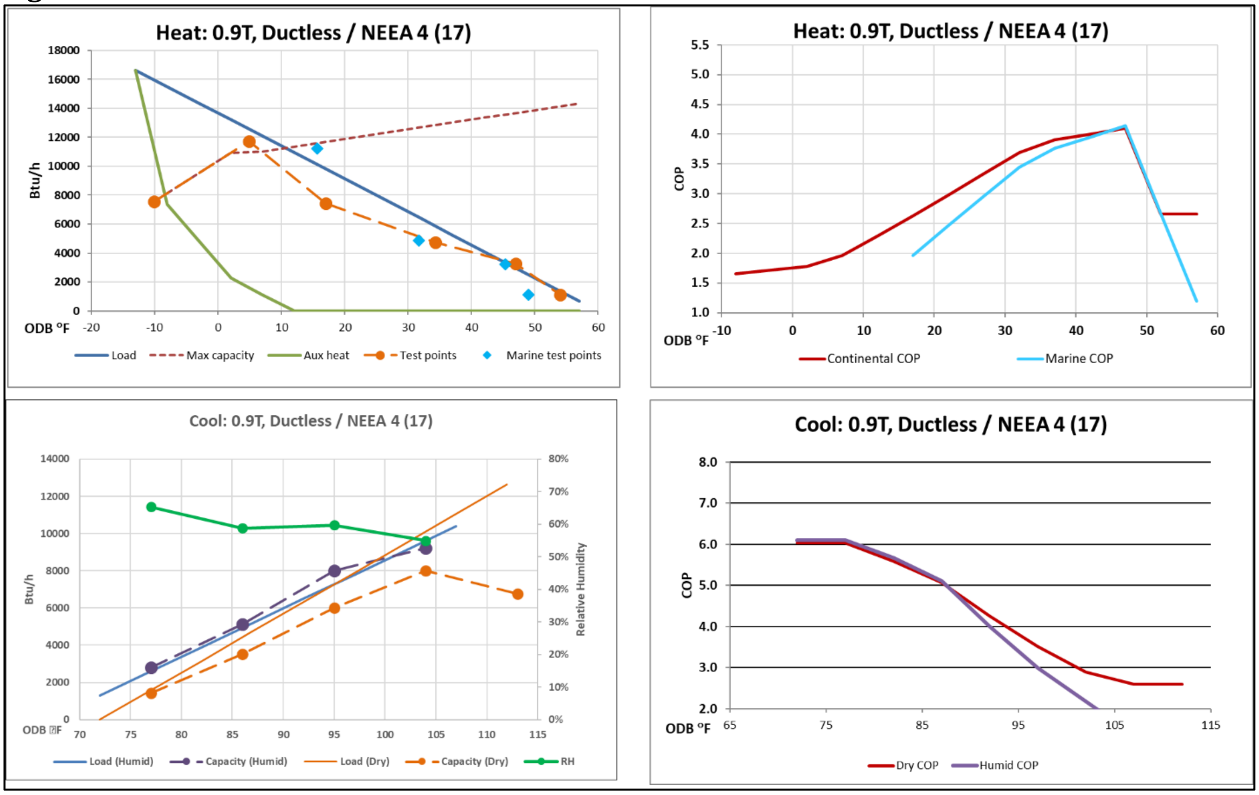


Figure 44. Test Plots for NEEA 5

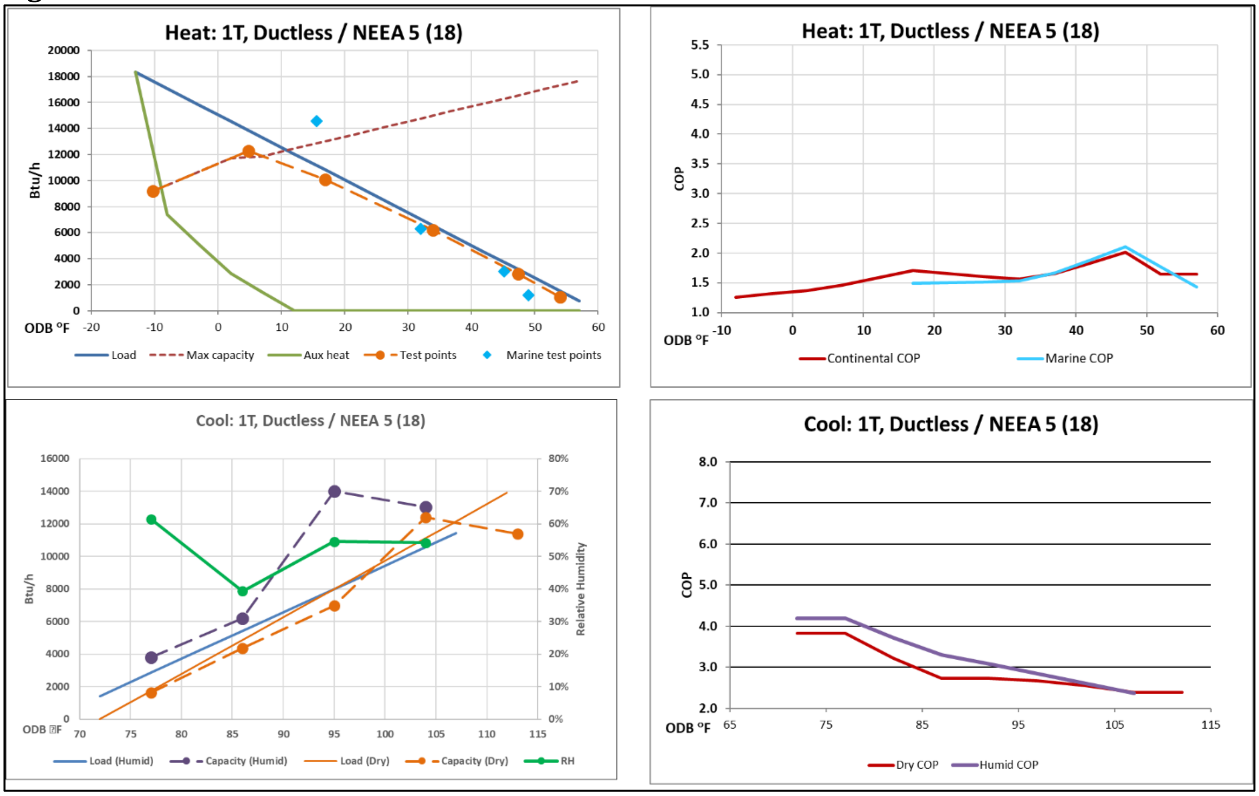


Figure 45. Test Plots for NEEA 6

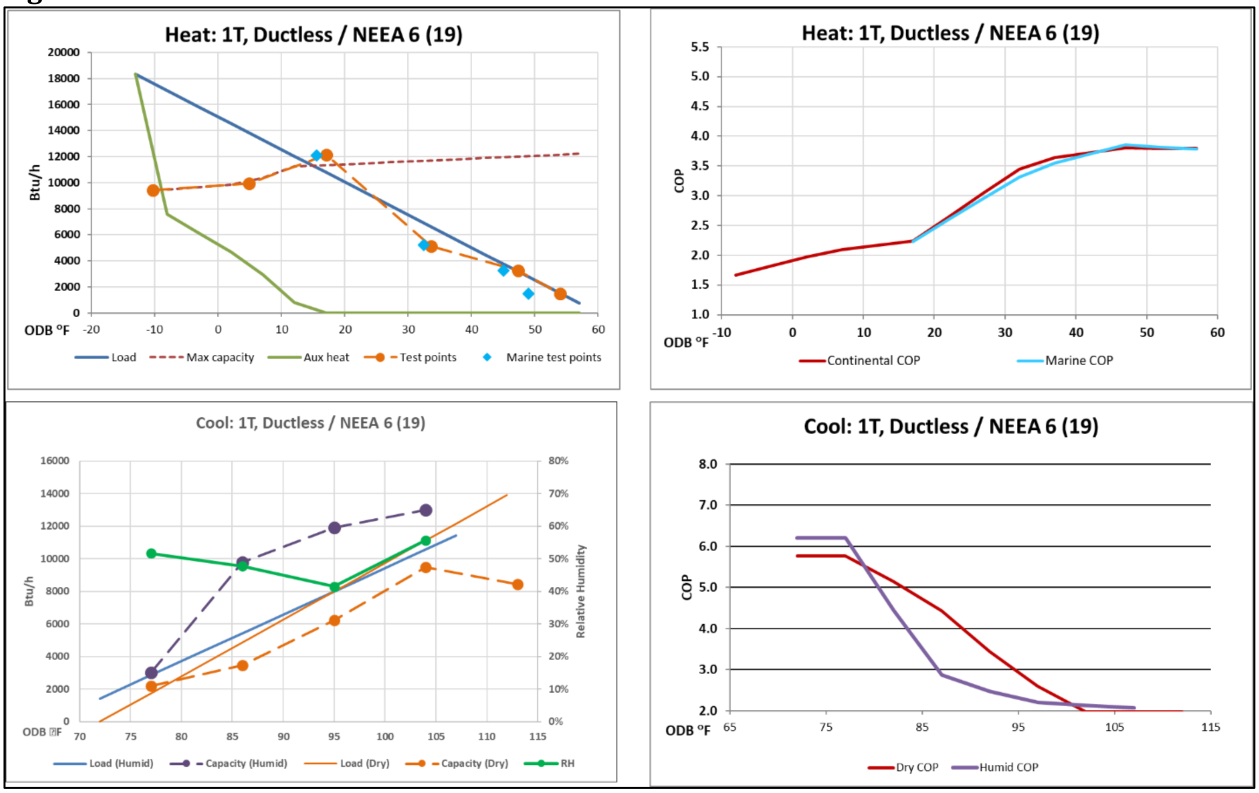


Figure 46. Test Plots for NEEA 7 (Ducted 2.75 Ton)

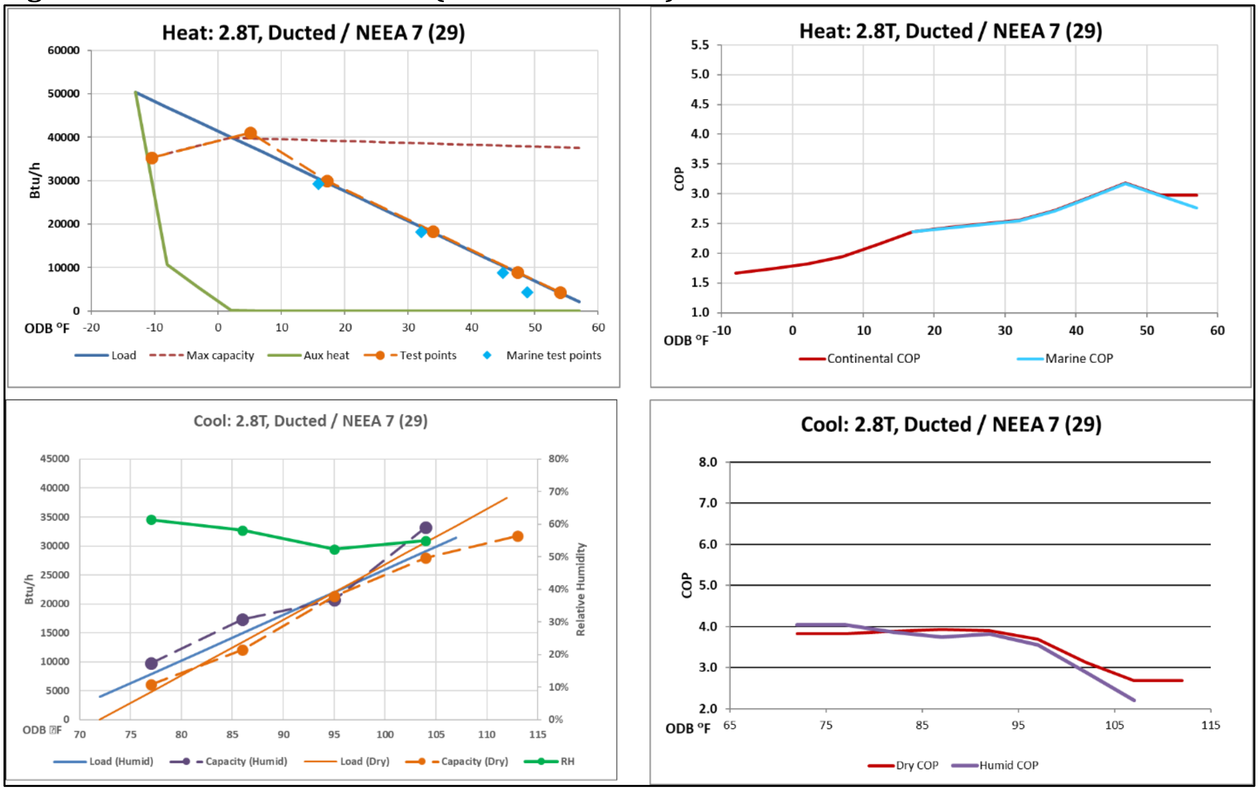
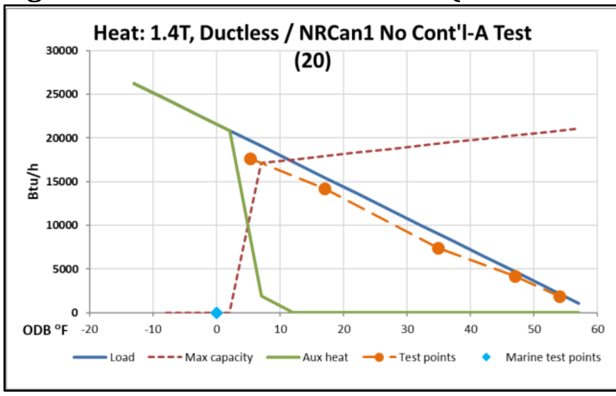
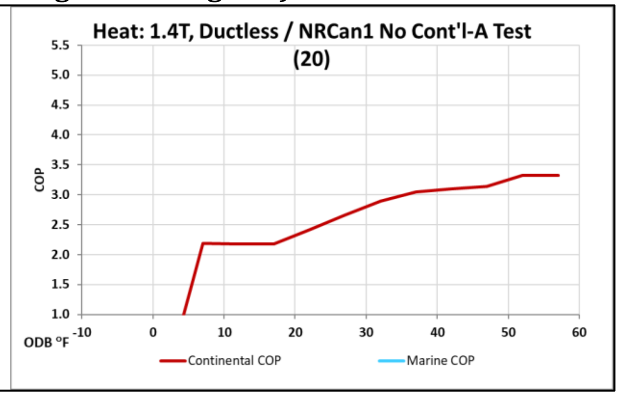


Figure 47. Test Plots for NRCan 1 (No marine heating, no cooling test)





Note that this unit also did not have the continental-A test conducted (at -10°F), so the capacity drops off the load line immediately at 5ºF.

Figure 48. Test Plots for NRCan 2

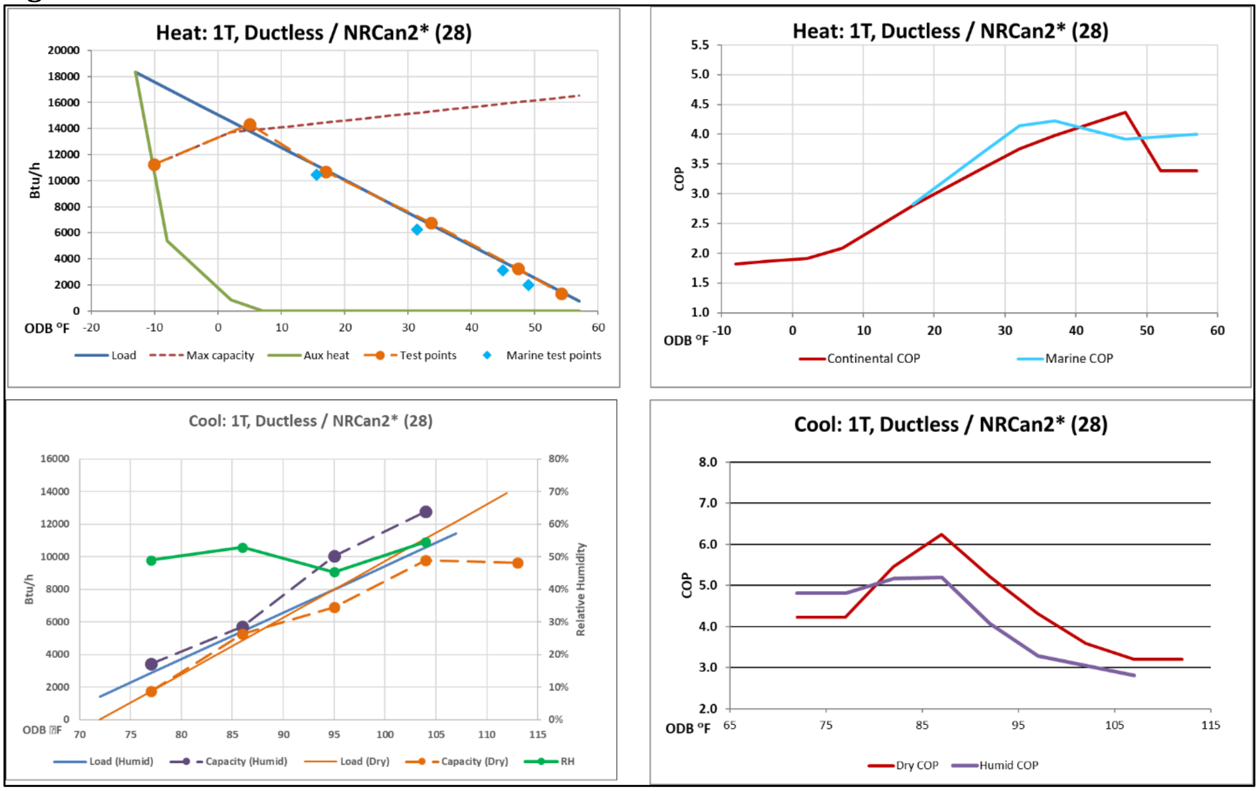


Figure 49. Test Plots for NRCan 3 (No cooling test)

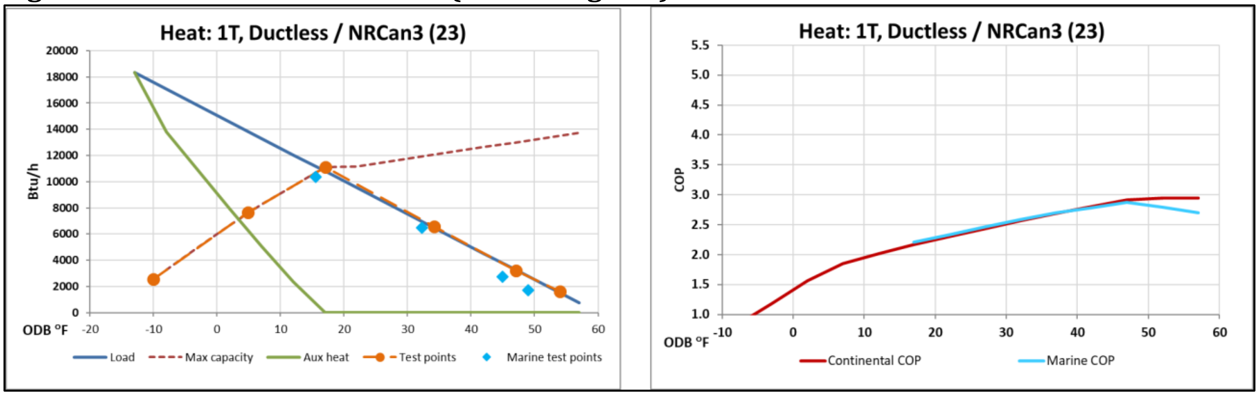


Figure 50. Test Plots for NRCan 4

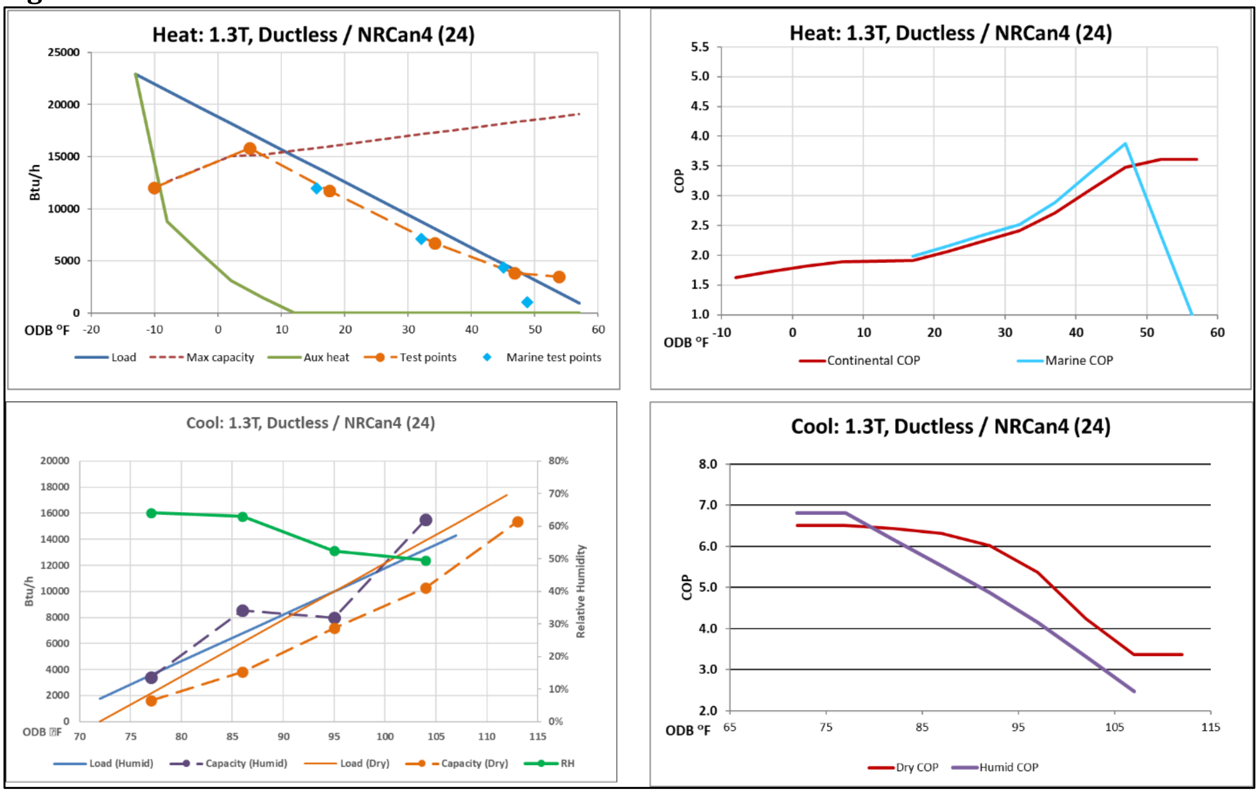


Figure 51. Test Plots for NRCan 5

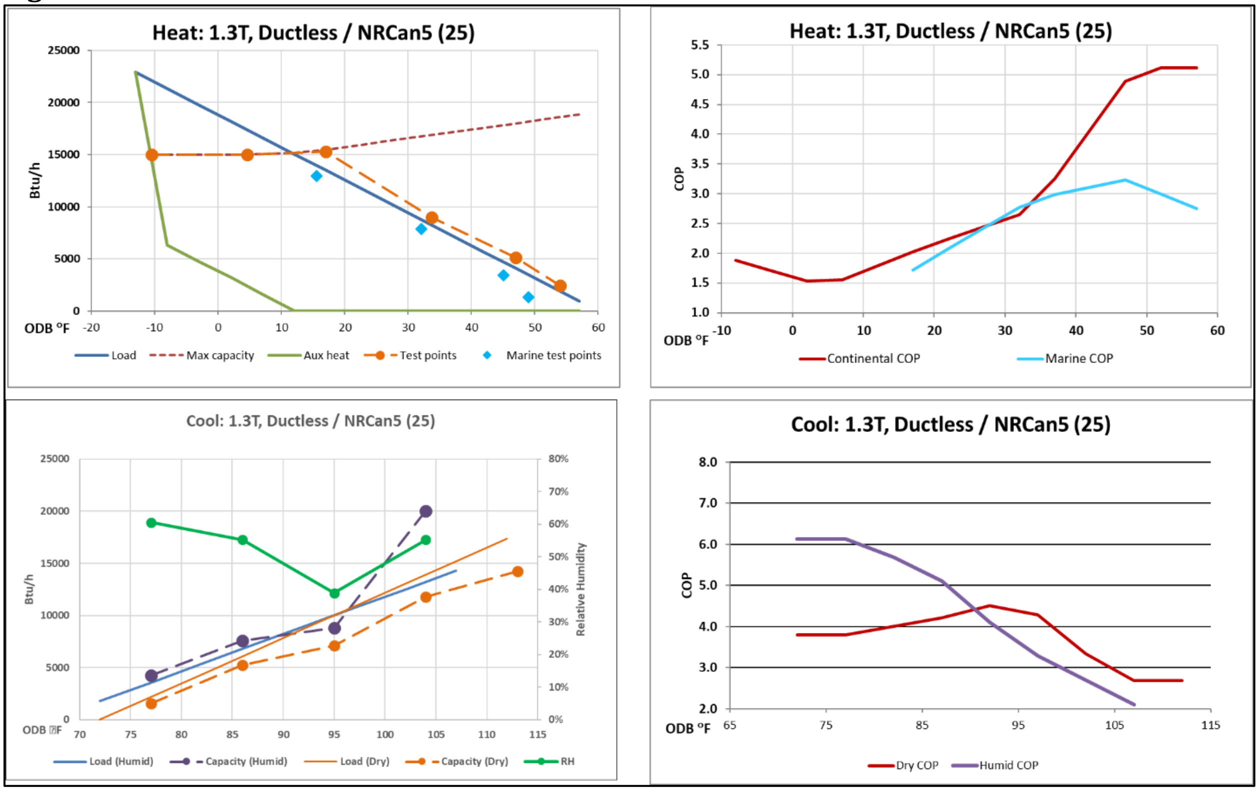
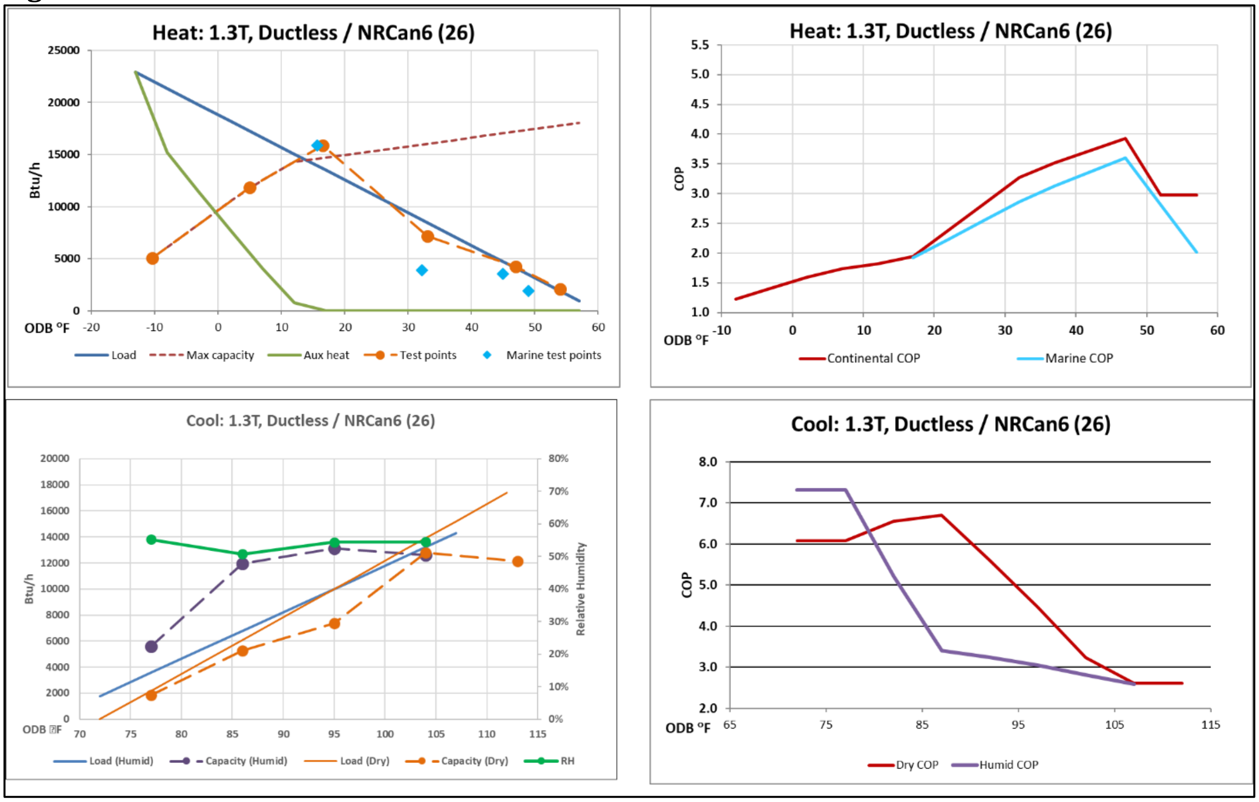


Figure 52. Test Plots for NRCan 6



Appendix B – Plain Language Guide to EXP07

Introduction

In 2015 the Canadian Standards Association (CSA) formed a standards development work group charged with developing draft test and rating procedures that would better represent installed performance of variable capacity heat pumps (VCHPs). This work was chaired by Gary Hamer of BC Hydro, with co-vice chairs Marshall Hunt of Pacific Gas & Electric (PG&E), and Rob Andrushuk of Manitoba Hydro. Initial lab research was led by Robert Davis at the PG&E lab and by Dr. Jim Braun and his team from Herrick Labs at Purdue University. Funding was provided by the Northwest Energy Efficiency Alliance (NEEA), Natural Resources Canada (NRCan), and PG&E. After several years of lab and committee work, the Canadian Standards Association (CSA) published a technical review version of EXP-07:19, Load-based and climate-specific testing and rating procedures for heat pumps and air conditioners, on March 29th, 2019 (referred to as EXP07).[10]

The purpose of this guide is to provide a plain-language summary description of EXP07. While EXP07 is a highly detailed engineering procedure, this description is intended for readers who are familiar with the basic concepts such as heat flow, measurements of heat and energy, and numeric representations of efficiency. For example, EPA vehicle mileage ratings are well-known and useful to consumers; EXP07 provides a Seasonal Coefficient of Performance (SCOP),[i] intended to portray energy efficiency of residential heat pumps in a similar manner.

This document is intended to foster an understanding of the test procedure itself, how it works, and how it differs from more traditional test and rating approaches. Readers who want more detailed technical information may refer to the procedure directly; however, this guide may serve as a brief introduction that may also be useful to more advanced readers. This guide does not cover the history or purposes of EXP07 in detail, nor does it provide a description of each section of the procedure. It does provide an overview of how load-based testing works, and generally explains the broad concept behind the EXP07 rating procedure. Endnotes with lower-case roman numerals (i, ii, iii, etc.) refer to a glossary of terminology found at the end of this document.

1.

Load-Based Testing

Most fundamental to EXP07 is its approach to testing using a simulated building load.[ii] Conventional lab tests for residential heat pumps and air conditioners (such as AHRI 210/240[11]) use fixed conditions (which hereinafter will be referred to as "fixed condition" tests), while EXP07 uses a dynamic, load-based approach that measures a heat pump system's performance across a wide range of outdoor temperatures. The unit under test[iii] is installed following the manufacturer's instructions as would be done by a qualified field

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[10] store.csagroup.org/ccrz__ProductDetails?viewState=DetailView&cartID=&portalUser=&store=&cclcl=en_US&sku=CSA%20EXP07%3A19 or go to store.csagroup.org/ and search for EXP07. The document is available at no cost.

[11] AHRI 210/240 (2017): Performance Rating of Unitary Air-conditioning & Air-source Heat Pump Equipment (with Addendum 1)

technician. During the test, the system meets heating and cooling loads that are typical for residential applications, using its own thermostat and internal control logic. In this way, the lab environment during the test process is as close as possible to a real-life installation in a house, while the lab environment allows for control and measurement so that each test can be consistent in its results, and thus provide fair performance comparisons among different models.

In the load-based test, as in a fixed-condition rating test, there is an "outdoor room" where the outdoor unit is placed, with highly-controlled conditions that represent the various outdoor temperature and humidity conditions at which the unit is tested. The laboratory setup of the outdoor room uses *reconditioning equipment*[iv] controlled by computer software to maintain those conditions for the duration of each test condition.

Both test approaches also employ an "indoor room," where the indoor unit is installed. Understanding the different control strategies for the indoor room is the key to understanding the load-based test. In a fixed-condition lab test, the indoor room (like the outdoor room) is set at a fixed condition of temperature and humidity for each test condition, controlled by the indoor room reconditioning equipment. The unit under test is set to run in a steady-state mode defined by the particular test condition, typically a proprietary "test mode" that overrides the unit's normal control sequences. The indoor room reconditioning system maintains the indoor room conditions in a steady-state manner for the duration of the test. The computer software controlling the test measures how much heat the unit under test is producing (in heating mode) or removing (in cooling mode), as well as the energy input and other key parameters (such as air flow) for the duration of the test.

By comparison, in a load-based test the computer software controlling the indoor room is programmed to mimic a room or space that would be heated (and cooled) by the unit under test. The loads have been carefully chosen to represent a typical house, scaled to the size (that is, the heating and cooling capacity) of the heat pump. The lab software controlling the reconditioning equipment is programmed with the indoor room "load" to be imposed, and it continuously senses the amount of heat the unit under test delivers (or removes) from the indoor test room. Based on these values, it updates the actual indoor room temperature every few seconds to simulate an actual load. The unit under test senses the room temperature and responds by turning on or off, or changing its output to match the load, according to its own internal logic: the same control logic used in a normal field installation. This is best understood graphically, as follows:

Figure 53 shows a simplified example of what might happen if the unit under test produces no heat at all in the indoor room. The test control software senses the output of the unit, and consequently it causes the room to cool off over time—in this theoretical example, it loses 50 degrees over an hour's time. In Figure 54, the unit under test is continuously producing half of the needed heat, so the room temperature drops at half the rate of that in Figure 53, losing only 25 degrees in an hour. (In reality, the temperature drop is not a straight line, but it is simplified here for illustrative purposes).

Figure 53. No heat added, temperature drops

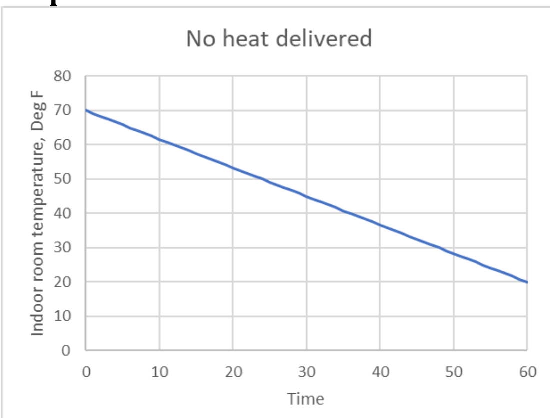

Figure 54. Some heat added, temperature drops more slowly

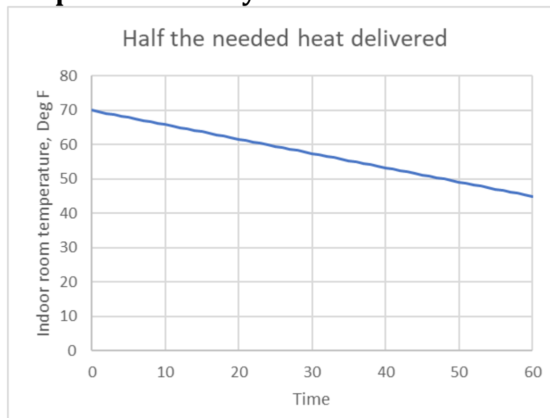

Figure 55 shows the temperature of the indoor room if the unit under test continuously generates *exactly* the amount of heat needed to keep up with the simulated heating load: the temperature stays constant throughout. In theory, the controls of a variable-speed heat pump should operate more or less this way, as long as the imposed load is within the range at which that the unit can operate, at the outdoor temperature condition in the outdoor room.

Figure 55. Heat added is correct, stable temperature

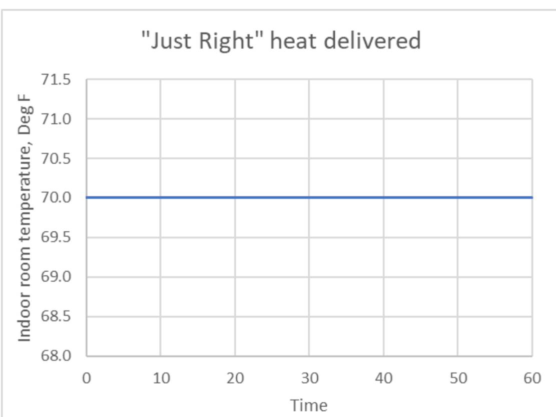

Figure 56. Heat added too quickly, temperature controlled by thermostat of tested unit

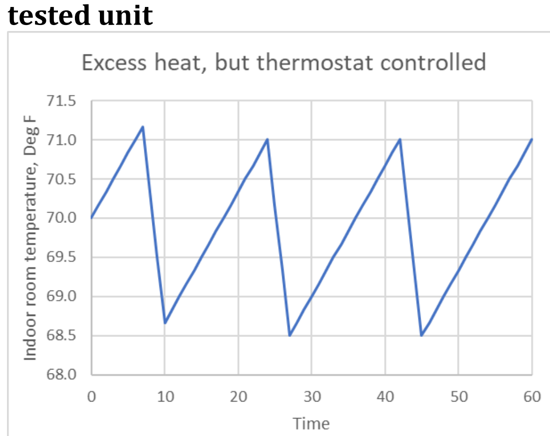

Figure 56 shows what happens if the heating output is *larger* than the load. This is also typical of how single-speed heating and cooling equipment works with a conventional thermostat. Imagine at time = 0, the reconditioning equipment is removing heat from the indoor room (simulating a heating condition in cold weather) and the thermostat is turned on at 70 degrees, just as the indoor temperature begins at 70. As the unit comes on and produces heat faster than the load, the room temperature will *increase* accordingly based on the test control programming. Then, at some point the internal controls *of the unit under test* sense that the room is warm enough, at which point it will shut off (in this example, at minute 8. This is typical of thermostat operation: thermostats will turn off a heater when the room is a bit warmer than selected.) The lab control software senses the unit shutting off, and causes the room temperature to drop again, as it would under a heating condition. At some point (in this case, below 69 degrees) the internal controls of the unit under test turn the unit back on (in this example, at minute 10). For this example, the unit has only a little more heating output than needed, so it adds to the indoor temperature more slowly; the temperature drops at a faster rate when it's off, because that rate depends only on the heating load being simulated.

Thus, the unit under test is responding to an indoor condition that simulates a heating or cooling load that would be found in a house or room, that is exposed to the same outdoor conditions as the outdoor room, where the outdoor unit is located. Although the lab control software and reconditioning equipment is actually "controlling" the indoor room temperature, the temperature is based on the response of the tested unit just as if it were in a room that was heating up or cooling off in response to a real load, and the actual output of the unit under test.

In an actual test, the behavior of the lab and the system being tested is more complicated than that shown in Figure 56. In some cases, variable speed systems can match the heating or cooling requirement closely (such as in Figure 55) but there will naturally be some variation depending on the unit's internal controls as it responds to the simulated load. As the need for heating or cooling decreases a variable heat pump will reduce its output to keep the indoor room temperature stable.

Unfornatly, variable speed systems cannot ramp "down" continuously all the way to "off"; they have a lower limit of heating or cooling output. The test is designed so that for most tested models, the smallest loads used (when outdoor temperatures are mild) will be lower than the lowest capacity that most tested units can deliver. When this occurs (usually for at least one or two of the test conditions) the response will be more like that shown in Figure 56, varying up and down regularly as the thermostat responds to the indoor temperature. In other cases, when the loads are at their highest (and outdoor temperatures are most extreme), it is expected that tested units will lack the heating or cooling output needed to maintain the steady state indoor temperature target (similar to Figure 54). For those test conditions, the unit is instead set to run "full out" (but still under its normal controls) and the remainder of the test is completed while the reconditioning equipment keeps the indoor room under steady state conditions. These "full load" tests are thus "fixed condition" tests, but the unit under test still uses its normal operating modes, and does not depend on locked compressor or fan speeds or other proprietary "test mode" settings.

At each test condition, the lab control software is required to collect data and verify that both the heating or cooling output of the unit under test, and the electricity input (power), are consistent over time. Sometimes this "steady state" operation over time occurs naturally (as typified by Figure 55 above). However, during the load-based test the indoor room conditions vary over time, causing the heating or cooling output to also vary in more complex ways. This may be due to the need to cycle off during low-load conditions because the variable-speed controls are "searching" for the right output to best match the load; the need for defrost cycles in some heating conditions; or for other reasons dictated by the internal control logic of the unit under test.

To account for this natural variation in the unit operation, the test procedure includes detailed instructions so the lab can determine at what point during a particular test condition the test may be considered "finished." This process is defined by a set of rules that require monitoring the heating or cooling output and electric input over time, searching for a period of time during which these measurements are either steady, or repeating over time in such a way that additional measurements will not likely change the result in a meaningful way. This is referred to as "convergence," and once convergence (or a test period time limit) is reached, the test condition is considered complete and the test procedure moves to the next condition, until all are completed.

2.

Test Conditions

The EXP07 test procedure uses a total of 11 different heating conditions and 10 different cooling conditions. The tests are run at each condition until the system achieves convergence, as outlined above. At each outdoor temperature, the amount of heating or cooling load that is dynamically simulated in the indoor room is appropriate for the outdoor temperature at which the equipment is tested, and is also scaled to the capacity of the unit under test, so that each unit is tested based on its rated capacity.

The heating conditions are divided into two general climate areas, Continental and Marine, each with its own sequence of outdoor temperatures and corresponding loads. The cooling test conditions are divided into Humid and Dry climate areas, each with its own sequence. In addition, in the humid cooling tests, a dynamic moisture load is applied by monitoring the removal of humidity by the equipment under test, and then updating the indoor humidity in the test room programming. This works in very much the same way that the dynamic heating and cooling loads are applied to indoor temperature for all of the tests, and it allows the test to measure how well the units remove moisture in the humid cooling tests. (By contrast, in a conventional test the reconditioning equipment is responsible for maintaining a constant humidity level in the indoor room). Figure 57 summarizes the four test sequences:

Figure 57. EXP07 Test Sequence Overview

Heating (Table B.5)	**Outdoor Conditions**	**Indoor Conditions**
Continental	6 Temperatures from **-10°F to 54°F**	**70°F (56% RH max)**
Marine	4 Temperatures from **17°F to 54°F**	
Cooling (Table B.3)	**Outdoor Conditions**	**Indoor Conditions**
Dry	5 Temperatures from **77°F to 113°F**	**79°F (21% RH max)**
Humid	4 Temperatures from **77°F to 104°F**	**74°F (55% RH max)**

Significant effort has been made to establish consistency with AHRI 210/240 wherever possible, for example in duct static pressure and full-speed air flow conditions, and in most of the required test and measurement practices. In general, the laboratory setup, the methods and materials specified in the measurement of air flows and temperatures, indoor and outdoor room conditions, refrigerant and electrical energy flows, etc. are consistent with AHRI 210/240, including (as applicable) the DOE adopted updates (effective in 2023) to AHRI 210/240, which is published as Appendix M1 in the Code of Federal Regulations.[12] Although the indoor unit air flows during all EXP07 tests are allowed to vary based on the internal controls of the unit under test, the initial setup to define and measure full-load air flows, and to establish static pressures for ducted systems, are harmonized with AHRI 210/240 and Appendix M1.

Efficiency Metrics

Once the test results have been measured and recorded, seasonal efficiency values are calculated. The result is a heating and a cooling Seasonal Coefficient of Performance (SCOP) for each climate zone: $SCOP_H$ and $SCOP_C$. (There is no cooling SCOP for the Subarctic zone.) The basic method to calculate seasonal efficiencies is consistent with other rating and common heating, ventilation, and air conditioning (HVAC) engineering analysis, called a bin model. For each climate, the analysis uses a specific number of hours that represent the number of heating (or cooling) hours at each temperature "bin" throughout the heating and cooling seasons. The temperature "bins" are in increments of 5°F, and the procedure specifies that the unit's heating or cooling output and energy input as measured in the lab is applied at each bin, for the number of hours in that bin.

The size of the heating and cooling loads used for the rating calculation are the same as those used during the tests. The bin hours used in the model are specific to the eight climates used in EXP07 (see Figure 58). For heating, at any outdoor temperatures for which the unit under test does not have enough heating capacity to meet the full heating load, it is assumed that the difference is made up with electric resistance supplemental heaters.

[12] Appendix M1 to 10CFR Part 430, Subpart B "*[6450-01-P] DEPARTMENT OF ENERGY 10 CFR Parts 429 and 430 [Docket No. EERE-2016-BT-TP-0029] RIN 1904-AD71* can be found at: http://www.energy.gov/sites/prod/files/2016/11/f34/CAC_TP_Final_Rule.pdf. Appendix M1 begins on page 226.

For each climate, the total delivered output for the season is divided by the total electrical input to determine the *Seasonal Coefficient of Performance (SCOP)* for that unit in that climate. The SCOP is a simple ratio, so a COP of 1.0 would represent 100% efficiency (such as electric resistance heat). Heating SCOP are generally higher in warmer climates and lower in colder climates, and cooling SCOP are generally lower in the hottest climates and increase as summer climates get cooler. The eight representative climate zones, with the applicable load-based test sequence used for calculating each zone's heating and cooling SCOPs, are shown in Figure 59.

Figure 58. EXP07 Representative Climates[13]

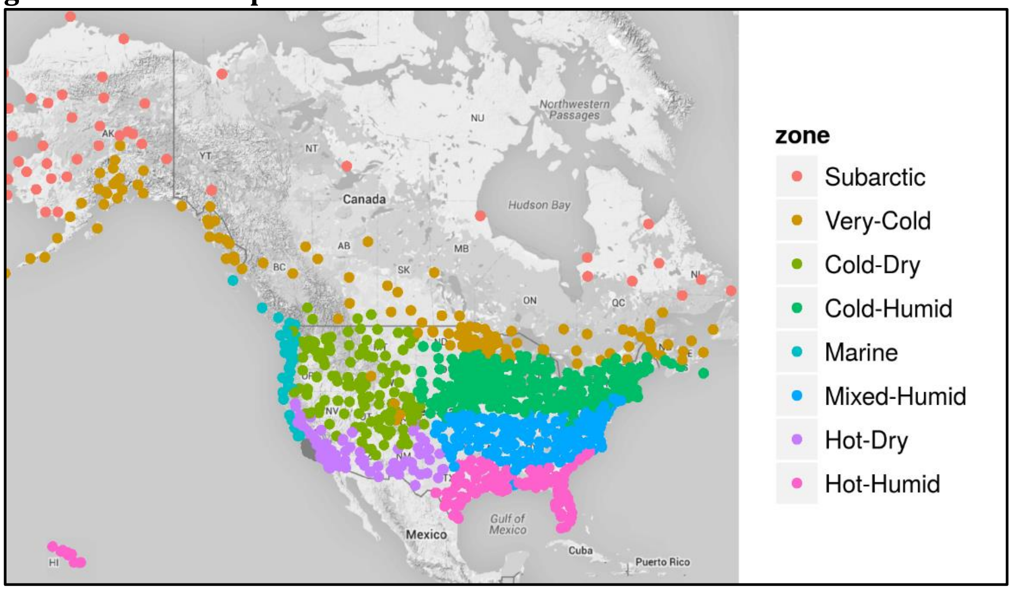

Figure 59. EXP07 Test Results Applied to Representative Climates

Rating Climate	Heating	Cooling
Subarctic	Continental	*- not used -*
Very Cold	Continental	Humid
Cold/Dry	Continental	Dry
Cold/Humid	Continental	Humid
Marine	Marine	Dry
Mixed	Continental	Humid
Hot/Humid	Continental	Humid
Hot/Dry	Continental	Dry

13 The Marine climate is circled for clarity only, to differentiate it from climates shown in similar colors.

Finally, there is a provision that the lab to test the energy input during “standby” modes of operation (when the unit is not heating or cooling), as a separate procedure. The results of those measurements are used in the analysis for seasonal COP. The standby power is added for the hours (based on each climate), during heating or cooling seasons, during which temperatures dictate no heating or cooling requirement but when the HVAC system unit thermostat is likely to remain in “heat” or “cool” mode.

Standby power is also applied to shoulder periods when there is no heating or cooling demand, and the unit controls are likely to be turned “off,” but the system is still powered on at the circuit panel. Besides a basic need to use some energy to maintain control circuitry and crankcase heating, many systems have been found to run the indoor unit fan continuously, or to operate crankcase and/or drain-pan heaters continuously when they are not needed. Any or all of these can result in a significant impact on annual energy use.

Once measured and calculated, the SCOP is reported both ways: with the standby power energy, and also without the standby energy. The difference between them illustrates the impact of standby energy on the annual heating and cooling energy use. As expected, standby energy makes a more significant impact on annual efficiency ratings in climates with long shoulder periods, and for equipment that has higher standby electric energy input.

3.

Application Ratings

In addition to the standard climates and heating and cooling load conditions, Annex F of EXP07 provides alternative rating calculations called “application ratings” so that users can vary the conditions used in the *model* in a predictable, standardized manner. This could be useful, for example, in a region with a climate that is not a close match for one of the eight representative climates, or for a designer to provide cost-benefit analysis for a specific customer and project. Annex F allows users to vary one or more of the following parameters, using the same test data already reported by the lab test:

1. Use a specific climate rather than a generalized climate zone (Annex G provides details of how to develop the bin values based on hourly “normal” climate data).
2. Use a specific equipment load that varies from the one used in the test, for example for a new and superinsulated house or a very old and inefficient house.
3. For an auxiliary heat source with a fixed heating output (rather than the variable output assumed for supplemental electric heat in the standard rating model). The auxiliary heat source may be electric resistance, or it may be some other fuel.

For any application rating, details are provided on how such a result needs to be reported so that the application-specific conditions are properly disclosed.

System Performance Metrics

The test data produced by EXP07 provide a “map” of system performance that can be used by hourly computer simulation programs to estimate the hourly power demand (kW) and the energy use (kWh) under varying conditions. Building energy efficiency standards such as California’s Title 24[14] use simulations to qualify proposed dwellings as meeting energy codes, by showing that they use less energy than the base case code-compliant dwelling. This performance approach allows the project to get appropriate credit for energy efficiency features and equipment, and more detailed performance data for specific models of equipment will allow much more accurate simulations and allow credit where credit is due.

Improved, climate-specific metrics such as SCOP (or full simulations) also provide a mechanism for energy efficiency incentive programs to estimate savings for specific heat pump models. Better predictions of performance, whether using simulations or specific SCOP or COP values, will allow programs to assign value for incentive payments more accurately, so they can incent systems that match their targets for savings at higher rates than they incent other systems. As EXP07 data become available, computer programs will start to implement the algorithms necessary to use the data. Some jurisdictions have already set goals to use EXP07 to support performance-based codes using simulations (California) or to establish a minimum performance standard based on SCOP (Canada).

[14] https://ww2.energy.ca.gov/2015publications/CEC-400-2015-037/CEC-400-2015-037-CMF.pdf

Terminology (Glossary)

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[i] **COP:** Coefficient of Performance is an efficiency metric, defined as the ratio of energy delivered divided by electric energy used. A COP of 1.0 represents a 100% efficient system (such as electric resistance heating). An 80% efficient furnace can be said to have a COP of 0.8. COP can be reported for a given operating condition (indoor and outdoor air conditions for example, as in Figure 57), or as a “Seasonal” COP (SCOP). Seasonal COP takes the sum of *all* the heat (or cooling) delivered for a winter (or summer), and divides by *all* the electricity input over the same time period. The COP for a properly operating heat pump or air conditioner is virtually always greater than 1, because the heat obtained from (or rejected to) the outside air is “free,” and not included in the efficiency calculation.

[ii] **Load:** A heating or cooling *load* is the amount of heat or cooling that is required to be added to a building in order to maintain comfortable indoor conditions. Heating loads increase as the outdoor temperature drops, and cooling loads increase as the outdoor temperature increases.

[iii] **Unit Under Test:** The specific model of equipment that is being tested for the purpose of efficiency rating.

[iv] **Reconditioning Equipment:** The mechanical equipment that is used to control the test-room conditions to simulate indoor and outdoor spaces.