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CSA EXP07: Ongoing Progress, Lessons Learned, And Future Work In Load-based Testing of Residential Heat Pumps

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ABSTRACT

The use of load-based testing for heat pumps and air conditioners is gaining global interest as stakeholders look for better ways to measure the complex performance of modern, variable-speed systems. This paper presents test results and experience gained using CSA EXP07:19, a load-based test and rating procedure for residential air-source heat pumps and air conditioners. EXP07 is an innovative lab test that uses simulated loads in contrast to existing test procedures that depend on proprietary, fixed test modes and static room conditions, such as AHRI 210/240. During the test, a heat pump's performance is measured as it responds to the simulated load according to its built-in control algorithms attempting to maintain indoor room temperature under loads that are scaled with outdoor conditions. This test methodology reveals complex equipment behavior that is often built into product firmware but not revealed in conventional lab test procedures, uncovering substantial performance variability and substantial differences in relative ranking of products.

The lab tests, mapped to a range of climates from Hot-Dry to Subarctic, inform heating and cooling efficiency metrics that may prove valuable to consumers, utility programs, and design professionals; detailed test results can be used to improve design practices, facilitate performance-based modeling and enhanced code compliance. Test results may also help manufacturers improve their products' performance and comfort. Lab results to date have established the merits of the procedure and suggest the value of stakeholder adoption of EXP07 as the procedure matures, with the goal of improving state and utility program design, home energy ratings, performance-based code compliance and other voluntary activities that support energy efficiency and carbon reduction.

EXP07:19 load-based and climate-specific testing and rating procedure for heat pumps and air conditioners has been updated based on extensive technical comments received from industry stakeholders and feedback from labs with experience implementing the procedure, and a new edition will be published in 2022. This paper summarizes the results of testing to date, discusses lessons learned and improvements that are being incorporated into the updated edition, and outline future directions for further development and validation of the procedure.

1. BACKGROUND

Interest in efficient, variable speed air conditioners and heat pumps has gained momentum around the world as efforts to decarbonize building systems ramp up. In many markets, however, air source heat pumps have a lingering negative reputation among contractors and consumers, particularly in cold climates where historically poor sizing and installation practices have led to low efficiency (NEEP, 2017a, 48-50; 2017b,1). Inaccurate efficiency ratings increase the potential for poor product choices, disappointed customers, and unexpected high bills. While other factors such as heat pump sizing, installation, operation, and maintenance practices can lead to poor performance, when a contractor or consumer chooses a product based on an efficiency rating, they should reasonably expect that the ratings will realistically represent that product, especially when comparing efficiency ratings of similar products. The impact of unpredictable performance ratings can reinforce existing bias, reflect negatively on utility and other publicly supported market transformation programs, and offers little motivation for manufactures to improve product performance.

In 2015 the Canadian Standards Association (CSA) formed a development committee to develop testing and rating procedures that would better represent installed performance of variable capacity heat pumps (VCHPs). The relevance of Heating Seasonal Performance Factor (HSPF) and Seasonal Energy Efficiency Ratio (SEER) ratings (AHRI, 2017; CFR430, 2017a) as realistic performance metrics to represent savings had been increasingly called into question. Concerns included substantial variations in equipment performance when installed in climates that vary substantially from those used for the ratings, and in-field monitoring suggesting that current ratings do not predict installed performance well (Proctor *et al.*, 2018; Wilcox *et al*., 2016). With many utilities and state/provincial energy offices increasing their market transformation efforts and funding to promote efficient HVAC installations, they are increasingly motivated to find equipment metrics that reduce incentive investment risk and improve evaluation results.

The development committee initially focused on variable-speed equipment, which depends on on-board firmware to operate, and for which field-measured performance has varied considerably from published ratings. HSPF and SEER appear to be effective at testing the performance of the hardware – the compressor, metering devices, fans and coils – under fixed steady-state conditions, but these tests intentionally bypass the on-board controls that are an integral component of VCHP operation in the field.

The result of this effort was a test procedure that includes the effects of on-board control algorithms and a wider range of outdoor conditions than current rating tests. Other objectives include 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, CSA published EXP07:19 (CSA, 2019) as a technical review document and stakeholders were invited to review and comment on the procedure during an extended comment period that ended in December 2020. This paper briefly summarizes the results of testing 19 heat pumps using EXP07 at one lab and explores the implications of the results. It also covers key lessons learned and incorporated by the CSA development committee in reviewing the technical comments and proposing the next published edition of the procedure.

2. EXP07 TEST PROCEDURE

2.1 EXP07:19 Test Method Summary

EXP07 is a load-based test method that uses a sequence of heating and cooling loads that are simulated in the psychrometric chamber containing the indoor equipment. These loads are scaled with outdoor room conditions that vary for each step in the sequence. The equipment under test is set up to heat or cool the indoor room in response to the simulated loads, using its own controls, while its heating or cooling capacity and power input are measured. For each test condition, the outdoor room conditions are held constant while the indoor room reconditioning equipment is programmed to respond in real time, simulating the temperature conditions of an actual room under load conditions. The test uses a "virtual" building load model that compares the heating or cooling capacity of the unit under test with the target heat loss or cooling gain, adjusting the indoor room conditions to reflect the difference, including a defined thermal capacitance. The tested equipment is thus subjected to conditions that closely represent real-world operation, and it responds using its native controls. By contrast, during AHRI 210/240 testing the indoor and outdoor rooms are held at fixed conditions, and the compressor and fan flows are locked in steady-state operation using proprietary test modes based on manufacturer discretion within parameters set by the procedure for each test condition. The normal logic of the tested unit's native controls is bypassed entirely, and in some cases the compressor and/or fan(s) may operate at speeds that are not available during operation under the system's normal control sequences.

The EXP07 test process incorporates defrost operations for heating and compressor cycling under low load conditions for heating and cooling without the need for separate tests and mathematical adjustments. This allows both the capacity and input power to be integrated over an appropriate timeframe using a detailed set of rules that define a result that is intended to be as consistent and repeatable as possible. The virtual loads are scaled to the rated capacity of the equipment and are designed such that the imposed loads will exceed the capacity of the equipment under the large loads defined at the more extreme outdoor conditions. In those cases, the virtual building load model is suspended, and the indoor room conditions are held constant with the tested equipment operating at maximum capacity while still using its built-in controls.

While the test method is novel, the laboratory equipment set-ups and measurement techniques were adopted almost entirely from Appendix M1 of 10CFR 430, Subpart B (CFR430, 2017b) with the intention to maintain consistent and familiar laboratory setups, to the extent possible.

2.2 EXP07:19 Test Conditions and Climate Ratings

EXP07 is comprised of two sets each of heating and cooling test conditions. Heating includes both Continental and Marine tests, where the Marine tests include higher outdoor humidity to simulate a marine climate. Cooling includes both Humid and Dry tests, with differences in the indoor room dry bulb setpoints and humidity conditions. The humid cooling test sequence also includes virtual latent loads that are simulated in the same manner by which the sensible loads are simulated for all the load-based tests. Table 1 and Table 2 show the indoor and outdoor conditions used during the EXP07:19 tests for cooling and heating tests, respectively.

Table 1. EXP07:19 Cooling Test Conditions

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

Table 2. EXP07:19 Heating Test Conditions

	Continental outdoor conditions		Marine outdoor conditions		Indoor conditions	
	Dry-bulb temperature, °F	Wet-bulb temperature, °F	Dry-bulb temperature, °F	Wet-bulb temperature, °F	Dry-bulb temperature, °F	Wet-bulb temperature, °F
HL	TOL	TOL-1	TOL	TOL-1	70	60 (maximum)
HA	-10	-11.4	N/A	N/A		
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		

The heating HL test (at TOL, the outdoor temperature operating limit) and HA tests are optional.

The test results are converted into seasonal efficiency ratings using a bin model, essentially the same method that is used in AHRI 210/240 and many other seasonal efficiency models. For each targeted climate, the bin model defines a specific number of heating and cooling hours at each temperature range throughout a typical year, and the measured performance is interpolated from the test results for each bin, dividing the summed delivered capacity by the summed energy input for the entire season to obtain the seasonal efficiency. EXP07 uses bin profiles derived from contemporary weather data for eight climate regions in the US and Canada (Wilcox, 2008; Numeral Logics, 1999), whereas AHRI 210/240 uses five climate zones for heating[1] and one for cooling, derived from weather data of unknown origin. The bin model results from EXP07 are expressed as heating and cooling Seasonal Coefficient of Performance (SCOP) ratings for eight prototypical North American climates including Subarctic (which has no cooling rating), Very Cold, Cold/Dry, Cold/Humid, Marine, Mixed, Hot/Humid and Hot/Dry.

3. LAB TEST OVERVIEW AND KEY FINDINGS

At the UL Plano, Texas lab, 19 heat pumps made by 9 manufacturers were tested using EXP07 between November 2018 and August 2020. Two of the units were not tested in cooling mode, and one unit did not complete the Marine test sequence due to a malfunction. 17 of the units were ductless, single-zone systems with rated cooling capacities between 12,000 and 18,000 Btu/h (1-1.5 tons). The other two were ducted systems rated at approximately 24,000 and 36,000 Btu/h (2 and 3 tons). All models had HSPF ratings between 10 and 14, with ten between 12 - 12.5 HSPF. All tested models had SEER ratings between 17-33, with 10 (of the 17 models tested for cooling) less than 23, and 5 between 23-26. All but one was listed at the time of testing in the NEEP cold-climate heat pump product list (NEEP, undated). While initial results of the first 13 tests were previously published in detail (Harley, 2020) the following brief summary is updated to include all 19 tests.

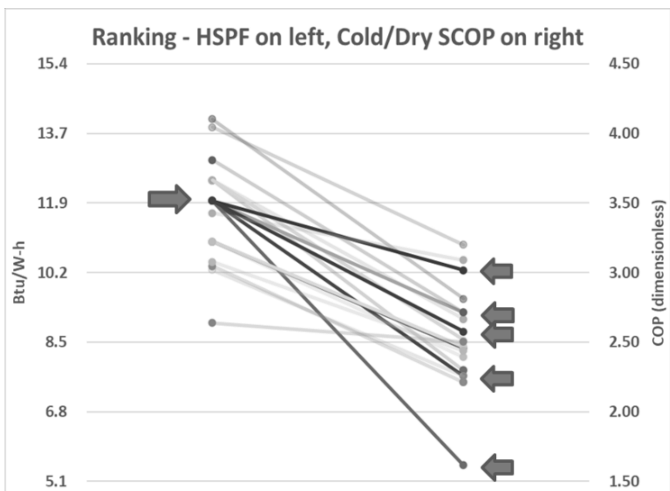

Figure 1. Heating HSPF (left) and Cold/Dry SCOP (right) rankings

3.1 Variations in Seasonal Efficiency

Figure 1 shows the ranking of HSPF and SCOP for all tested units, compared using the Cold/Dry climate, which is closest to the DOE Region IV used for HSPF ratings. Five units with HSPF ratings of 12.0 are highlighted with arrows, to illustrate the wide range of EXP07 results. The same five units represent nearly the entire range of results and vary by nearly a factor of two, despite having the same HSPF rating. The left and right axes are aligned, as HSPF units are 3.41 times that of SCOP.

Cooling SCOPs results diverge even more widely, when compared by rank order with the SEER ratings. Figure 2 shows the 17 cooling test results, using the Mixed/Humid climate (which is closest to the climate used for calculating SEER). Like the heating rankings above, there is significant variability in efficiency rankings for each unit from one test to the other, but even more so with the cooling results. The highest-rated unit using SEER is in a tie for the worst

[1] Only one is reported for the HSPF equipment rating.

SCOP, using EXP07:19. Other units with lower SEER ranking (between 17-22) encompass nearly the entire range of SCOP results, from very close to the bottom all the way to the highest measured SCOP.

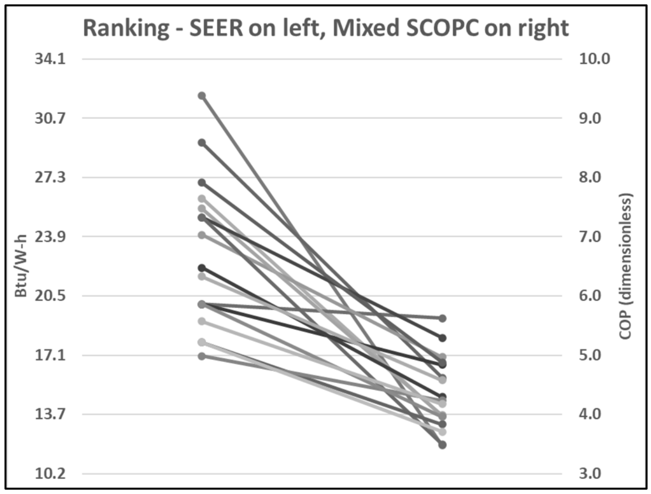

Figure 2. Cooling SEER (left) and Mixed SCOP (right) rankings

The sample of products tested is too small to form any broad conclusions about the relationship between HSPF or SEER and load-based SCOPs, if there is indeed any relationship. Direct comparisons are not suitable for any individual product, because EXP07 inherently measures different aspects of a unit's performance than AHRI testing. Also, some manufacturers may under-report specific models' performance using AHRI tests, for the purpose of publishing ratings; but it seems highly unlikely that this practice is widespread or explains the wide variability found in the comparisons shown in Figure 1 and Figure 2. It is clear that EXP07 generally yields different performance results, sometimes *very* different results, than one would expect from the HSPF and SEER ratings. The SCOP ratings in the aggregate are consistently lower than the HSPF and SEER ratings would suggest, even when comparing similar climates. Also, the relative ranking of heating or cooling SCOPs among different models would indicate different conclusions about their performance relative to each other than HSPF or SEER rankings would suggest.

3.2 Impact of Controls

Because of the differences in the test procedures, the variation from AHRI ratings found during the load-based test results is not surprising. Allowing the units' built-in controls to respond during the load-based test resulted in a wide range of behaviors that are not apparent under locked operating conditions. This wide range of operating behavior is anecdotally consistent with the VCHP systems observed in field metering studies. The tested units' responses to changing load conditions varied from unit to unit, sometimes quite dramatically, even when comparing units with similar or identical HSPF and SEER ratings. "The apparent explanation for the wide variability in response and performance is the embedded control algorithms" (Harley, 2020), which can result in substantial differences in unit performance.

A dramatic example of the impact of controls was observed when testing two products submitted by the same manufacturer. These products were the same nominal size, and in the same advertised product line, such that the new model is for all practical purposes an updated version of the old product. It has some hardware changes and, most importantly, new built-in firmware. The "old" unit was tested in 2019 using EXP07:19 during the initial round of 13 tests at the UL lab, and the "new" unit was tested in the summer of 2020. Figure 3 shows the old product in cross-hatched columns, referring to the original unit from 2018. The solid-color columns represent the new version of the product. The two pairs of columns on the left side represent heating and the two pairs on the right represent cooling performance.

For each mode, the left pair of bars represents the rated HSPF and SEER. For both heating and cooling the 8% rating improvements determined by the AHRI test procedure demonstrate that modest hardware improvements were included in the product update. The EXP07 test results (the right pair of "SCOP" bars in each group) reveal the impact of both the firmware and hardware changes. The seasonal efficency of the new unit improved dramatically, by 59%

in heating and 80% in cooling, as compared with the old product, resulting in a calculated seasonal energy savings of 37% for heating and 44% for cooling. Although the new-product cooling SCOP is still much lower than the equivalent rated SEER, the heating SCOP of the new product is actually 14% *better* than the equivalent HSPF, while the old one was 22% *worse*. This is a dramatic example not only of the impact of controls, but also the extent to which the test method can impact the resulting rating.

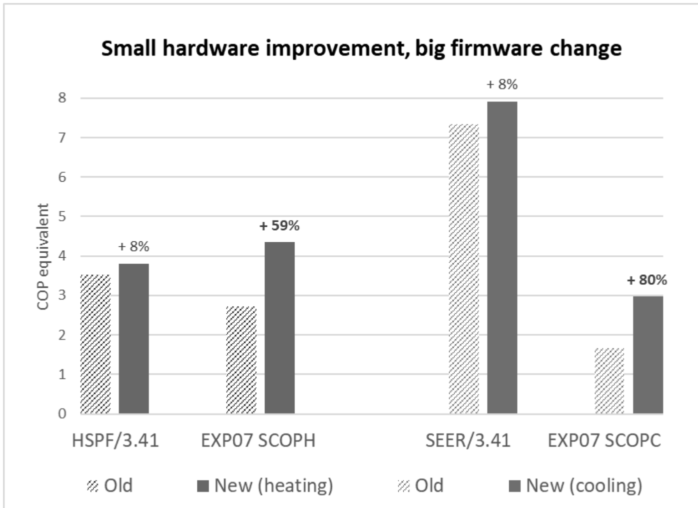

Figure 3. Efficiency Improvement of an Updated Product, HSPF/SEER (in dimensionless units) vs. EXP07 $SCOP_H/SCOP_C$

The 8% increases in HSPF and SEER in the product update indicate that the hardware components were somewhat improved. To illustrate why the much larger improvement revealed by EXP07 results mostly from the built-in firmware, Figure 4 shows an example of one EXP07 test condition conducted on the old product. The unit cycles on and off repeatedly to maintain the target indoor comfort condition, and in each cycle the power swings rapidly up and down before settling on a value of over 900W. Each cycle wastes energy by starting with a cooling output that is too high for the load, and so the unit subsequently shuts off to avoid over-cooling the room. Figure 5, by contrast, shows the new product's response under the same test condition (Test CC, Dry), operating in a manner that would be expected from a VCHP: it ramps up a bit, then reduces the compressor power until it finds a steady cooling output that maintains the room temperature at the desired setting, modulating to a power of about 400W. For this test condition, the resulting COP was 2.73 for the older unit , and 4.36 for the new unit. Such dramatic differences in behavior between the two units occurred at almost every test condition, during both the heating and cooling tests: the old model cycled at high power under all but the largest loads, and the new model modulated within a wide range, as a VCHP is expected to.

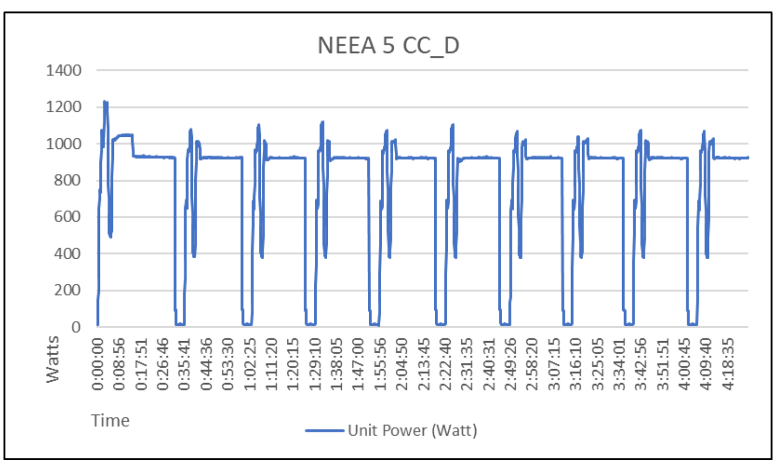

Figure 4. "Old system" behavior showing significant power consumption and high-power cycling

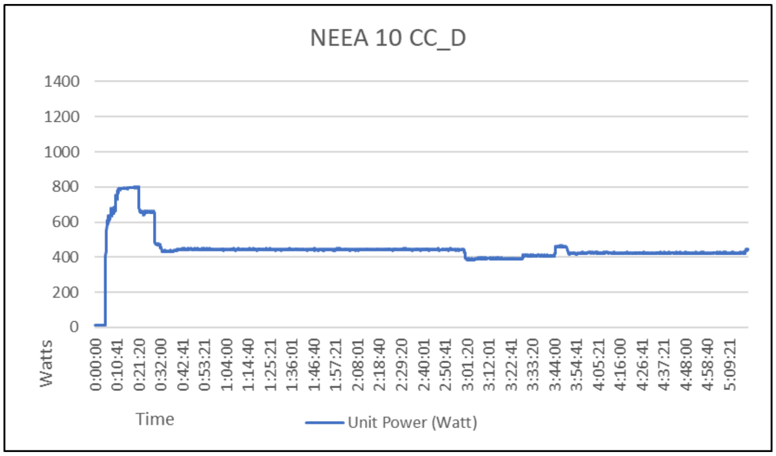

Figure 5. "New system" behavior showing modulation at much lower power input

It is noteworthy that the manufacturer was made aware of the old system's poor test results, and the high-power short cycling during most operating conditions. Figure 5 shows that the manufacturer corrected the problem in the new product by updating the firmware. The EXP07 lab testing process confirmed that the short-cycling was largely curtailed in the update and improved the SCOP values accordingly. This specific example illustrates that the standard metrics of HPSF and SEER entirely missed the short cycling and its performance impact in the original design, and failed to capture the increased performance impact of the improved controls.

3.3 Other Unexpected and Erratic Behavior

It is important to remember that the actual test results and ratings of EXP07 are not intended to be directly comparable to those of AHRI 210/240. There are minor differences in the indoor and outdoor temperature and humidity conditions and the load lines used in the seasonal rating computations. The EXP07 test attempts as closely as possible to mimic the operating conditions that a unit would encounter during a real-world installation, by allowing the unit's firmware to manage its operation. Even when EXP07 dictates full-load tests the compressor still operates using the on-board firmware. In full-load testing, some of the units ramped up to a higher capacity than they would operate during an AHRI test under similar temperature conditions. Other units produced lower capacities during dynamic testing than they would during an AHRI test. Lab results reveal many other examples of firmware impact including repeated on-off cycles at high power, when modulation could be possible; units that cycled at higher loads after they modulated at lower loads; cycling for 30-90 minutes prior to settling into a modulating mode; and slow "loading up" processes that sometimes took 60 minutes or more as tested units struggled initially to control the indoor conditions but didn't attempt to run near maximum output. Other observations while testing to EXP07 included:

- Thermostat settings and offsets are inconsistent, not only from model to model, but in some cases even for a given unit under varying test conditions. In some cases, thermostat offsets appear to be intentional efforts to anticipate differences between average room temperature and the location where the temperature is sensed (e.g., at the intake of a ductless unit). Offsets present challenges, both in finding the right control setting that allows the test unit to maintain indoor conditions within the allowed tolerances, and by increasing the lab time needed for testing and re-calibration of the thermostat settings to account for the offset(s).
- Irregular modulation during steady load conditions leads to longer test times and increased uncertainty in the results at some test conditions. Some units were tested multiple times at the same conditions to obtain results, and in many cases the convergence criteria were not met. This requires extending the test to a maximum prescribed test time and integrating the results over the entire period.
- Anecdotally, these irregular operating modes and erratic behaviors are similar to the observed behaviors during field monitoring (Proctor and Wilcox, 2019), and in general they seem to result in poorer overall performance both in measured efficiency and occupant comfort.

- If manufacturers were to adjust their control algorithms to provide more consistent response to indoor and outdoor conditions, better calibration to indoor temperature, and to the extent possible to favor modulation rather than cycling at lower load conditions, test times could be shortened, and greater consistency between lab and in-field performance would result.
- Such improvements in equipment response would likely not only improve both rated and in-field performance, they would also likely improve test repeatability and lab-to-lab reproducibility, which are parameters that are currently being investigated.

4. LESSONS AND PENDING UPDATES

During the technical review period, 86 distinct comments regarding EXP07:19 were received. Although the comments encompassed numerous topics, most of the individual detailed comments centered on two subjects. The test burden (lab time to complete setup and testing) is a concern raised by several stakeholders. The second area broadly focused on a range of challenges that stem from the nature of load-based testing using on-board controls and that affect test to test repeatability and lab to lab reproducibility. Reproducibility is particularly challenging when unit behavior is erratic, even during controlled lab tests. Considerable effort has been made to address these concerns during the disposition of the comments. The following constitutes a summary of the major issues and a description of how their resolution was incorporated into the new edition of EXP07. These include:

- Incorporating a latent virtual building load for dry cooling as well as humid cooling test conditions to better represent typical operating conditions in dry climates.
- Removal of several heating test conditions, by replacing both the HL and HA tests with an optional "lowest catalogued" temperature test condition and eliminating all but one of the unique Marine test conditions.
- Clarification of test set-up procedures to reduce ambiguity and the potential for different labs to misunderstand or interpret instructions, including:
    - Differentiating between the control settings that are accessed during installer setup from the "user" controls that establish unit operation during test periods
    - Refining and clarifying a process to establish offset(s) between user temperature settings and the room temperature that tested systems actually maintain, so that the user controls can be set properly
    - Clarifying procedures for verifying proper refrigerant charge, and for establishing full-load air volume(s) and their associated external static pressures. The latter is critical for load-based testing to allow indoor fan speed to modulate according to the on-board firmware.
    - Clarifying some instrumentation requirements and tolerances to better represent measurements under dynamic conditions rather than the more typical steady-state conditions
- Clarification of the convergence criteria used to determine integration periods during each test condition, including:
    - Defining the measurement recording time scale, and the use of the virtual building load
    - Reducing potential for lab discretion or misunderstanding in determining convergence under some conditions
    - Revising criteria such that the maximum test period (4 or 6 h) is always required during certain low-load test conditions
    - Clarifying criteria to reduce "false" or misleading convergence scenarios during modulation or cyclic variation (on/off or up/down compressor cycling)
    - Reducing moisture capacitance in the latent virtual cooling load model to favor convergence and repeatability
    - Increasing the wait time used to trigger the transition to full-load testing, to improve lab-to-lab and test-to-test consistency
- Converting control parameters from wet bulb/dry bulb combinations to dry bulb and humidity ratio to eliminate sensitivity to lab elevation and pressure variations
- Updating test condition and test operating tolerances
- Creating a procedure for construction and use of a "thermostat environment emulator" to improve control of thermostat exposure to the changes in room conditions dictated by the virtual building load simulation
- Allowing the use of optional manufacturer-developed test plans
- Adding an option for the manufacturer to specify extension of the learning cycle to include break-in period

- Fixing a number of typographical errors and omissions and improving organizational content to improve consistency of lab interpretation and application

5. SUMMARY AND CONCLUSIONS

At this stage in the process of developing the EXP07 test procedure, the most significant conclusions are as follows:

- The performance results of EXP07 will likely lead stakeholders to different conclusions about the relative efficiencies of various models, generally and for specific climates, compared with the current AHRI 210/240 test and rating results.
- The single largest reason for the performance variability is a result of the equipment's built-in controls. Those controls are not tested using current AHRI locked test and rating procedures. The fact that a significant number of units perform much more poorly using the EXP07 test, relative to their peers with similar or higher AHRI ratings, calls into question the validity of using AHRI ratings to estimate energy consumption and savings for consumers, utilities, and government agencies.
- An improved test procedure is likely to reduce uncertainty and improve test-to-test repeatability and lab-to-lab reproducibility.
- Manufacturer optimization of on-board firmware algorithms to reduce erratic behavior and provide faster, less expensive lab testing using EXP07 is likely to improve the reliability of the test procedure results, while at the same time improving field performance and efficiency by reducing erratic performance, irregular temperature sensing, and short-cycling behavior.
- A load-based test such as EXP07 promises to increase transparency in the testing and rating process and provide improved differentiation among products to help regional markets select the best products for their applications. To the extent that the rating results are more representative of true performance, it has the potential to improve market responsiveness and provide greater leverage for incentive programs.

It is clear from the current findings of various field studies that operational performance is not always well-predicted by the current standard AHRI ratings and EXP07 testing further supports those findings. AHRI ratings may be effective at measuring the hardware performance but neglect the built-in operational "intelligence" during the test procedures, omitting a critical component of real system operation. A load-based test that includes the built-in controls "intelligence" provides very different ranking of performance across units for both heating and cooling operation. Many of the same anomalies have been observed in both the EXP07 lab testing and in field monitoring, so it is reasonable to expect that the EXP07 results will be validated with a model-by-model comparison using in-field and lab-tested measurements; two such studies are currently underway. Based on the results to date, EXP07:22 has the potential to be an extremely valuable tool to aid in market transformation by offering performance ratings that more closely represent real-world performance, reducing uncertainty in program evaluations, improving the quality of information available for customer and contractor product choices, and increasing the savings potential of programs.

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