ORNL/TM-2015/387

Review of Test Procedure For Determining HSPF's of Residential Variable-Speed Heat Pumps

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August 2015

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Energy and Transportation Science Division
Building Technologies Program

REVIEW OF TEST PROCEDURE FOR DETERMINING HSPF's OF RESIDENTIAL VARIABLE-SPEED HEAT PUMPS*

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* Report for DOE Standards Program Related to Residential Central AC and HP Test Procedure Rulemaking

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABBREVIATED TERMS

ANSI	American National Standards Institute
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
BPA	Bonneville Power Administration
COP	coefficient of performance
DHR	design heating requirement
DOE	U.S. Department of Energy
EPCA	Energy Policy and Conservation Act of 1975
HPF	heating performance factor
HSPF	heating seasonal performance factor
NIST	National Institute of Standards and Technology
ORNL	Oak Ridge National Laboratory
RH	relative humidity
SEER	seasonal energy efficiency ratio
TVA	Tennessee Valley Authority
VS	variable speed

1. SUMMARY

This report reviews the suitability of the existing Heating Seasonal Performance Factor (HSPF) ratings and testing requirements for the current generation of variable-speed (VS) air-source heat pumps. Recent field test results indicate larger discrepancies between rated HSPF and field-observed HSPF for VS models than for single-speed models in the same houses. These findings suggest that the heating season test and ratings procedure should be revisited for VS heat pumps. The ratings and testing procedures are described in ANSI/AHRI 210/240 (2008) for single-speed, two-capacity, and variable-speed units. Analysis of manufacturer and independent test performance data on VS units reveals why the current VS testing/ratings procedure results in overly optimistic HSPF ratings for some VS units relative to other types of heat pumps. This is due to a combination of extrapolation of low speed test data beyond the originally anticipated ambient temperature operating range and the constraints of unit controls, which prevent low speed operation over the range of ambient temperatures assumed in the procedure for low speed. As a result, the HSPFs of such units are being overpredicted relative to those for single- and two-capacity designs. This overprediction has been found to be significantly reduced by use in the HSPF ratings procedure of an alternative higher-load heating load line, described in a companion report (Rice et al., 2015).

2. BACKGROUND OF PRESENT VS RATINGS AND TEST PROCEDURE

The Energy Policy and Conservation Act of 1975 (EPCA) requires that test procedures shall produce energy efficiency or energy use results that are representative of a covered product operating over an average period of use, and shall not be unduly burdensome to conduct. [42 U.S.C. 6293(b)(3)]

A recent Bonneville Power Administration (BPA)-commissioned study done by Ecotope, Inc. (Larson et al, 2013, Table 13) found the tested VS air-source heat pumps achieved lower performance in the field than would be suggested by their HSPF ratings. This underperformance averaged 25% for VS units but only 5% for single-speed units in U.S. Department of Energy (DOE) climate region IV and VI locations in Oregon. A recent Oak Ridge National Laboratory/Tennessee Valley Authority (ORNL/TVA) field test (Munk et al 2013, Table 2) identified a similar large discrepancy of more than 30% lower heating season performance than the rated 13 HSPF in the DOE region III location of Knoxville, Tennessee. Both field test projects used VS units introduced to the market in 2011, and having high HSPF ratings. These field results suggest that the heating season ratings procedure for VS heat pumps should be revisited, especially for VS models with rated HSPFs above 10.

VS units have the potential to match space heating needs closely over a wide range of ambient temperatures. By reducing cyclic losses and the heat exchanger loadings to better match the lower heating loads at milder ambient temperatures, higher operating efficiencies can be achieved compared to single- and two-capacity designs. Units that have overspeed operation in heating mode, relative to the maximum rated cooling mode speed, also provide higher heating capacities at low-ambient-temperatures than units without this capability, reducing the use of electric resistance heat.

The National Institute of Standards and Technology (NIST) (Domanski, 1988) developed a test procedure to calculate HSPF of VS heat pumps, addressing some of their unique features. To avoid an excessive number of test points, the test procedure was based on a simple VS design concept and the typical range of compressor speeds of units available at the time. This approach was adopted as the industry test standard for VS air conditioners and heat pumps. The first goal of the current study is to evaluate whether the test procedure appropriately captures all performance characteristics of recently-introduced VS units. If the procedure is found to be lacking for such units, the second goal is to determine the potential range of differences between the performances predicted by the procedure as compared to that calculated from more detailed data sets.

The HSPF rating procedure for residential heat pumps is defined in ANSI/AHRI 210/240 (AHRI 2008) as described in Appendix C. The rated HSPF is calculated based on application of a minimum heating load line and 5°F temperature bin data for DOE climate region IV. VS HSPF ratings calculations are based on five required test points:

- Two each at min and max compressor operating speeds,
  62°F and 47°F ambient temperatures at min speed (tests $H0_1$ and $H1_1$), and
  47°F and 17°F ambient temperatures at max speed (tests $H1_2$ and $H3_2$)

- One at an intermediate compressor speed one-third of the way between min and max speeds, at 35°F ambient temperature ($H2_V$). This is a frost/defrost (F/D) test, which is conducted with higher humidity that causes frost accumulation and which includes defrost periods.

Three optional test points are:

- One test ($H1_N$) at 47°F, using the max compressor speed used for cooling operation, if less than the max heating speed—this test can be used to determine the nominal heating capacity, which is used to define the heating load line.

- One max speed F/D test (test $H2_2$) at 35°F ambient temperature and higher humidity, which can be used to more thoroughly characterize operation in frosting conditions at max compressor speed.

- One min speed cyclic test at 62°Fambient temperature, If this test is not done, a default cyclic degradation coefficient Cd of 0.25 is used in the HSPF calculations.

The variable-speed HSPF ratings procedure requires low speed test points only at 47 and 62°F ambient temperatures. This limited low speed testing requirement implies that the minimum speed balance point (the ambient temperature at which the unit's minimum speed capacity exactly matches the heating load) is expected to be above the 37°F temperature bin, closer to the 42°F temperature bin. This implication follows from the selection of the intermediate speed test point at 35°F. If the balance point is lower than about 40°F, use of low speed test points at 47°F and 62°F extrapolated to temperatures below 40°F to characterize performance may not give accurate results. For non-VS units the HSPF ratings procedure is designed to minimize extrapolation error. For example, for two-capacity units where the low capacity stage is allowed by controls to operate below 40°F, low-speed test points at 35°F and 17°F are required.

Even more significantly, it is also assumed for the VS ratings procedure that the unit controls allow unrestricted operation between min and max speeds to match the load line. A review of the operation of recent variable-speed units with high HSPF ratings indicates that, more often than not, this simplifying assumption does not hold. In combination, these two simplifying assumptions, which are built in to the current HSPF ratings procedure, can lead to overprediction of HSPF.

For current variable-speed units, the extrapolated lowest speed balance point for the minimum heating load line used for ratings is typically between 30°F and 37°F rather than in the low to mid-40s. Performance extrapolated from tests at 47°F and 62°F can overpredict minimum speed performance below 40°F due to dropoffs in compressor and heat exchanger performance, presuming of course that unit controls allow lowest speed operation at ambient temperatures below 40°F. If the unit controls do not allow lowest speed operation down to the minimum speed balance point of 30-37°F, performance can be especially overpredicted because the current procedure essentially underpredicts the operating speed of the unit over an extensive range of ambient temperatures. For the HSPF calculation, based on DOE climate region IV, this error can be quite significant, because the bins between 27°F and 37°F have the majority of heating load-hours across all the temperature bins, with the most heat being delivered around the 32°F bin. As a result, this ratings procedure simplification can have a large impact on the HSPF calculation. The net result is that the benefits of VS units over single-speed and two-capacity units may be overpredicted by the relative increase in their HSPFs from this inaccurate representation.

3. TECHNICAL BASIS FOR RECENT ISSUES WITH THE VS RATINGS PROCEDURE

For VS units, the heating load line is allowed by 210/240 to be defined based on the max cooling speed (maxC). This allows the heating load line to be defined for VS units at a speed consistent with that for single- and two-capacity units. Accordingly, the minimum speed heating balance point for a VS unit is typically determined by the ratio of the max cooling speed to the min heating speed (minH). The lower the min heating speed, the higher the maxC/minH ratio. Current VS units generally have a higher minH speed relative to the maxC speed than did the VS units when the VS test procedure was developed in 1988. This gives a higher minimum capacity relative to the heating load line and so a lower min speed balance point than originally expected. The lower this min speed balance point, the more potential error from the extrapolation of min speed data at 47 and 62°F. The error is even more significant for units that limit min speed operation to ambients above 40°F because the allowed min capacity operation is at a higher speed, so higher capacity, with typically lower steady-state COP and higher cyclic loss.

As noted earlier, given that the intermediate speed test point is at 35°F, the implied premise of the VS ratings procedure is that the minimum speed balance point is above the 37°F temperature bin. This would typically require a maxC/minH ratio ≥ 2.5 and a moderate-to-high min capacity slope (based on the measured 47°F and 62°F capacities). A relatively low ratio of maxC/minH, especially when combined with a flatter min capacity slope, results in lower min speed balance points between 30-37°F ambient.

The VS unit example given by Domanski (1988) in the development of the current ratings procedure had a maxC/minH capacity ratio of 2.6, which implies a corresponding speed ratio of ~2.8 or larger. In fact, some of the leading variable-speed designs in the 1980s had maxC/minH speed ratios of 2.8, 3.6, and 4.75 (Rice 1992). Hence current ratings may have been well suited to vintage 1980s VS units. However, samplings of current VS units with high HSPF ratings from two manufacturers have an average maxC/minH speed ratio of 2.1. A primary reason why speed ratios are lower in many current VS units is that the minimum heating speed is generally higher today than in the earlier designs. VS units that overspeed in heating mode usually have even lower maxC/minH speed ratios, as is the case with northern-climate two-capacity and VS units, where the max cooling speed is set somewhat lower than the max heating speed.

Figure 1 provides another way to look at the impact of maxC/minH speed ratio, since speed ratios are closely related to capacity ratios. According to current rating procedures, the VS unit nominal heating capacity at 47°F and the heating load line used for HSPF ratings are both set based on the max cooling mode speed. In this figure, the unit heating capacity and the heating load line are both shown normalized to the nominal (rated) heating capacity Q(47). The solid triangle represents the rated unit capacity and the blue circles give the relative capacities at the min speed rating points. Hence the nominal heating capacity to min heating capacity ratio at 47°F is 1.0/0.6, or 1.67. This is an approximate indicator of the maxC/minH speed ratio designed into the particular VS unit. This capacity data is more readily available than compressor speed data and can be used to quickly evaluate whether the minimum capacity (aka speed) balance point will be near or below the 37°F temperature bin. In Figure 1, the minimum speed balance point temperature is defined by where the two lines cross, so ~ 30°F in this example.

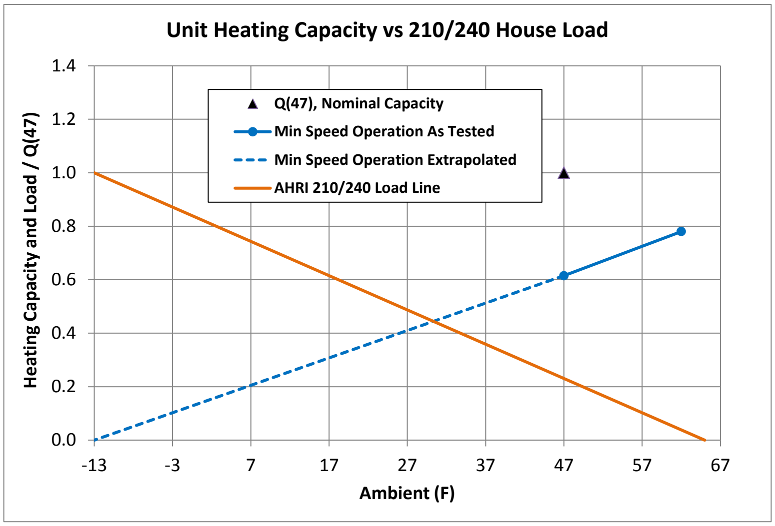


Fig. 1. Heating capacity and house load / $Q(47)_{nom}$
-- extrapolation example for min speed data with ~ 30°F min speed balance point.

In summary, inflated HSPF ratings are resulting in some current VS designs because the test procedure allows characterization of low capacity performance using extrapolations of capacity and power based on tests conducted at 47°F and 62°F at minimum speed. The use of speed limiting unit controls below 47°F ambient temperature can result in significant overprediction of performance at minimum capacity from this test procedure simplification. For units so controlled, the unit operates in reality at a higher compressor speed in this temperature range, with a lower steady-state COP, higher cyclic loss , and more frost accumulation and required defrosting, for which the net COP can be significantly lower than for the extrapolated performance. Such VS units which have high HSPF ratings are, in large part, obtaining the high ratings from effects of extrapolated low speed performance at low ambient temperatures where the unit's own control system will not allow it to operate. Even for units with significant overspeed heating capability, the high HSPF ratings under current procedures are more attributable to this loophole than to the benefit from overspeed units reducing resistance heat use. In fact, with the current procedure, manufacturers could boost HSPF ratings further by reducing low speed performance at the 62°F test point. This would first lower the extrapolated power values below 47F; second, this could reduce the slope of the minimum capacity line and further lower the calculated min speed balance point. The current HSPF procedures can give some VS units performance significant credit for the wrong reason while failing to sufficiently credit known energy saving features such as overspeed capability at lower ambient temperatures due to the atypically low heating load line used in the HSPF ratings (Rice et al 2015). As such, the current procedure can give undue performance credit at temperature bins where most of the seasonal heating is done (between 27 and 37°F ambients) while minimizing the benefits from overspeed operation at low ambients in reducing resistance heat use.

4. COMPARISON ANALYSIS FOR 2-TON VS UNIT, RATED 13 HSPF, USING MANUFACTURER'S PUBLISHED DATA

The following example using manufacturer's published performance data illustrates existing rating procedure overprediction of HSPF as a result of minimum speed extrapolation and unit controls limiting minimum speed operation to ambient temperatures of 47°F and above. This nominal 2-ton unit has a 13 HSPF rating, max/min cooling speeds of 3200/1800 rpm, and max/min heating speeds of 5700/1800 rpm. This gives a ratio of max cooling to min heating speed of 1.78 (3200/1800) and a ratio of nominal to min heating capacity at 47°F of 1.64 1.

The manufacturer provides expanded heating performance data at minimum and maximum capacity operation as a function of ambient temperature, as shown in Figure 2 for the 2-ton VS model. Inflection points in capacity curves below 47°F indicate that the compressor speed is changing. From Figure 2, one can deduce that the controls allow min compressor speed only at ≥47°F. Below that temperature, the minimum allowed compressor speed increases with decreasing temperature until a new higher minimum is reached around the mid-20°F ambient temperatures. A similar speed control approach is used for the maximum allowed speed, with overspeeding (operation higher than the max cooling speed) enabled below 47°F. At 47°F and higher ambient temperatures, the unit is operating at the maximum heating speed allowed by the controls (i.e., the max cooling speed) which provides the nominal rated heating capacity $Q(47)_{nom}$ at 47°F of 23,700 Btu/h.

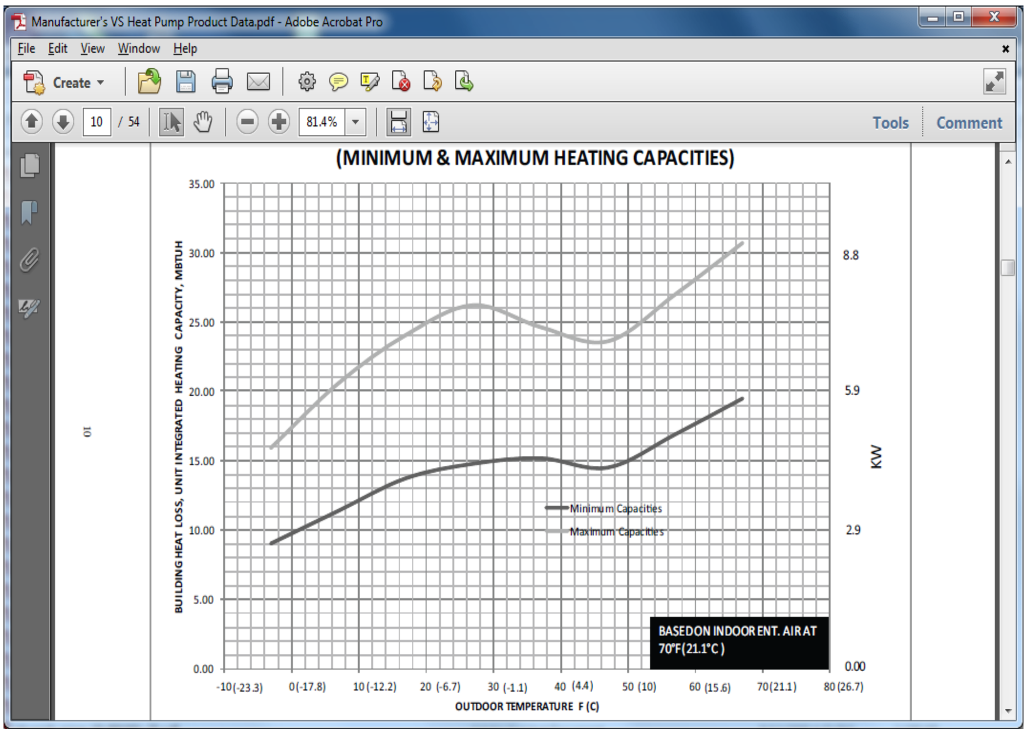


Fig. 2. Example 13 HSPF VS heat pump with overspeed heating operation and ambient control of minimum and maximum speed.

The heating load line for the ratings calculation is set based on $Q(47)_{nom}$. In Figure 3, the heating load line has been plotted along with the min and max capacity lines provided by the manufacturer. A dashed line showing the extrapolation assumption of the 210/240 procedure is also given. From the intersections of the heating load line with first the dashed line and at a much lower ambient with the minimum capacity line, one can see that a minimum capacity balance point of just over 30°F is predicted by the test procedure; this is in contrast to a min capacity balance point below 20°F, at a necessarily higher compressor speed, based on how the unit is actually controlled. Looking overall in Figure 3 at the available operating max/min capacity ratios at any given ambient temperature, it is seen that ratios range between a max of 1.81 (1.12/0.62) at 27°F to a min of about 1.6 on either side of that ambient. The 1.81 value compares with a max/min capacity ratio of 2.73 (1.12/0.41) that is assumed by the procedure between the min and max speeds at 27°F.

Between the minimum and maximum capacity line intersection points with the load line, manufacturer's capacity data can be used to interpolate the system power and heating performance factor (HPF) values for each temperature bin to represent operation at intermediate speeds/capacities based on matching the 210/240 load line between min and max capacity lines. In this way, the manufacturer's performance data, in combination with the defined heating load line, can be used to calculate an actual operating HSPF based on load matching between the min and max capacity lines and cyclic operation above the actual min capacity balance point. Note that for this unit, interpolation is not needed until below 20°F ambient temperature due to the speed limiting controls. Above this ambient, the unit must cycle on and off to match the assumed load line.

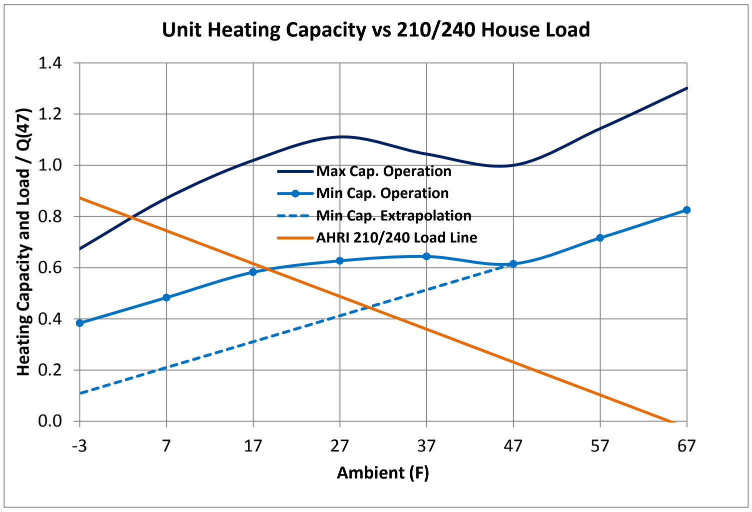
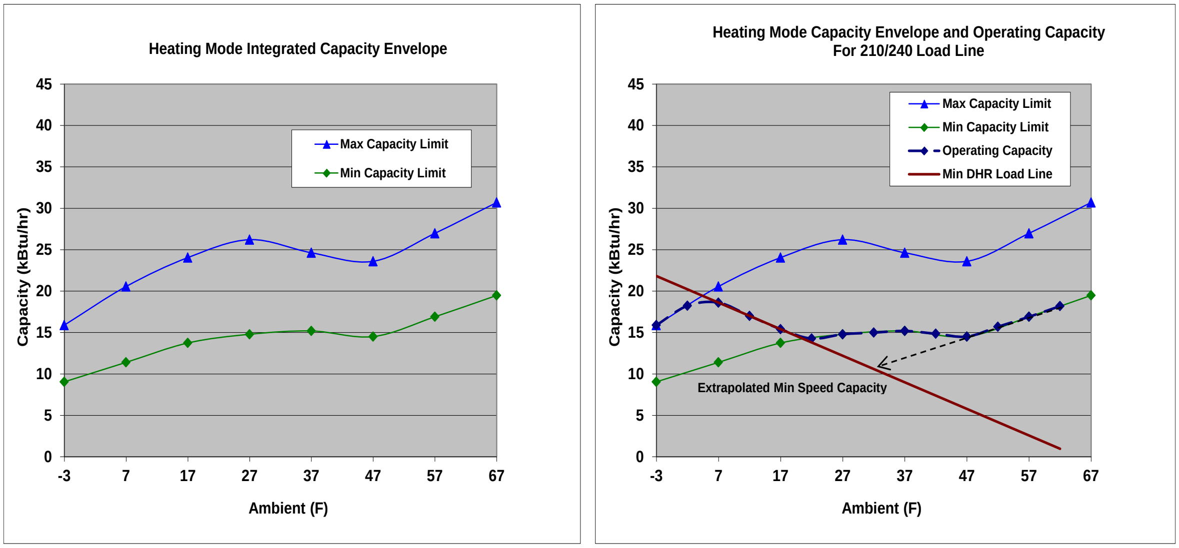


Fig. 3. Heating capacity and house load / $Q(47)_{nom}$
-- manufacturer's expanded data for 2-ton 13 HSPF VS unit, with extrapolation

Figure 4a shows again the min and max capacity operating lines for the 2-ton unit with points plotted at the 5°F temperature bin steps of 210/240. This plot is overlaid in Figure 4b by the load line from the 210/240 procedure given by the minimum design heating requirement (DHR) where minimum speed operation is assumed by the procedure to apply down to the 32°F temperature bin. However, for the operating line using the manufacturer's capacity data, the minimum speed is increased below 47°F so that the minimum capacity line intersects with the load line below the 22°F bin, at compressor speeds somewhat higher at minimum speed.



(a) **(b)**

Fig. 4. a) Min and max capacity data and 4b) with load and operating lines.

In Figures 5a and 5b, we show the effect of the speed-limiting controls on the heating performance factor HPF (i.e., COP/3.412). Figure 5a shows the envelope of HPFs (i.e., COPs×3.412 Btu/W-h) at min and max capacity operation, based on manufacturer's published data. Figure 5b shows with the dashed line the minimum speed HPFs extrapolated per 210/240 down to 32°F, giving a value at 32°F above 12 HPF, while the operating HPF based on the interpolated capacity at the 32°F bin along the dashed operating line (to match the load line) is just over 10. The lower HPF of the min capacity curve in Figure 5b than that of the extrapolated line is due to the speed limiting operation of the unit controls. The lower net operating HPF below the (steady-state) minimum capacity HPF curve is due to cyclic operation down to the minimum capacity balance point below the 22°F bin. (The default cyclic degradation Cd of 0.25 was used for the analysis as a close approximation to the expected level for a variable-speed unit at low speed.) Below the max capacity balance point near the 7°F bin (as can be seen from Fig. 4b), supplemental resistance heat is needed and so the operating HPF drops below the max capacity HPF curve in Fig. 5b. Between 22F and 7°F bins, the net operating HPFs are determined by finding the required capacity fractions between the min and max capacity levels to match the load line and interpolating the power levels, assuming no cycling losses.

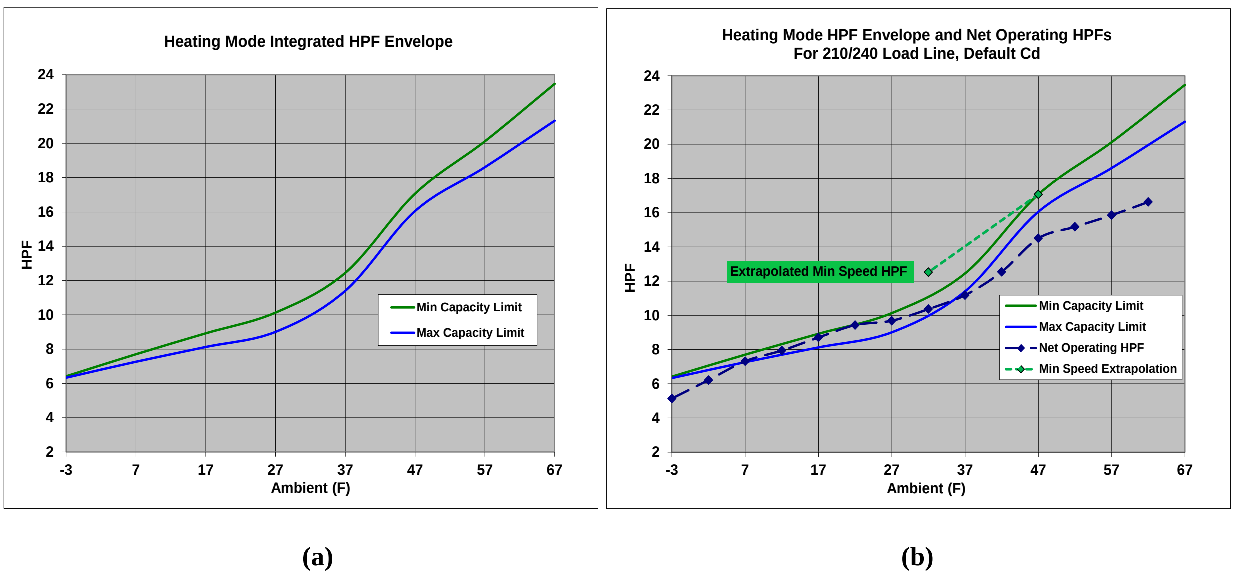


Fig. 5. a) Min and max HPF data and b) with extrapolated vs. operating lines.

Figure 6 shows that, for DOE Region IV used for the ratings, the delivered load hours are centered around the 32°F bin, with most delivered loads between 22°F and 42°F, where the interpolated HPFs run lower than the 210/240 values. As a result the calculated HSPF of 10.64 is 18% lower than the rated HSPF of 13.

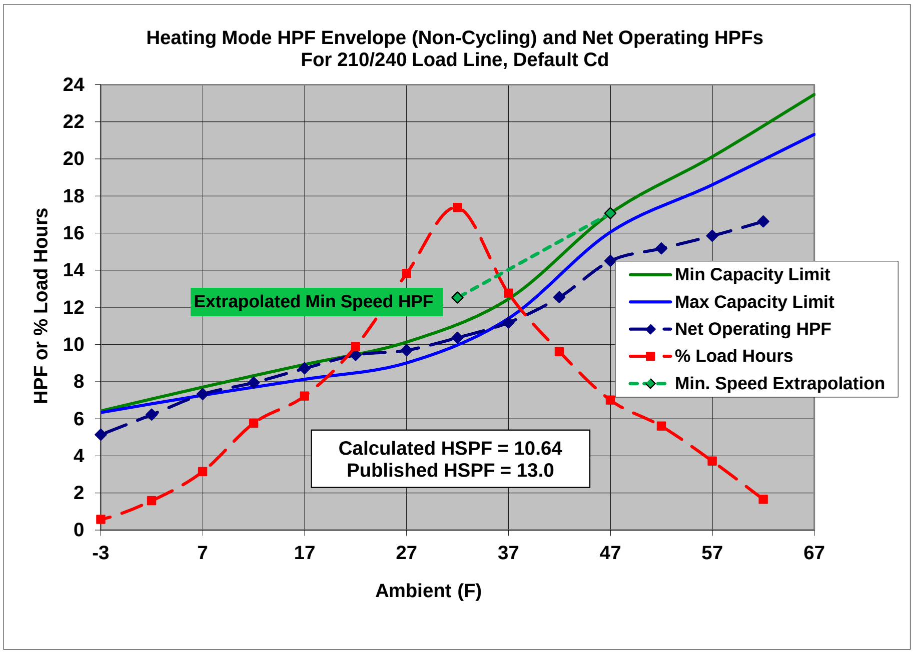


Fig. 6. Operating vs procedural HSPF calculation -- shown against load-hours distribution.

In summary, the interpolated HSPF from manufacturer's expanded data gives an 18% lower HSPF than the rated value, while a similar interpolation procedure applied to the cooling mode performance data was 0.5% above rated SEER. There are two known limitations of this analysis. First, for the performance interpolations in the capacity matching operating region between min and max capacity, manufacturer's data are only available at two capacity levels, while in 210/240, a third performance curve is developed from a test point for a speed 1/3 of the way between min and max speeds. The second limitation is that the manufacturer's published data are provided only in the comfort mode at min capacity (per communication with the manufacturer) and in efficiency mode at max capacity, whereas all rating procedure test points are conducted in efficiency mode. The effect of the comfort and efficiency mode discrepancy is difficult to estimate. Likely the effect of only having min and max performance data could have a larger effect on the difference between the procedural and operational HSPF ratings. To help answer these questions we sought further data sets where all measurements were taken in efficiency mode, and the measurements had three levels of capacity and HPF performance versus ambient temperature. We found one set of heating mode data available from Electric Power Research Institute (EPRI) on a similar VS unit that met these two criteria (Hunt 2013)

5. COMPARISON ANALYSIS, UNIT A, 2-TON VS. UNIT, RATED 10.5 HSPF, INDEPENDENT TEST DATA

This unit was from the same manufacturer as the initial unit studied, using the same outdoor unit, but with a smaller indoor air handler (Hunt 2013). The researchers at EPRI used an AHRI test controller provided by the manufacturer for their steady-state (SS) testing; as such, the manufacturer's unit control algorithms, set for efficiency mode, were active over the full operating range. Using the AHRI controller in a psychrometric test chamber, the researchers mapped performance at AHRI indoor conditions at maximum, 75%, and minimum capacity levels between 7°F and 62°F ambient temperatures at outdoor relative humidity (RH) levels per the test procedure. They also conducted the intermediate speed frosting / defrosting (F/D) test at 35°F ambient. A summary of the test points is shown in Table 1. All were tested with 70°F indoor return air temperature and outdoor RH conditions consistent with 210/240. For the tests at 35°F ambient temperature, only the $H2_V$ test was a full F/D test, with the other tests run at the same higher humidity levels but without a defrost test (Hunt 2013). It was reported that minimum frosting degradations were observed in these tests. For the tests at 27°F, lower RH levels were used consistent with those for the 17°F rating test.

Table 1. Heating mode test matrix for variable-speed unit A

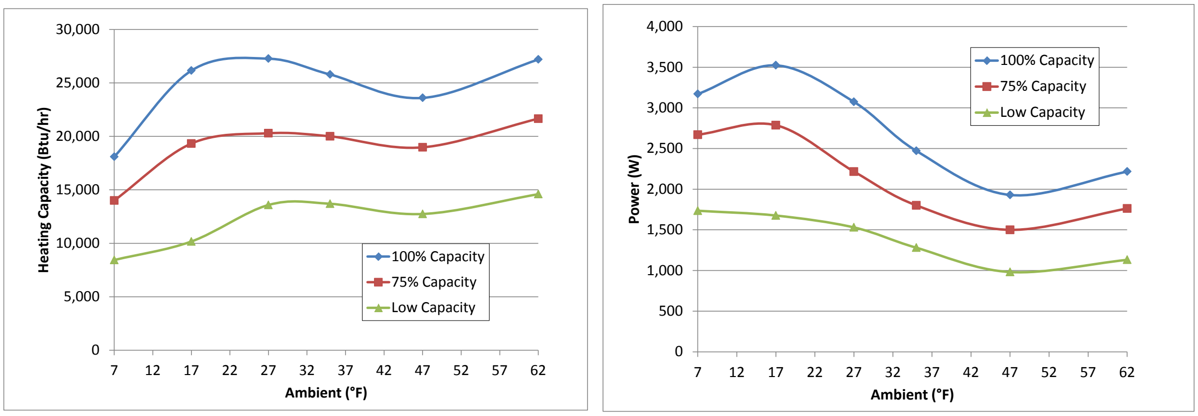
	Ambient Temperature (°F)					
	7	**17**	**27**	**35**	**47**	**62**
Max Speed		S-S ($H3_2$)[1]				
Max Capacity	S-S		S-S	S-S	S-S ($H1_N$)	
Mid Capacity		S-S	S-S	S-S	S-S	
Interm. Speed				F/D ($H2_V$)		
Min Capacity		S-S	S-S	S-S	S-S ($H1_1$)	S-S ($H0_1$)

S-S = Steady-State Test, F/D = Frost/Defrost Test, AHRI 210/240 test points labeled in ().
[1]Max Speed and Max Capacity are the same compressor speed at this condition.

The one exception to tracking the 210/240 test conditions was the nominal external static pressure (ESP) experienced by the air handler, which was at a level of ~0.66” of water column (wc) at the nominal cooling flow rate of 900 cfm rather than the 0.1” wc per AHRI 210/240 for the 2-ton capacity with filter installed. This was because a booster fan was not available in the airflow loop to offset the pressure drop of the airflow measuring station. At low airflows, of course, the ESP dropped naturally to levels as low as 0.12” wc, since the static pressure head drops with the airflow rate by approximately the square of the airflow ratio.

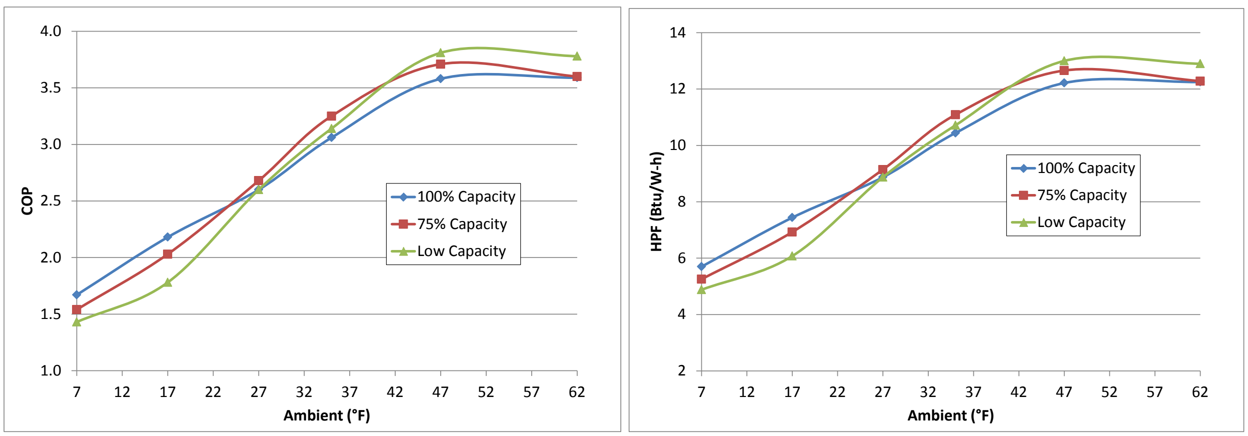
Having the three capacity levels as shown in Table 1 allows more precise calculation of capacity and performance using interpolation, as compared to using only the min and max capacity levels provided by the manufacturer. At each capacity level, the minimum compressor speed is controlled by the unit to increase at lower ambient temperatures, from a minimum level held fixed above 47°F, to some relative maximum speed limit. At the min-capacity setting, compressor speed starts increasing monotonically below 47°F from minimum speed to some intermediate speed limit at ~27°F. At max-capacity setting, compressor speed increases monotonically from nominal compressor speed ($H1_N$ speed) at 47°F to the absolute maximum speed at ~22°F. (The compressor speed levels were not reported by EPRI and the max speed ambient temperatures are estimated here based on the shapes of the reported capacity versus ambient temperature curves.)

In Figures 7a and b, plots are shown for the SS heating capacity and total power versus ambient for the three capacity levels tested. The shapes of the capacity curves are generally consistent with those seen in Figure 2-4 for the manufacturer’s data. COPs and HPFs calculated from the test data are shown in Figures 8a and b, respectively. The efficiency trends with ambient temperature for min and max speeds are similar to those in Figure 5b between 27°F and 47°F, although the absolute efficiency levels are lower, due primarily to the smaller indoor air handler and to a lesser extent to the higher nominal ESP levels. These two differences likely also account for the somewhat different HPF slopes and relative efficiency trends below 27°F and above 47°F. However, it is important to note that most of the delivered heating and unit operation in the rating procedure is between 27°F and 42°F ambient temperatures where the EPRI data and manufacturer’s data exhibit quite similar trends.



(a) **(b)**

Fig. 7. a) EPRI measured VS capacity data and b) EPRI measured VS power data.



(a) **(b)**

Fig. 8. a) EPRI measured VS COPs and b) EPRI measured VS HPFs.

As done previously with the manufacturer's data set, we interpolated the EPRI capacity and power test data to find the operating lines matching the AHRI minimum heating load line used for HSPF rating. As noted earlier, we now have three sets of data (here including performance for a mid-capacity level) rather than the two min and max capacity levels previously from the manufacturer and so we expect that the interpolation to determine actual operation to meet the load is more accurate. In Figure 9, we show the three sets of capacity data and the dashed operating line of SS capacity, matching the 210/240 load line to the extent possible. The results show that above the 22°F temperature bin, the unit is predicted to be cycling at minimum capacity operation, while between 2°F and 22°F temperature bins, the unit is capable of tracking the assumed load line exactly. Below the 2°F bin, supplemental resistance heat is needed to meet the required load. This load tracking is the expected operational (i.e, the functional) performance based on the heat pump unit controls. This is in contrast to operation at the speeds assumed by the 210/240 ratings procedure, which we will call henceforth the procedural operation.

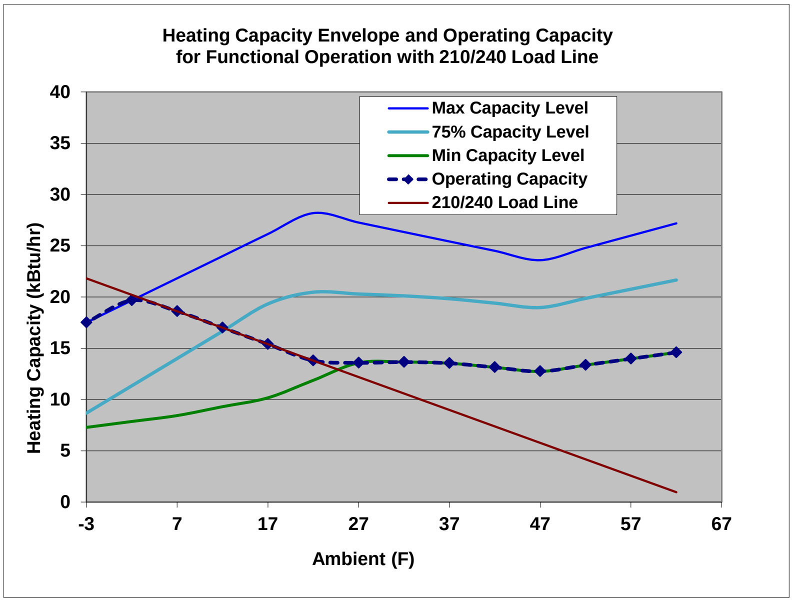


Fig. 9. Functional heating capacity levels of EPRI tested unit and load matching with the 210/240 load line.

In Fig. 10, we show the contrast in minimum speed operation with that applied by the 210/240 procedure, based on extrapolation of the minimum capacity data at 47°F and 62°F ambient temperatures. Here the unit is assumed by the procedure to operate down to ~31°F in the minimum speed mode (as opposed to the minimum capacity mode limited by the unit controls).

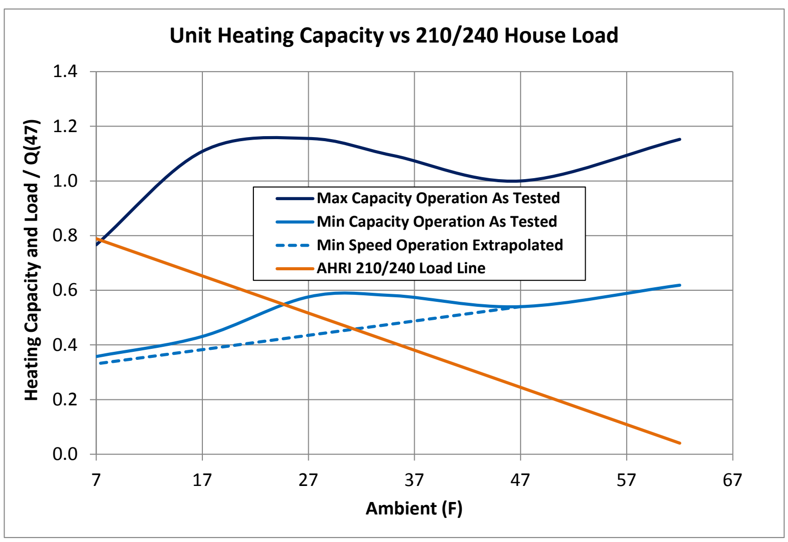


Fig. 10. Heating capacity and 210/240 heating load / Q(47)nom
-- EPRI min and max capacity lab test data
-- for 2-ton 10.5 HSPF VS unit, with extrapolation to
~ 31°F balance point

Next we determined the full set of 210/240 rating point values from the test data, supplemented by the manufacturer's expanded ratings data to estimate the max capacity ($H1_2$) ratings point. For the optional max speed $H2_2$ F/D test point we used the default F/D reductions of the capacity and power from the linearly interpolated values at 35°F between 17°F and 47°F ambient temperatures as prescribed by the test procedure when the $H2_2$ test is not conducted. Once all the ratings procedure test points were determined, we evaluated the procedural operating capacity and HPF levels as matched to the same 210/240 ratings load line. The procedural operating capacity is shown by the dashed line in Fig. 11, along with the capacity lines calculated for the three speed levels from the ratings point data. The test data points are shown on the plot as the solid dots. This plot shows that the procedure calculates that operation between minimum and intermediate speeds is between the 32°F and 17°F as compared to between the 22°F and 12°F bins with the actual functional controls. Next in Figures 12 and 13, we show similar plots of functional and procedural net HPFs as applied to the 210/240 load line, as given by the dashed lines, along with the functional HPFs at min/max capacity levels and the procedural HPFs at the assumed min, intermediate, and max speeds. (In Figure 12, the HPF curve for the 75% capacity level was omitted to simplify the plot.) The same default cyclic degradation factor of 0.25 was assumed for both cases. It should be noted in Figure 13 that the HPF performance line at min speed based on the 62°F and 47°F test points results in a continued slight increase in HPF at lower ambient temperatures which is quite unlikely as the thermal loading on the indoor unit is further reduced below 47°F ambient temperature. As such, extrapolation of min speed performance from the more highly loaded condition at mild ambients (with this smaller indoor unit) to that at lower ambient temperatures becomes more problematical than for the earlier configuration.

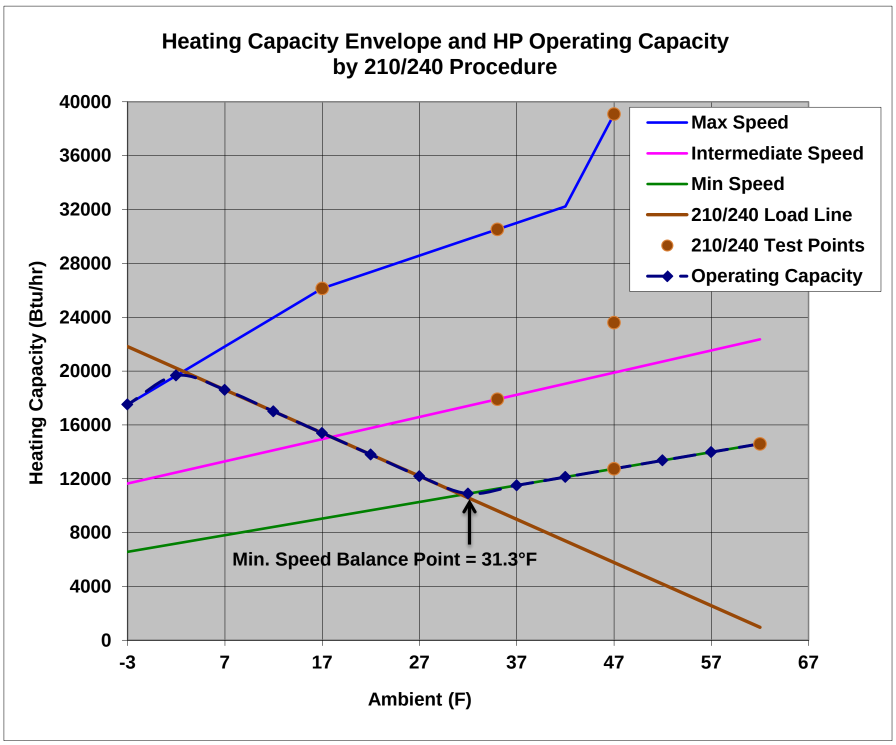


Fig. 11. Procedural heating capacity levels of EPRI tested unit and load matching with the 210/240 load line.

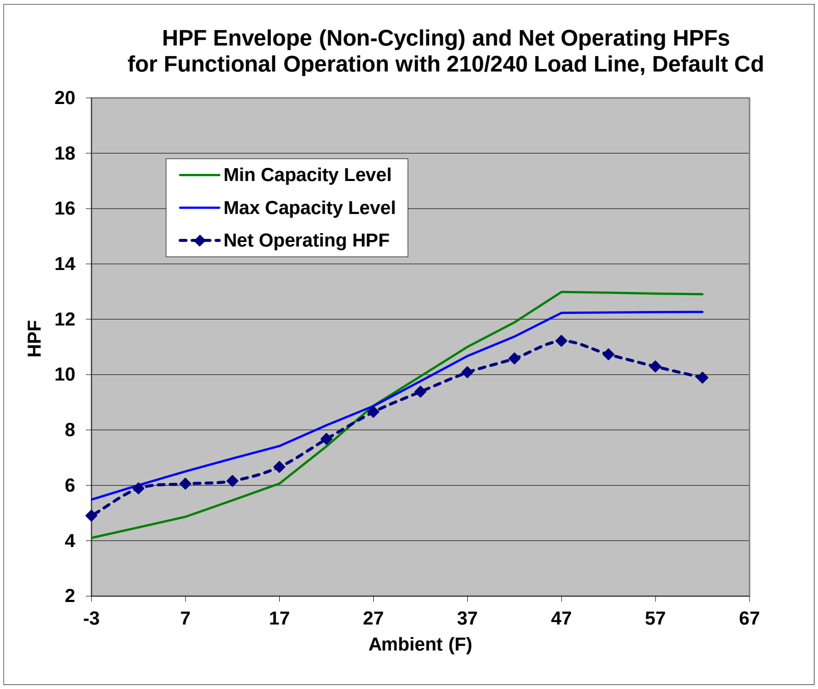


Fig. 12. Functional HPFs at min and max capacity levels and along the actual operating line.

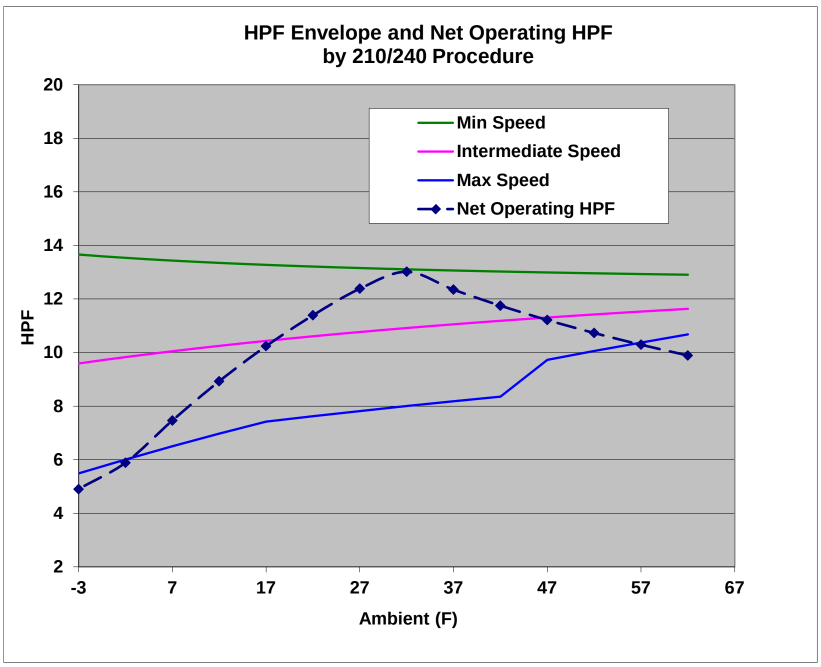


Fig. 13. Procedural HPFs at min, intermediate and max speed levels and along the assumed operating line.

In Figure 14, we directly compare the procedural to the functional HPFs over the range of ambient temperatures, as taken from Figures 12 and 13. This comparison shows the significant difference in calculated HPF levels between the two approaches, with the largest absolute differences seen to be between the 32°F and 17°F temperature bins, In terms of HSPF effect, the strongest effect is around the 32°F ambient temperature bin, because that ambient temperature is at the peak of the delivered load-hours in DOE Region IV, as was shown in Figure 6. The resultant HSPF's from the two approaches are also given in Figure 14, with the functional HSPF being 21.6% lower than the procedural HSPF.

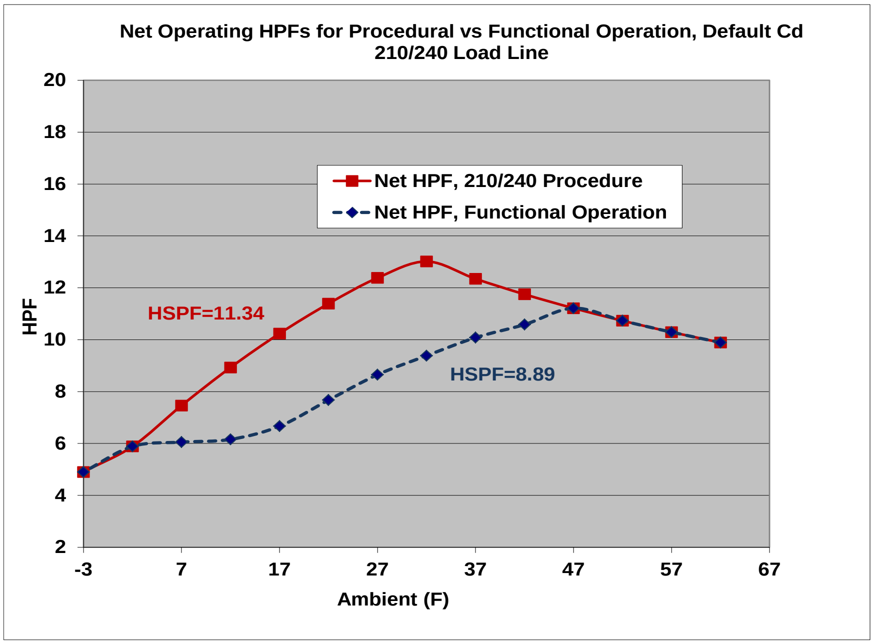


Fig. 14. Comparison of procedural versus functional HPFs and the resultant HSPFs for the 210/240 heating load line.

This compares with the 18% lower functional HSPF for the earlier analysis versus the rated HSPF using the manufacturer's expanded ratings. The higher difference in this case may be attributed to the nearly flat HPFs at min speed between 47 and 62°F as shown in Figures 8a and 13 as compared to the decreasing HPFs for the same ambient temperatures using the manufacturer's data as shown in Figure 5a. As can be seen in Figure 13, this also contributes to a rather slow predicted drop in HPF with lower ambient temperatures for the intermediate speed level as determined from HPF trends interpolated between the min and max speed levels. The earlier data set was with the comfort control setting at min capacity and presumably at or near min ESP requirements, while the EPRI data were with the efficiency control setting but tested at a higher nominal ESP level of 0.65" wc. As these differences would tend to cancel each other, it is most likely that the smaller indoor unit in the EPRI test is the primary reason for the different efficiency trends from the min speed ratings tests. (Note that both units have the same outdoor unit.) A check of the reported test pressures at these ratings points against the compressor maps confirms the measured trends of capacity and power

It should be noted that, in follow-up work, the EPRI researchers demonstrated that this unit operating under a steady load (in load-based testing) with the manufacturer's thermostat performed similarly to psychrometric testing (Domitrovic 2014). Later, they also obtained agreement within 5% between load-based and psychrometric results when the dynamic load was steadily increased over time (Hunt et al, 2015).

In summary, functional HSPFs were found to be about 20% lower than procedural HSPFs based on the analyses of manufacturer's data and EPRI measured data described above. It is of interest to see how much of the difference goes away if the higher alternative heating load line (Rice et al, 2015) is substituted for the 210/240 procedure (min DHR) load line while leaving the rest of the rating procedure unchanged. This alternative heating load line is somewhat steeper than the AHRI 210/240 minimum heating load line and has a lower "no-load" ambient temperature of 55°F compared to 65°F. This load line was applied to the EPRI data set and the resulting HPF curves for the procedural versus the functional approaches are shown in Figure 15. Here the HSPF difference has dropped from 21.6% to 8.7%. This suggests, based on analysis of one current VS product, that the use of the alternative heating load line can significantly mitigate HSPF overprediction by the current rating procedure. This is generally because a higher load line narrows the region for minimum speed extrapolation by giving a higher minimum speed balance point. The higher load line also tends to bring the intermediate speed test point at 35F ambient temperature in closer alignment with the intermediate speed balance point.

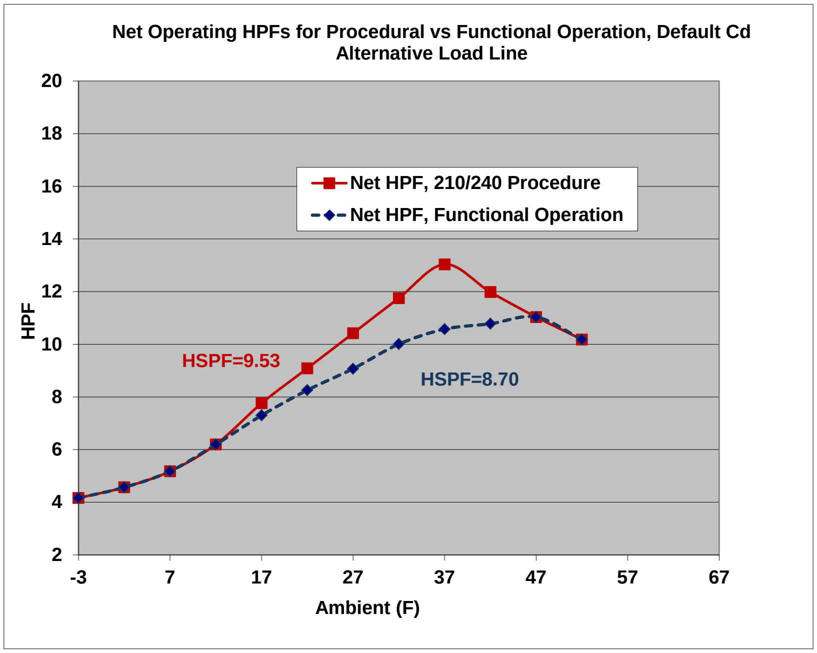


Fig. 15. Comparison of procedural versus functional HPFs and the resultant HSPFs for the alternative heating load line.

6. LABORATORY TESTING AND ANALYSIS OF VARIABLE-SPEED UNITS AT ORNL

Based on the initial analyses of existing data sets, we decided to conduct new heating mode laboratory tests on two current VS heat pumps to achieve a more robust understanding of HSPF ratings differences for both the present 210/240 ratings load line and the alternative load line approach developed by Rice et al, 2015. Both of these units had controls that limit the compressor's minimum speed based on ambient temperature. In this testing, we followed the general approach taken for the EPRI tests by testing at three levels of capacity or speed (depending on the available controls) over the range of heating mode ambient temperatures. The tests included the full set of 210/240 VS heating mode ratings tests. AHRI test controllers were provided by the manufacturers for these tests and were supplemented as needed by their standard companion thermostats.

Indoor return air conditions were controlled at 70°F for all tests. The outdoor ambient RH conditions were at levels consistent with the nearest steady-state ratings tests, with the exception of the F/D tests which were tested per 210/240 F/D conditions. The external static pressures were either controlled to levels specified in AHRI 210/240 or the blower power and heating capacity levels were adjusted to those levels using manufacturer's blower curves confirmed by in-situ blower testing. The ESP levels at reduced airflow were set to be proportional to the square of the air flow.

As was done with the EPRI test data, we used the three levels of speed or capacity data to interpolate the functional unit performance while tracking the 210/240 load line. These performance results were then compared to the predicted procedural performance using the 210/240 test points and load line. Following these comparisons, the alternative heating load line was substituted for the min DHR load line in the 210/240 rating procedure, and the analysis to determine the difference between functional and procedural HSPF repeated.

6.1 Comparison Analysis, Unit B, 3-Ton VS Unit, Rated 10 HSPF, Independent Testing

6.1.1 Unit B Test Setup

Laboratory tests were performed in independently controlled, side-by-side environmental chambers. The outdoor unit was installed in one chamber, Fig. 16, and the air handler was installed in a horizontal-right orientation in another chamber, Fig. 17. The system was instrumented per ASHRAE Standard 37 (ASHRAE 2009) for indoor air enthalpy and refrigerant enthalpy methods for calculating the delivered capacity of the unit. All measurements were recorded on a five-second interval. After initial setup, additional refrigerant charge was weighed in per the manufacturer's recommendation based on the air handler model and length of refrigerant lines. A charge check was then performed in the cooling mode at A2 test conditions to verify the correct charge based on comparing the measured liquid line subcooling to the manufacturer's recommended subcooling.

All tests on this unit were performed with a thermostat that was specially programmed by the manufacturer for running AHRI 210/240 tests. The thermostat allows the user to select heating or cooling tests at the various speed levels required by the tests, minimum, intermediate, nominal, and maximum. The compressor speed range is varied by the thermostat based on the outdoor air temperature sensor that is provided with the unit.

Fig. 16. Variable-speed unit B outdoor unit installed in environmental chamber.

Fig. 17. Variable-speed unit B air handler installed in horizontal-right orientation.

6.1.2 Unit B Heating Performance Test Results

Once the system was properly charged, the heating performance tests were begun. Table 2 shows the heating tests performed on the unit. In addition to the seven AHRI 210/240 test points an additional 10 tests were performed. The additional tests were run at the three available capacity levels, minimum, intermediate, and maximum. All tests were performed at indoor and outdoor conditions consistent with AHRI 210/240. The external static pressure during these tests was not controlled. However, published blower data from the manufacturer's air handler specifications was used to correct the blower power and heating capacity to external static pressure levels consistent with AHRI 210/240. (Comparisons of the manufacturer's published blower data with the laboratory-measured blower data at higher statics were found to be in close agreement. As the air handler used an airflow-controlled indoor blower (i.e. a constant-airflow indoor fan), the tested airflow was only minimally affected by the higher ESP levels during testing.) Steady-state test data were averaged over a minimum period of 30 min. Frost/defrost tests began with a coil free from frost, and the heat pump was operated for a minimum of 30 min for the preconditioning period. Data were then collected for a preliminary defrost cycle and for the official test period following this defrost cycle and terminating at the end of the next defrost cycle or after 6 h, whichever occurred first.

Table 2. Heating mode test matrix for variable-speed unit B

	Ambient Temperature (°F)						
	7	**17**	**27**	**35**	**41**	**47**	**62**
Max Speed	S-S	S-S (H3$_2$)	S-S	F/D (H2$_2$)		S-S (H1$_2$)	
Nominal Speed						S-S (H1$_N$)	
Interm. Speed		S-S[1]	S-S[1]	F/D (H2$_V$)	S-S	S-S	
Min Capacity			S-S[1]	F/D	S-S	S-S (H1$_1$)[2]	S-S (H0$_1$)[2]
Min Speed							

S-S = Steady-State Test, F/D = Frost/Defrost Test, AHRI 210/240 test points labeled in ( )
[1]Interm. Speed and Min Capacity are the same compressor speed at this condition.
[2]Min Speed and Min Capacity are the same compressor speed at this condition.

Figure 18 shows the laboratory measured heating capacities of Unit B for each of the test points in Table 2. It can be seen from the nearly linear maximum capacity line that this unit does not increase the compressor speed at low ambient temperatures, relative to the max capacity speed at 47°F. (The maximum operational capacity level at 47F is also the same as the $H1_2$ test point for this design.) The small difference between the max and nominal capacities at 47°F also shows that the amount of heating mode overspeeding is small relative to the max cooling speed (same as nominal heating speed). The unit does, however, increase the minimum compressor speed significantly at ambient temperatures below 47°F. The minimum compressor speed appears to increase linearly from 47°F to ~12°F where the minimum speed and maximum speed become one and the same, and the unit runs at this maximum speed at temperatures below this point. The orange dotted line indicates where the minimum capacity extrapolates from the test points at 62°F and 47°F to meet the load line. This point is the minimum capacity balance point calculated by the 210/240 ratings procedure, below which the unit is assumed to run continuously without cycling losses. Figure 19 shows the heating capacity operating envelope of the unit as determined by the AHRI 210/240 rating procedure from the seven AHRI 210/240 test points. The maximum speed balance point of 13.4°F indicates the ambient temperature below which the heat pump will begin using supplemental electric resistance heat to the meet the load. Figure 20 shows the assumed capacity of the unit as it meets the heating load based on the AHRI 210/240 procedure and based on the actual functional operation found by interpolating between the additional test points. It can be seen that the procedural approach assumes a lower capacity than actual unit controls allow over the range of 17°F to 47°F. This is due 1) to extrapolation to lower ambient temperatures the minimum capacity of the unit observed at the 47°F and 62°F test points and 2) to assuming that there are no other speed controls limiting operation between min max speeds by ambient temperature. In functional operation, the unit must cycle to match the minimum 210/240 load line until reaching the maximum speed balance point at 13.4°F.

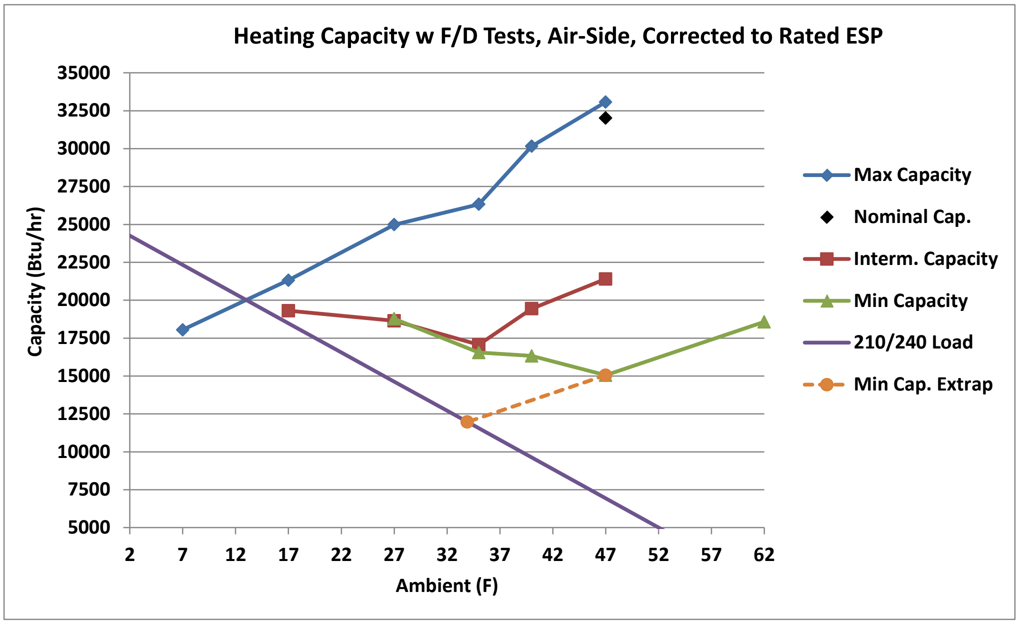


Fig. 18. Variable-speed unit B air enthalpy method heating capacities and AHRI 210/240 minimum heating load line.

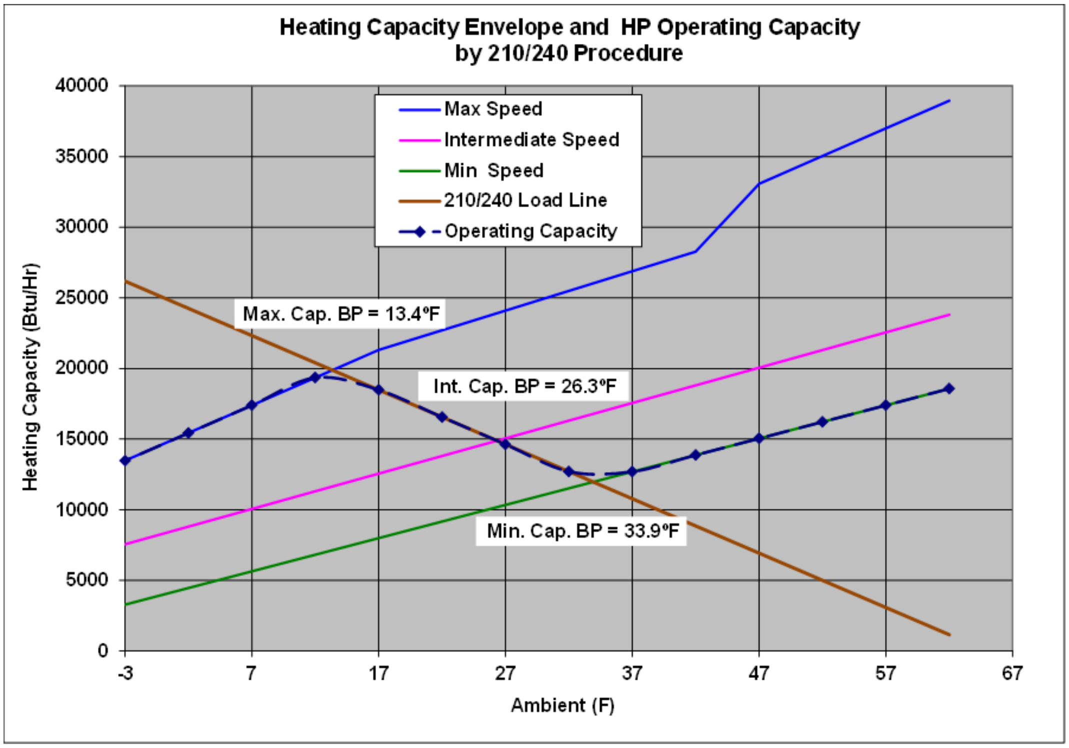


Fig. 19. Variable-speed unit B heating capacity envelope and operating capacity based on AHRI 210/240 test points and procedure and the minimum heating load line.

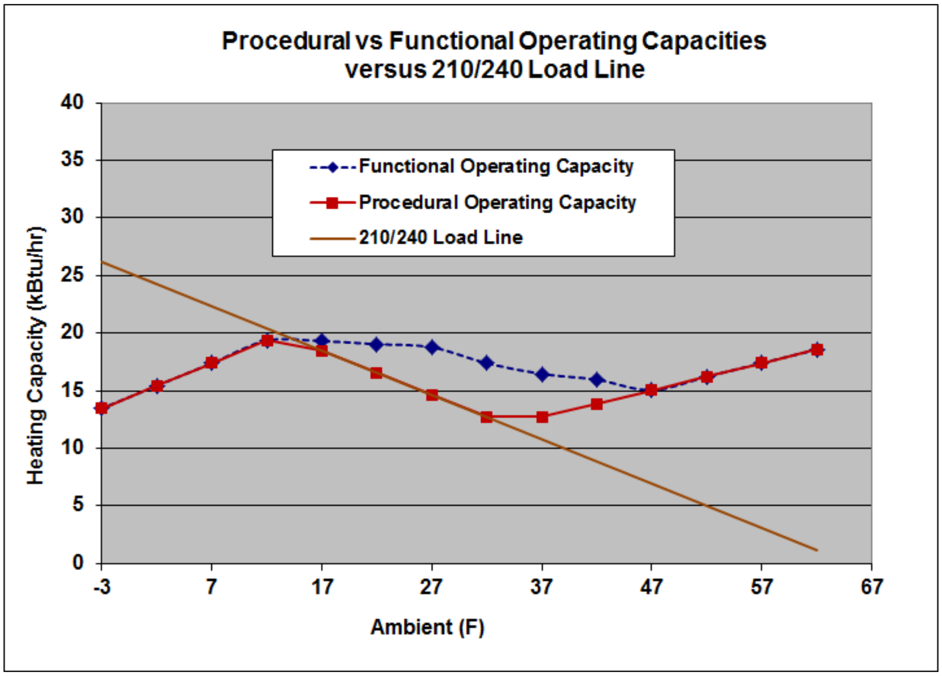


Fig. 20. Variable-speed unit B functional and procedural operating capacity.

The heating performance factors calculated from the capacities are shown in Fig. 21. Once again, the orange line shows the extrapolated minimum capacity efficiency that is used in the procedural approach.

It results in a heating performance factor that is more than 10% higher than the test data indicate at minimum capacity. This discrepancy is the result of the unit's control increasing the minimum allowable compressor speed of the unit as the outdoor ambient temperature drops below 47°F. Figure 22 shows the procedural efficiency operating envelope of the unit as well as the operating efficiency while meeting the heating load line. At ambient temperatures above the minimum speed balance point, 33.9°F, the minimum speed efficiency is degraded due to cycling losses by the use of a cyclic degradation coefficient. For this study, the cyclic degradation coefficient was taken as the default value in the rating procedure of 0.25. At ambient temperatures below the maximum speed balance point, 13.4°F, the efficiency is degraded from the maximum speed efficiency due to the use of supplemental electric resistance heat that is required to meet the heating load.

Figure 23 compares the procedural and functional operating efficiencies from the test data using the AHRI 210/240 minimum heating load line and the default cyclic degradation coefficient of 0.25. The extrapolation of the minimum speed efficiency from the 47°F down to the minimum speed balance point results in an overestimate of the unit's efficiency, most significantly in the 32°F and 37°F temperature bins where the delivered heating load hours are the largest. The net result is a procedural HSPF value that is ~7% higher than the functional HSPF.

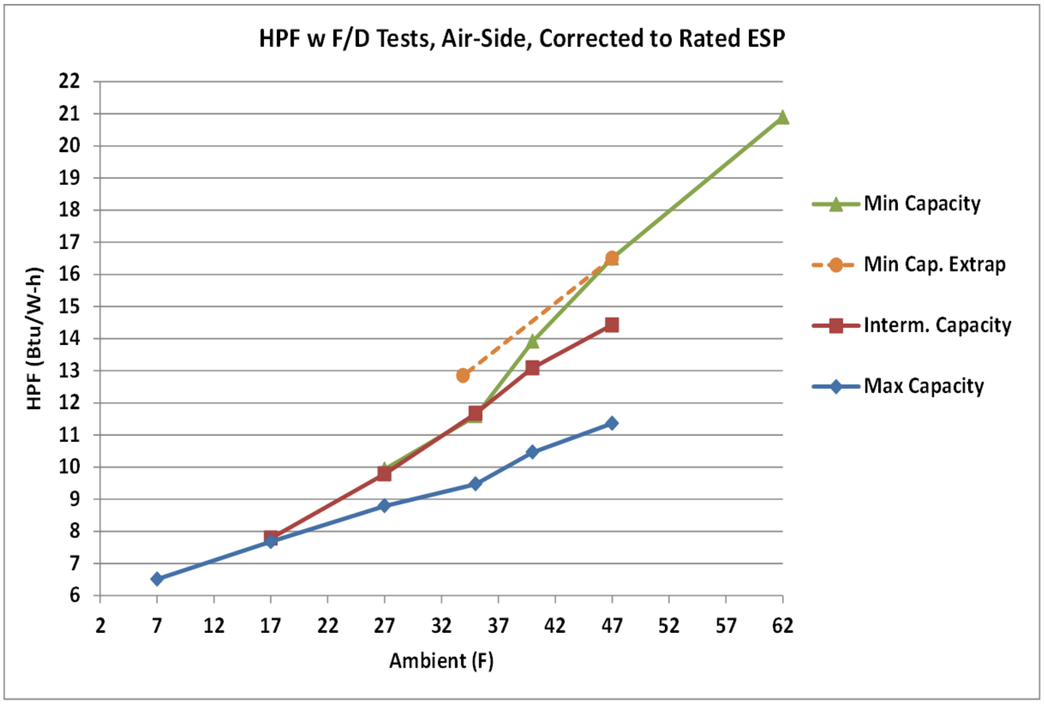


Fig. 21. Variable-speed unit B heating performance factors.

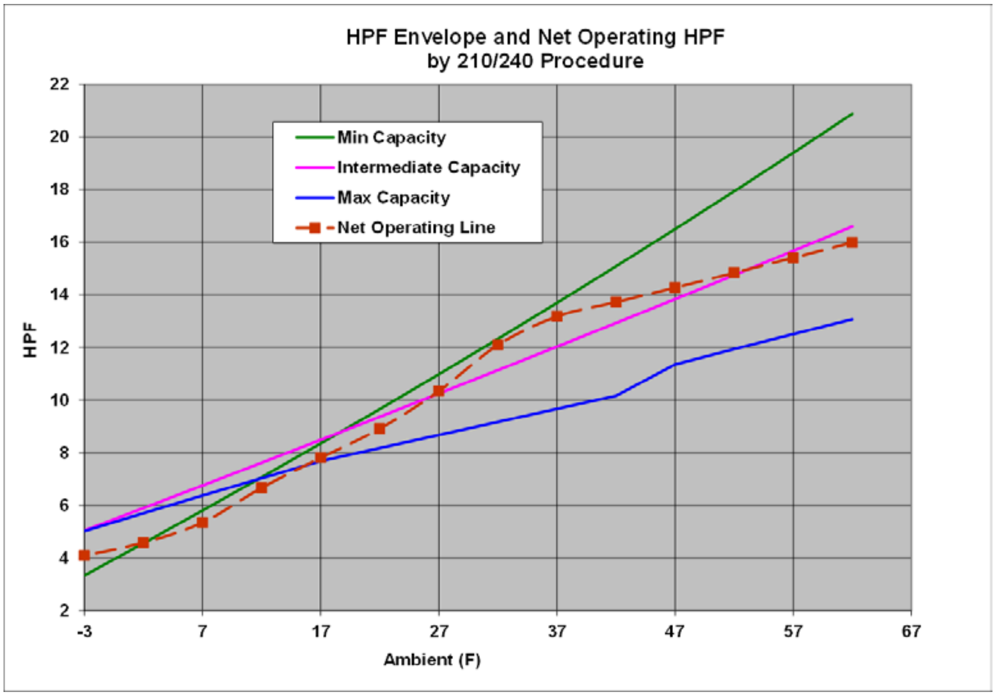


Fig. 22. Variable-speed unit B efficiency envelope and operating efficiency based on the AHRI 210/240 test points and procedure.

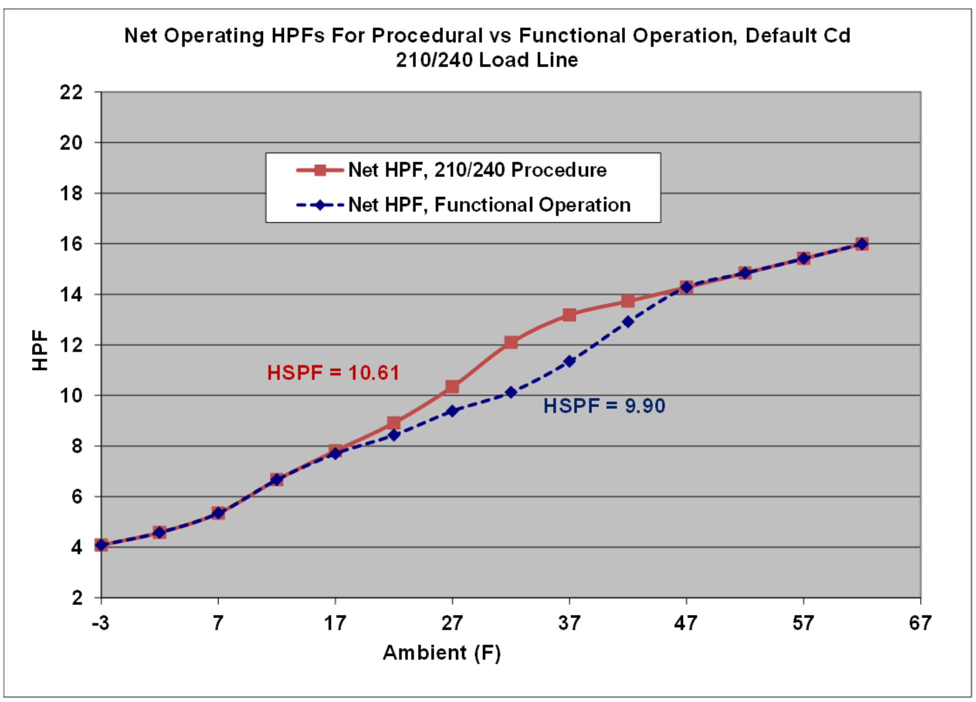


Fig. 23. Variable-speed unit B procedural and functional net heating efficiency using the AHRI 210/240 minimum heating load line, and default cyclic degradation coefficient.

Figure 24 shows the same data as Figure 3 with VS unit B data substituted in for the heat pump capacities, and the addition of the alternative heating load line developed by Rice et al. (2015). The alternative load line reduces the minimum capacity extrapolation and falls in line with the intermediate speed frost/defrost test point at 35°F. This results in the operational frost/defrost performance of the unit being more accurately captured by the procedure. If the HSPF is recalculated for both the procedural and functional approaches using the alternative load line, the results are very close as shown in Fig. 25. The HSPF calculated using the AHRI 210/240 rating procedure is less than 1% lower than the functional HSPF calculated by interpolating between all laboratory test data due to close agreement for the 32°F and 37°F temperature bins and offsetting differences on either side of this region.

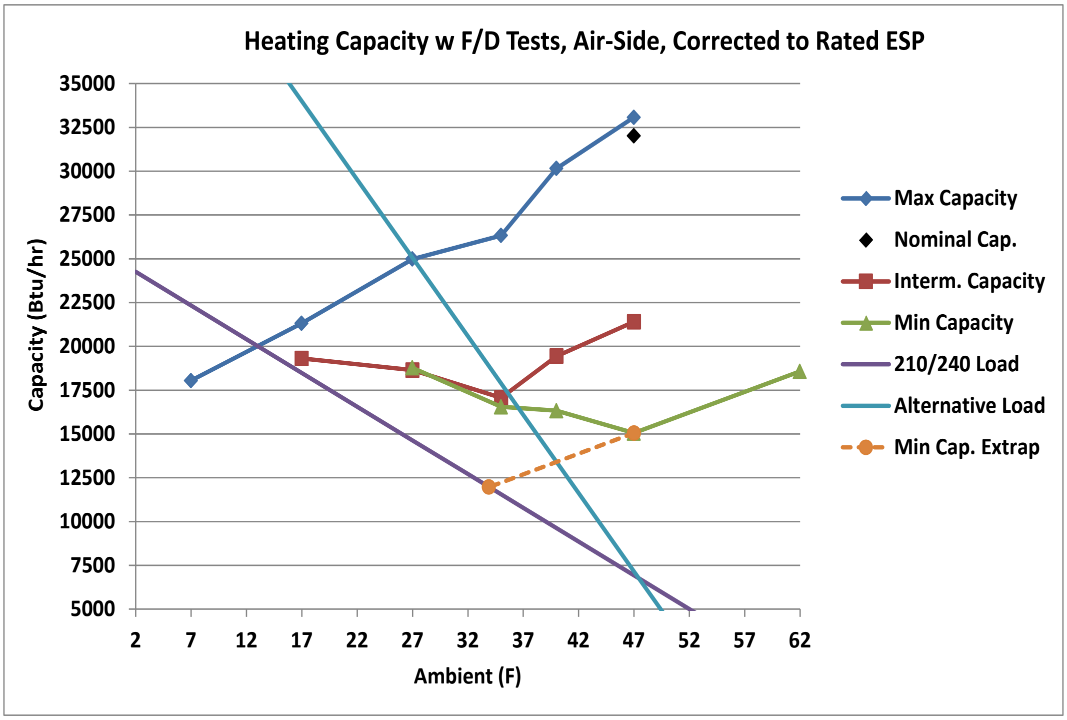


Fig. 24. Variable-speed unit B heating capacities, AHRI 210/240 minimum heating load line, and alternative heating load line.

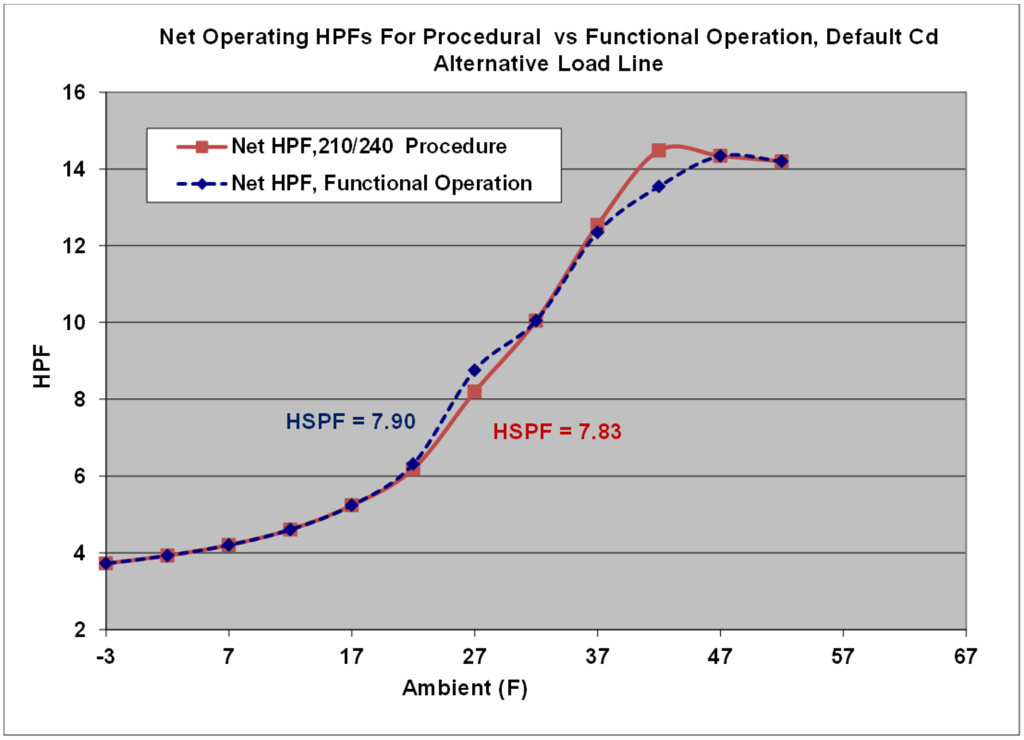


Fig. 25. Variable-speed unit B procedural and functional net heating efficiency using alternative heating load line, and default cyclic degradation coefficient.

6.2 Comparison Analysis, Unit C, 3-Ton VS Unit, Rated 13 HSPF, Independent Testing

6.2.1 Unit C Test Setup

Unit C was tested in the same environmental chambers as Unit B, and the instrumentation and data acquisition were identical. Photos of the outdoor unit and air handler can be seen in Figures 26 and 27. Two thermostats were utilized during testing, a commercially available model and one that had been specially programmed by the manufacturer to run AHRI 210/240 tests. The commercially available thermostat allows the user to select the capacity percent for the system to operate. The capacity range is bounded by the typical compressor operating speed range based on the unit's outdoor air temperature sensor. The specially programmed thermostat allows the user to select a specific AHRI 210/240 test, e.g., $H1_1$, $H3_2$, etc. After a test is selected, the system will operate the compressor and fans at the appropriate speeds for the selected test conditions. The unit's outdoor air temperature sensor does not affect the compressor speed with this thermostat, and the unit can be operated outside of its normal operating limits, which is necessary for the $H1_2$ test.

Fig. 26. Variable-speed unit C outdoor unit installed in environmental chamber.

Fig. 27. Variable-speed Unit C air handler installed in horizontal-right orientation.

6.2.2 Unit C Heating Performance Test Results

Once the system was properly charged, the heating performance tests began. Table 3 shows the heating tests performed on the unit. The seven AHRI 210/240 test points were performed using the specially programmed thermostat and the additional 14 tests were performed using the standard thermostat. The additional tests were run at three capacity levels, minimum, maximum, and a midpoint capacity lying between the two. The minimum and maximum capacity limits were controlled by the standard thermostat and represent the normal operating limits of the unit. All tests were performed at indoor and outdoor conditions consistent with AHRI 210/240, and the external static pressure on the air handler was maintained at 0.15” wc with the manufacturer’s filter installed. Steady-state test data were averaged over a minimum period of 30 min. Frost/defrost tests began with a coil free from frost, and the heat pump was operated for a minimum of 30 min for the preconditioning period. Data were then collected for a preliminary defrost cycle and for the official test period following this defrost cycle and terminating at the end of the next defrost cycle or after 6 h, whichever occurred first.

Table 3. Heating mode test matrix for variable-speed unit C

	Ambient Temperature (°F)						
	7	17	27	35	41	47	62
Max Speed		S-S ($H3_2$)[1]		F/D ($H2_2$)		S-S ($H1_2$)	
Max Capacity	S-S		S-S	F/D	S-S	S-S ($H1_N$)	
Mid Capacity		S-S	S-S	F/D	S-S	S-S	
Interm. Speed				F/D ($H2_V$)			
Min Capacity		S-S	S-S	F/D	S-S	S-S ($H1_1$)	S-S ($H0_1$)

S-S = Steady-State Test, F/D = Frost/Defrost Test, AHRI 210/240 test points labeled in ()
[1]Max Speed and Max Capacity are the same compressor speed at this condition.

The heating capacities for all tests are shown in Fig. 28. This unit begins increasing the minimum and maximum compressor operating speeds at temperatures below 47°F. This can be seen by the nearly constant capacity of the different capacity levels between ambient temperatures of 41°F and 47°F. The tests at 35°F include penalties for frosting and defrosting the unit, which are reflected by the dips in the lines at this temperature. The orange dashed line indicates the extrapolation that is performed by the rating procedure to determine the minimum capacity balance point, the ambient temperature below which the unit stops cycling and runs continuously at minimum speed. It should be noted that the intermediate speed frost/defrost test indicated with the solid red square is at a capacity level that is 50% higher than the capacity required by the heating load line. This indicates that the frosting and defrosting efficiency losses are likely not accurately captured in the rating procedure. Figure 29 shows the heating capacity envelope and operating capacity of the unit based on the AHRI 210/240 test points and procedure and the minimum heating load line. The maximum capacity balance point, the ambient temperature below which the unit requires supplemental heat to meet the heating load, as well as the intermediate and minimum capacity balance points, are indicated on the plot.

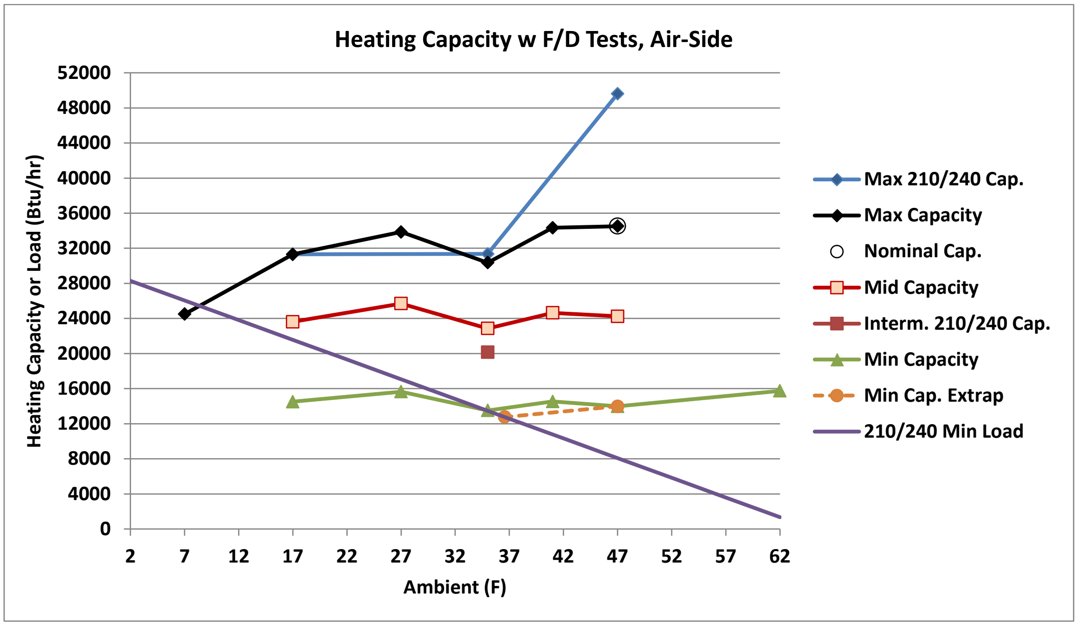


Fig. 28. Variable-speed unit C heating capacities and AHRI 210/240 minimum heating load line.

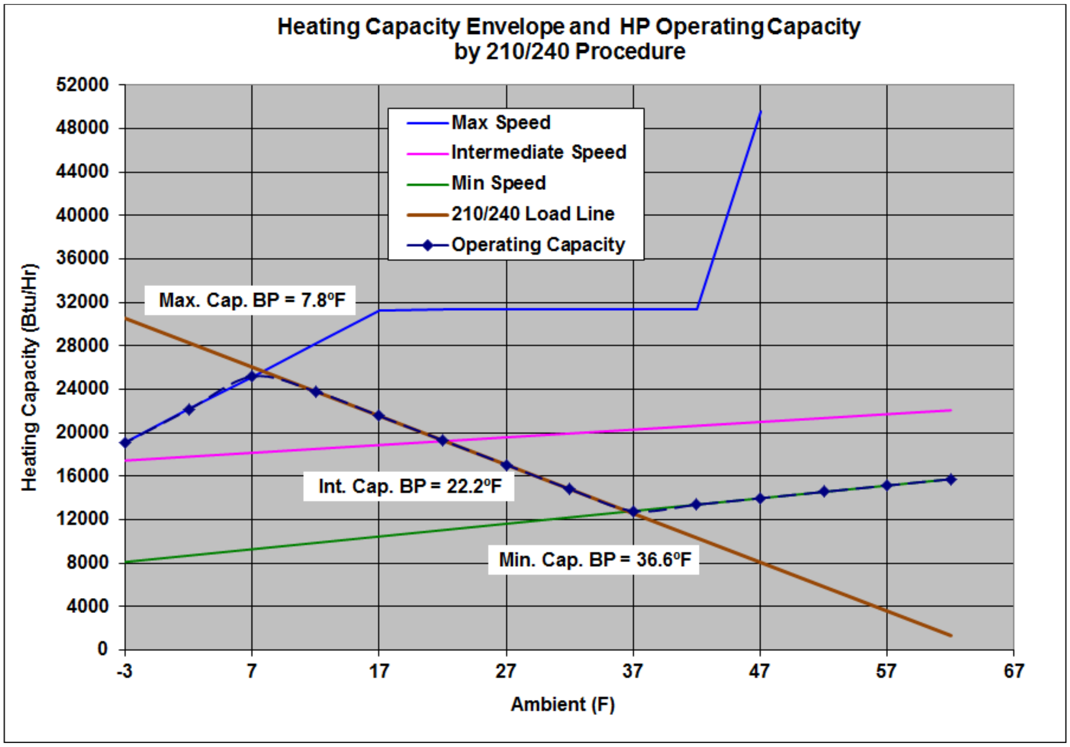


Fig. 29. Variable-speed unit C heating capacity envelope and operating capacity based on AHRI 210/240 test points and procedure and the minimum heating load line.

Figure 30 shows the efficiency of all test points in the form of heating performance factors (HPFs), units of Btu/W-h. Once again the orange dashed line indicates the extrapolation performed by the rating procedure to determine the efficiency at the minimum capacity balance point that was shown in Fig. 28. It is clear from this plot that the extrapolation of the heating efficiency from the 47°F and 62°F test points results in a significantly higher efficiency than the functional tests of the unit indicate. Figure 31 shows the procedural efficiency envelope of unit C with the net operating efficiency of the unit for each temperature bin indicated by the dashed line. Note that at temperatures above the minimum capacity balance point of 36.6°F, the efficiency is lower than the minimum capacity efficiency line. This results from the losses in efficiency due to the unit cycling between off and minimum capacity operation. The default cyclic degradation coefficient of 0.25 was used in the procedure. At ambient temperatures below the maximum capacity balance point of 7.8°F, the efficiency is reduced from the maximum capacity efficiency line due to use of supplemental electric resistance heat to meet the heating load.

Figure 32 compares the net operating efficiency as calculated by the procedure to that calculated by interpolating between the functional test data using the AHRI 210/240 minimum heating load line and default cyclic degradation coefficient. As indicated in Fig. 30, there is a large discrepancy between the efficiency at the minimum capacity balance point of 36.6°F. This is due to the procedure extrapolating the minimum capacity efficiency from the 47°F and 62°F test points, but not accounting for the increase in compressor speed that occurs below 47°F or the frosting and defrosting losses in this temperature range. Based on the test data, the procedural HSPF of 12.88 is about 8% higher than the functional HSPF.

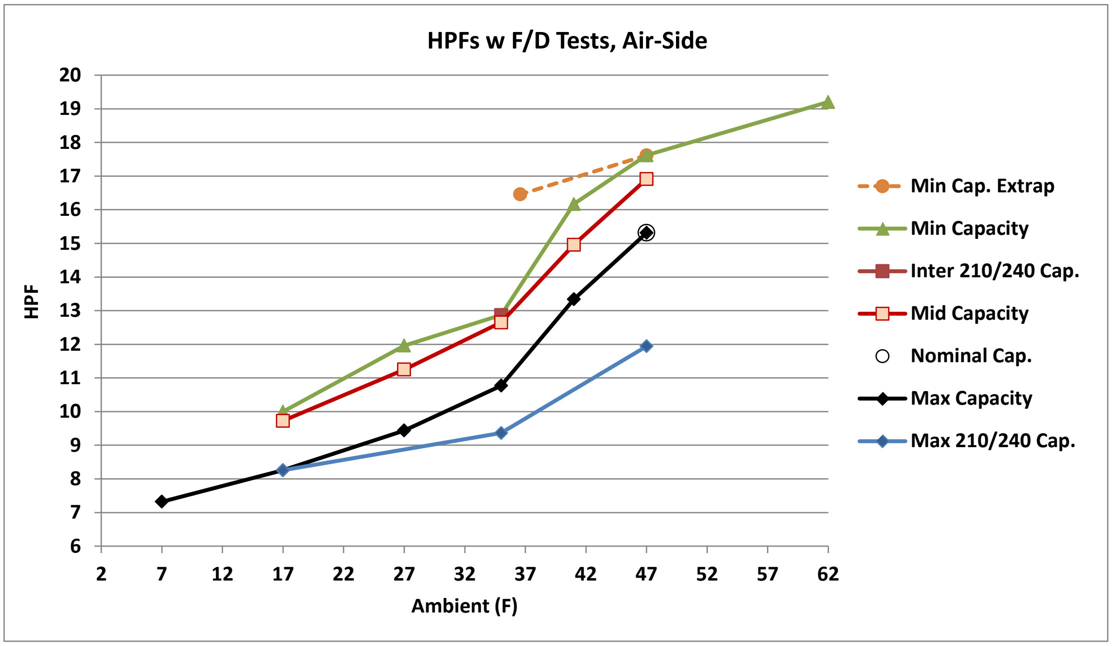


Fig. 30. Variable-speed unit C heating performance factors.

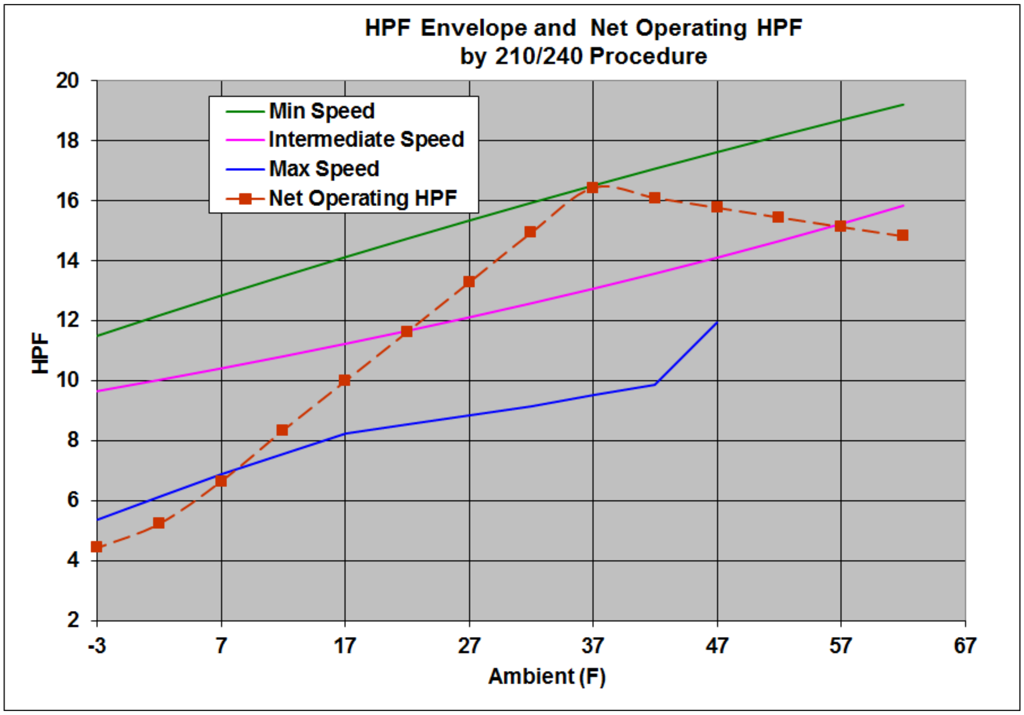


Fig. 31. Variable-speed unit C efficiency envelope and operating efficiency based on the AHRI 210/240 test points and procedure.

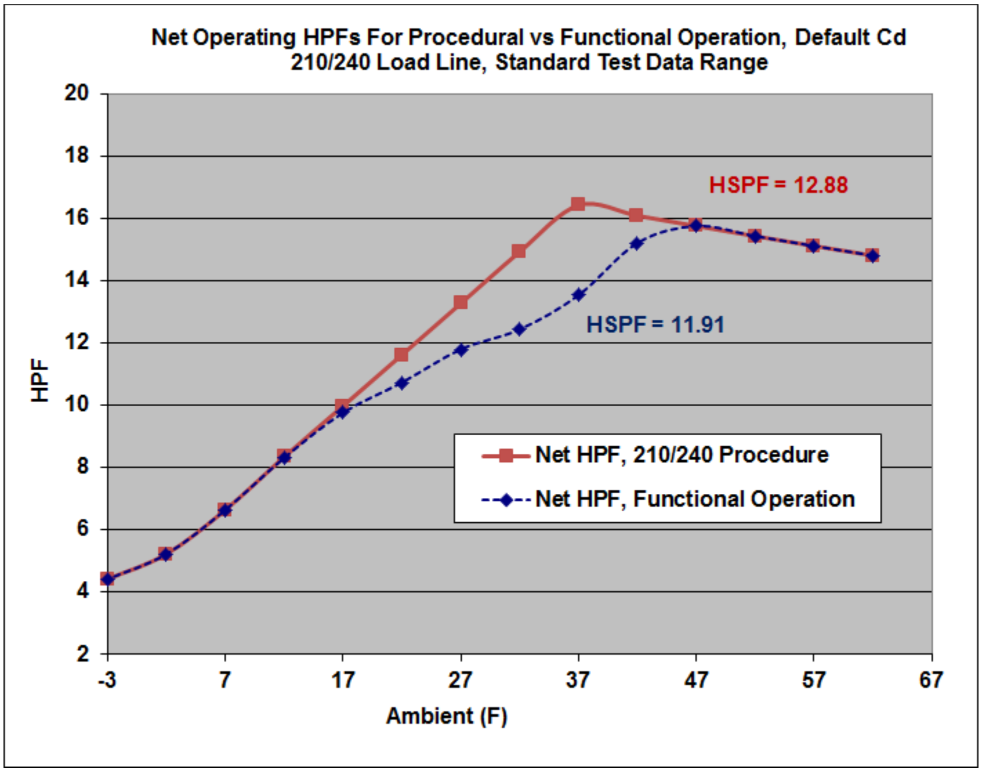


Fig. 32. Variable-speed unit C procedural and functional net heating efficiency using the AHRI 210/240 minimum heating load line, and default cyclic degradation coefficient.

The alternative heating load line (Rice et al. 2015) is shown in Figure 33. This load line is much steeper than the AHRI 210/240 minimum heating load line and has a lower "no-load" ambient temperature of 55°F compared to 65°F. Figure 33 is the same as Fig. 28, with the addition of the alternative heating load line. It can be seen here that the alternative load line increases the minimum capacity balance point, reducing the ambient temperature range of extrapolation from the 47°F and 62°F test points. The $H2_V$ frost/defrost test at 35°F is also much closer to the alternative load line than the AHRI 210/240 minimum load line, indicating that the frosting and defrosting efficiency losses from the F/D test at intermediate speed will be more representative when applied to the alternative load line.

Evaluated for the alternative heating load line, the AHRI 210/240 and the interpolative functional net operating efficiencies are shown in Fig, 34. The overall HSPFs between the two methods are within 1% of each other. While there is very good agreement between procedural and functional HSPFs when using the alternative heating load line in the rating procedure, it should be noted that the HSPFs calculated per AHRI 210/240 but using the alternative load line are ~25% lower than those calculated per AHRI 210/240 in its entirety (using the DHR min load line). This decrease is due to a number of factors, including the reduction in heating hours at mild temperatures where variable-speed equipment is most efficient and the more accurate representation of the minimum capacity efficiency at the minimum capacity balance point.

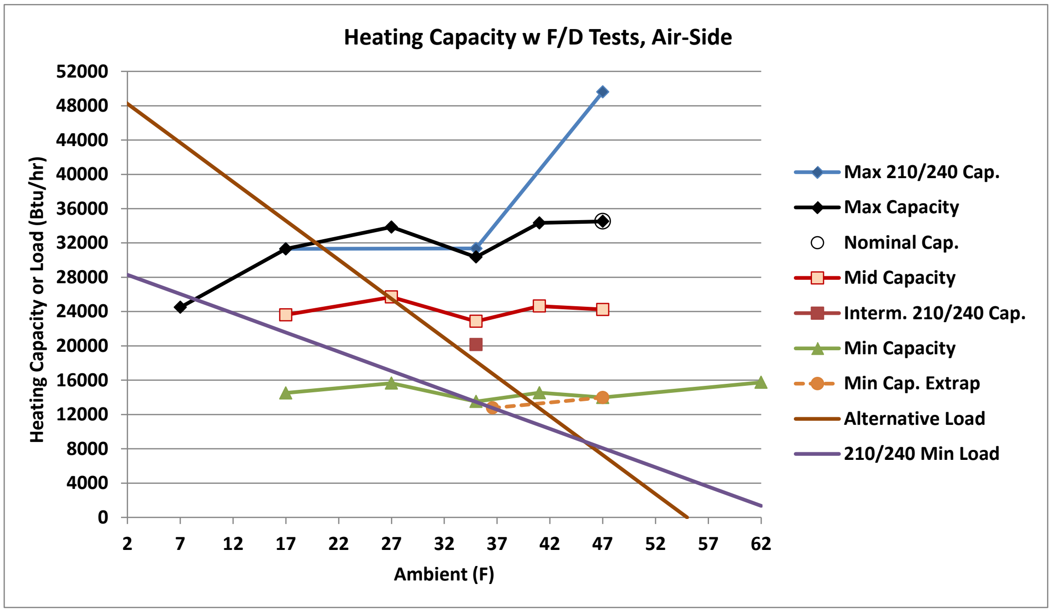


Fig. 33. Variable-speed unit C heating capacities, AHRI 210/240 minimum heating load line, and alternative heating load line.

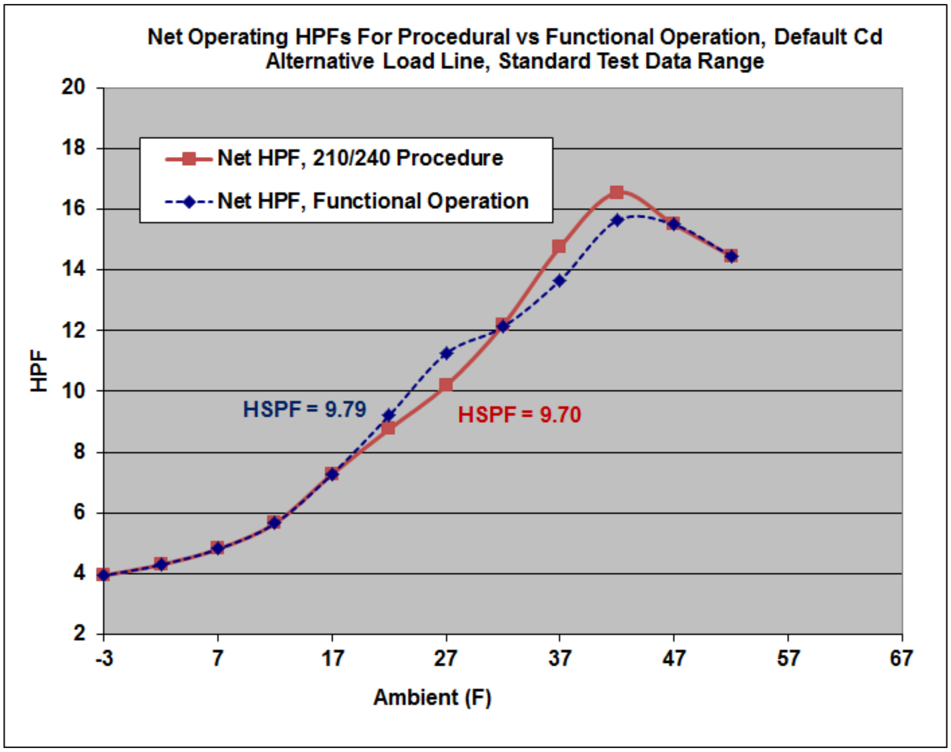


Fig. 34. Variable-speed unit C procedural and functional net heating efficiency using alternative heating load line, and default cyclic degradation coefficient.

6.3 Comparison Analysis, Unit C, 2-Ton VS Configuration, Rated 13 HSPF, Based On 3-Ton Test Data

To obtain one further comparison case, we used the 3-ton VS test data from Unit C to construct a suitable set of data for the 2-ton 13 HSPF configuration. This unit has the same indoor and outdoor hardware as the 3-ton unit with the same minimum speed level and lower maximum speed level. For this analysis, we assumed that the control of airflows, as a function of compressor speed, were the same as for the 3-ton 13 HSPF configuration. We used our available test data and suitable interpolations to the lower speed levels to obtain close estimates of six of the seven test procedure rating points as well as the more detailed functional data points at three capacity levels. For the optional max speed F/D test point ($H2_2$), we used the default 210/240 capacity and power reductions from a straight-line interpolation of maximum speed steady-state data at 17°F and 47°F ambient temperatures. As with the 3-ton configuration, we calculated the procedural and functional capacity matching to the current and alternative load lines and resulting HPF trends with ambient temperature, and net HSPFs. The default cyclic degradation factor of 0.25 was also assumed for this analysis.

Figure 35 shows the heating capacity envelope and operating capacity of the 2-ton 13 HSPF unit based on the AHRI 210/240 test points and procedure and the minimum heating load line. The balance points at minimum, intermediate and maximum capacity are also indicated on the plot.

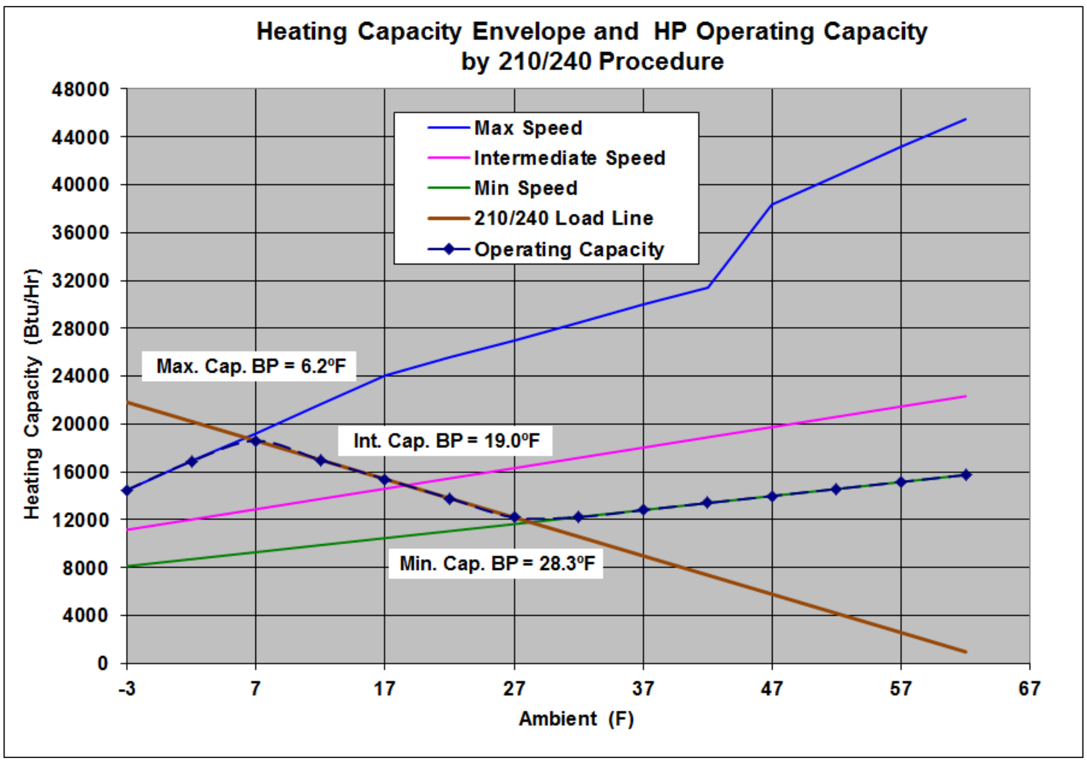


Fig. 35. 2-ton unit C, heating capacity envelope and operating capacity based on AHRI 210/240 test points and procedure and the minimum heating load line.

In Fig. 36, we show the corresponding procedural efficiency envelope for the 2-ton unit with the net operating efficiency of the unit over the temperature bins indicated by the dashed line.

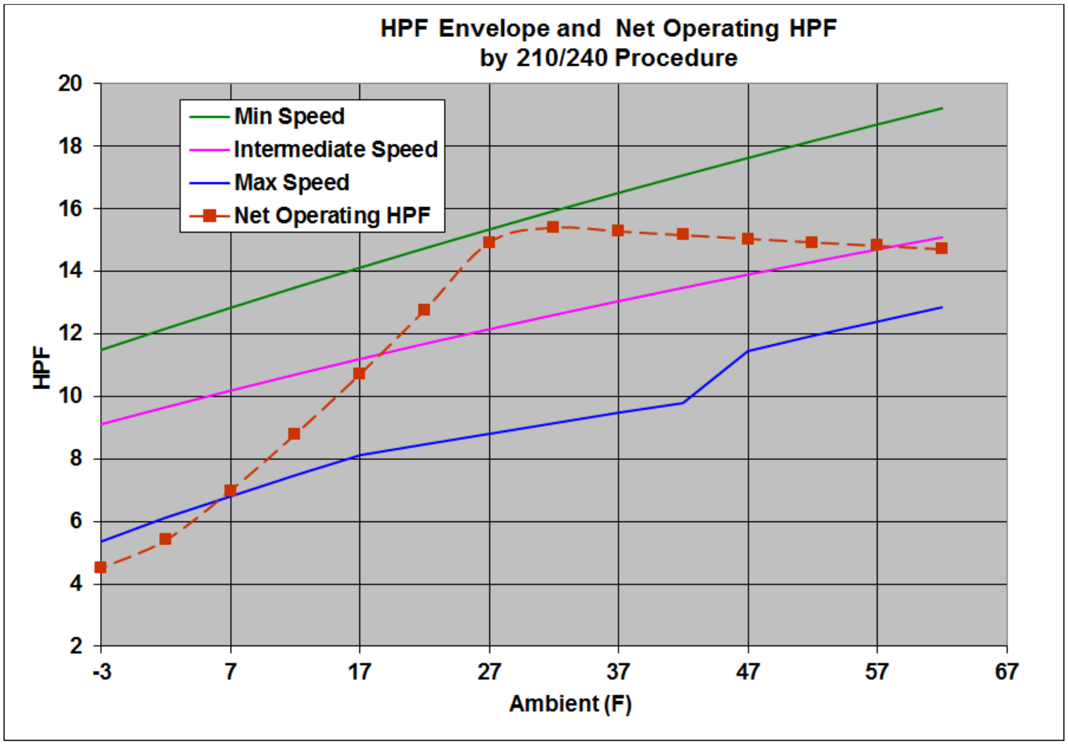


Fig. 36. 2-ton unit C efficiency envelope and operating efficiency based on the AHRI 210/240 test points and procedure.

In Fig. 37, the procedural HPFs versus ambient temperature are compared to the functional HPFs for the 210/240 load line, and the resulting respective HSPFs are given. A similar trend of HPF differences is seen as for the earlier cases, with the functional HSPF being ~11% lower than the procedural HSPF of just over 13. The 11% lower HSPF for the actual functional operation for this unit compares with the 18% lower performance calculated from the manufacturer's minimum and maximum capacity data for this same 2-ton unit in the first example case. This suggests that the use of three rather than two sets of capacity data results in lower, but still significant, discrepancies between procedural and functional HSPFs for such units.

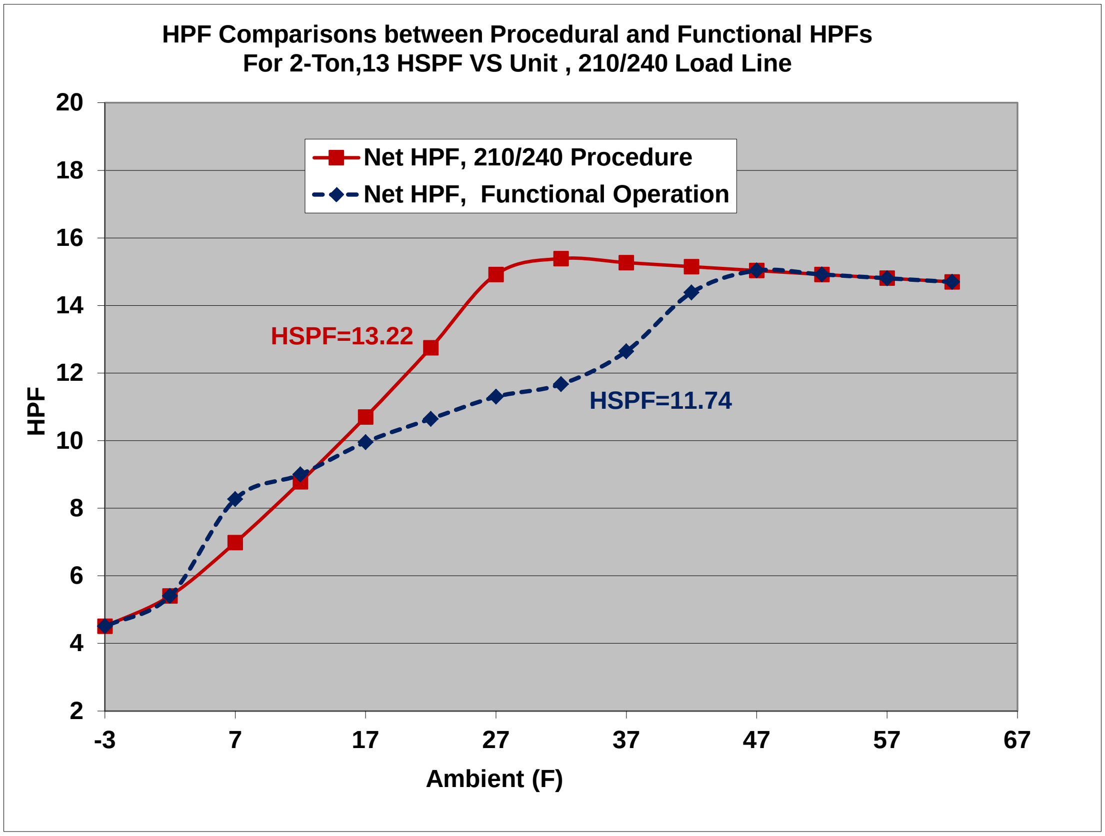


Fig. 37. 2-ton unit C procedural and functional net heating efficiency using the AHRI 210/240 minimum heating load line, and default cyclic degradation coefficient.

Last, a similar comparison of HPFs and HSPFs is made for the alternative load line in Fig. 38. Here the higher load line is seen to result in calculated HSPFs within 1% due to offsetting differences on either side of the procedural minimum balance point of 28°F. This case again indicates that use of the alternative load line brings the procedural and functional HSPF results into close agreement even though there remain differences in HPF trends with ambient temperature due to the simplified control assumptions of the ratings procedure for variable-speed units.

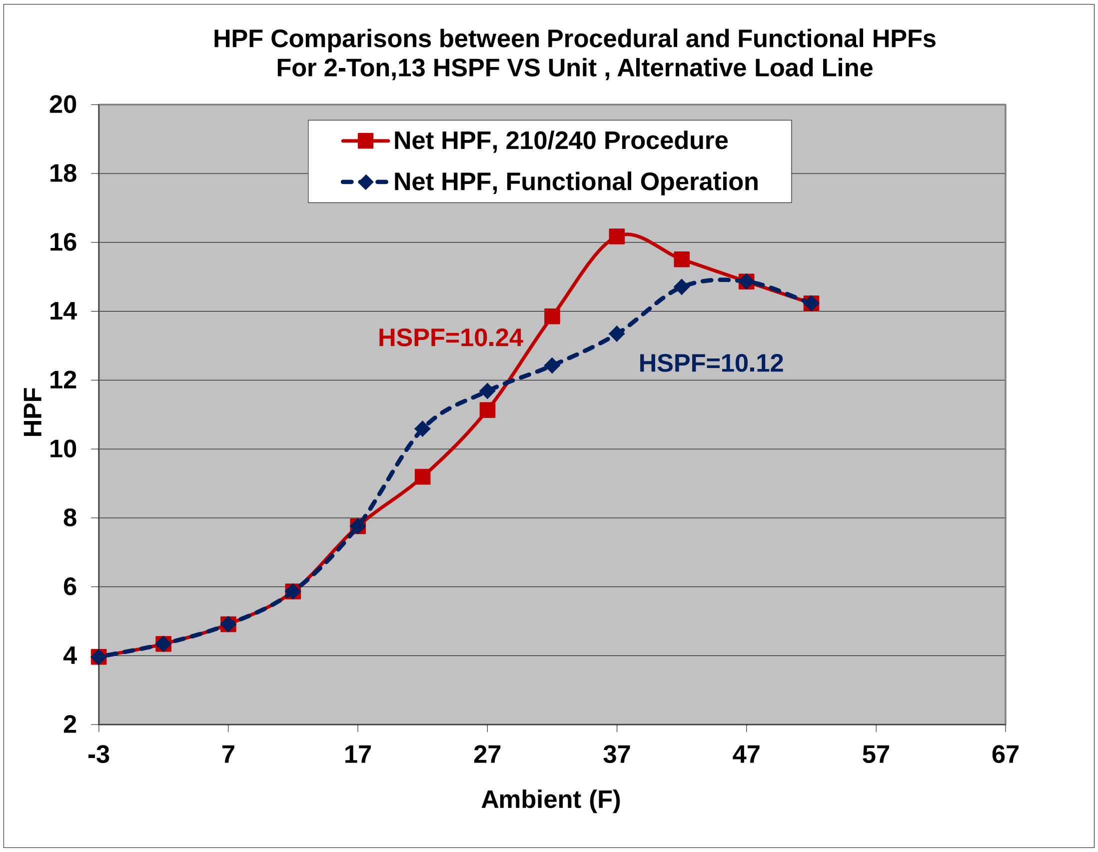


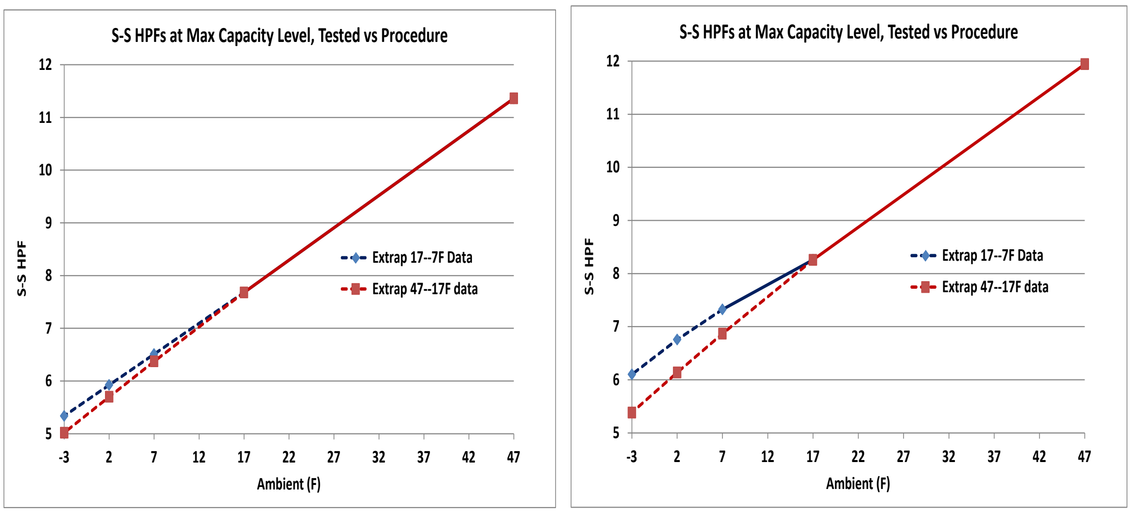
Fig. 38. 2-ton unit C procedural and functional net heating efficiency using alternative heating load line, and default cyclic degradation coefficient.

6.4 Test Findings on Low Ambient Temperature Performance from Units B and C

In the course of testing of unit C, we found that the max speed level reached at 17°F was not maintained at the tested 7°F ambient condition, and the compressor speed continued to drop at ambient temperatures below 7°F. Because the VS test and ratings procedure assumes that the max capacity line is at a fixed speed at all ambient temperatures, this is another ambient operating region where the simplifying assumptions of the VS test and ratings procedure may not hold for some VS units. Furthermore, even for cases where the maximum speed level is maintained below 17°F, the higher speed operation at max capacity for VS units that overspeed in heating mode can potentially result in more error in capacity, power, or HPF extrapolations at low ambient temperatures from max speed test points at 17°F and 47°F ambient temperatures. For both of these reasons, it is of interest to consider for such units whether a more representative low ambient temperature test such as 2°F would be a useful alternative.

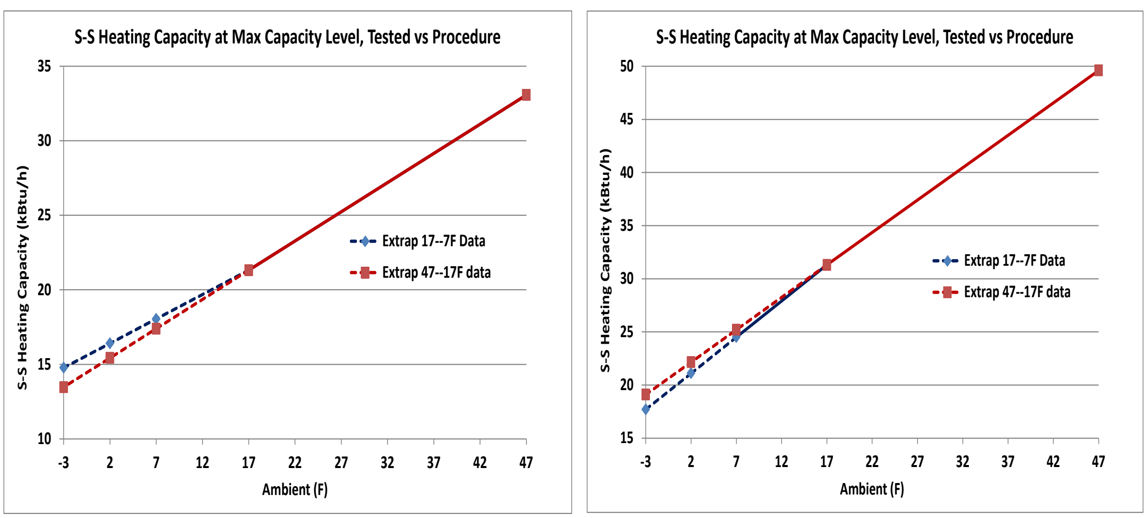
From tests of VS units B and C at ORNL, we found that extrapolation below 17°F from max speed ratings tests at 47°F and 17°F (per the current 210/240 test procedure) slightly underestimated low-ambient SS efficiencies. This is shown in Fig. 39 (a) and (b) for units B and C, respectively. As for heating capacities, the fixed max speed case of unit B also had slightly higher levels based on low-speed testing than from the procedural extrapolations, while unit C had lower actual heating capacity due to the dropoff in compressor speed below 17°F. These results are shown in Fig. 40(a) and (b). If an optional test were considered at 2°F in place of the 47°F max speed test, we found this could give a slight HSPF gain (an increase of up to 1.6% net HPF at 2°F for the two units tested). (A 2°F ambient temperature test point is recommended to be consistent with the 15°F differential between the min speed tests at 47 and 62°F ambient temperatures.) The optional low ambient test would also provide more reliable low ambient data for extrapolations to even lower ambient temperatures for VS designs intended for northern climate applications.

In addition, this could avoid the need to test at max speed at 47°F (test $H1_2$) for units whose controls do not allow such high-speed operation at that temperature; currently such testing requires a separate test controller to override the unit's standard controls. (In this option, the max speed 47°F ambient test would only be needed if the max speed F/D test at 35°F, i.e., test $H2_2$, were not run.)



(a) **(b)**

Fig. 39. a) Unit B low ambient heating efficiency representations, b) Unit C low ambient heating efficiency representations.



(a) **(b)**

Fig. 40. a) Unit B low ambient heating capacity representations, b) Unit C low ambient heating capacity representations.

7. SUMMARY FINDINGS FROM HSPF EVALUATIONS OF SPEED–CONTROLLED VS UNITS

The initial two speed-controlled VS cases evaluated in this report indicated lower HSPFs from procedural to functional analyses averaging ~20% with the 210/240 load line used for ratings. These analyses were limited by the number of available capacity levels and data based on inconsistent efficiency mode settings, or high ESP levels and their potential effects on minimum speed performance trends. Subsequent laboratory testing at ORNL of similar current VS units with fully consistent efficiency mode settings and ESP levels gave HSPF reductions from procedural to functional calculations averaging 8.4% with the 210/240 load line.

All the cases investigated indicate that the core causes of the overprediction of HSPF are extrapolation of low speed performance below 47°F and speed controls that limit allowed minimum speeds based on ambient temperature. Further, equity in HSPF ratings between two- and variable-speed units would seem to suggest that extrapolation should not be allowed for VS units below 40°F, since it is not allowed for two-speed units. Given the strong weighting of the 27, 32, and 37°F temperature bins in the HSPF calculations, extrapolations of low speed data below 40°F, as is the case with the current load line for many VS units, should be replaced by some means to more accurately represent minimum capacity in the HSPF calculations.

On the other hand, use of the alternative load line reported by Rice et al. (2015) was found to narrow the large difference between procedural and functional HSPF found using EPRI data by about 60%. In addition, for the three cases analyzed based on ORNL measurements, the procedural and functional HSPF differences were reduced to ~1 percentage point. These results suggest that the existing ratings procedure can yield reasonably accurate HSPFs for current VS units if the alternative load line is substituted for the current 210/240 min DHR load line.

Substituting the alternative load line for the min DHR load line results in HSPF reductions for current VS units ranging from 14 to 25%, which is generally larger than the average 16% reduction reported by Rice et al. (2015) for single- and two-speed units. The reasons for the larger VS unit HSPF reduction are two-fold. First, use of the alternative load line significantly reduces the artificial increase in HSPF accruing from extrapolation of 47°F and 62°F min-capacity performance to lower ambient temperatures. Second, with the alternative load line, less heating capacity is delivered at the milder ambient temperatures where VS units have the highest efficiencies. In general, current VS units having little or no minimum speed controls were found to have lower procedural HSPF reductions, ranging between 14 and 18%, close to the 16% average for the single- and two-speed units. In Fig. 41, the procedural HSPF reductions for VS units from the alternative load line are shown versus the ratios of rated heating capacity at 17°F, Q(17), divided by rated cooling capacity at 95°F, Q(95). As expected, units with a higher heating capacity at 17°F relative to their nominal cooling capacity have a lower reduction in HSPF with the higher alternative load line. A similar plot for single- and two-speed units for HSPF reductions from the alternative load line versus Q(17)/Q(95) ratio was shown in the companion report by Rice et al. (2015).

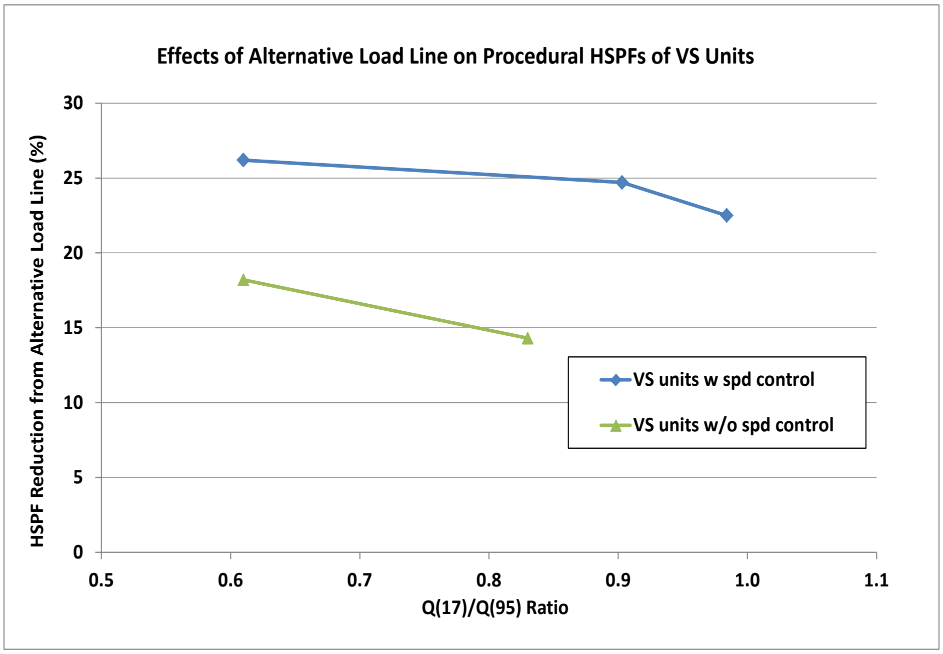


Fig. 41. Procedural HSPF reductions from alternative load line versus Q(17)/Q(95) ratio for VS units with and without speed controls.

8. POSSIBLE TEST REVISIONS IN HEATING MODE FOR VS HEAT PUMPS WITH PRESENT HEATING LOAD LINE

To provide more accurate HSPF ratings with the present heating load line, VS units which allow the unit to run at minimum speed below 40°F should be tested at minimum speed at the 35°F ambient rating point, in addition to the current 1/3 intermediate speed test at 35°F. Although this is typically a frost/defrost test point, low frost accumulation is expected at low speed, so an approach could be considered that defines a pseudo-steady-state test for a defined period of time over which integrated frosted coil performance could be calculated.

For VS units which cannot run at minimum speed below 47°F, performance should be provided along the controlled minimum speed curve versus ambient temperature. If the controlled minimum speeds between 47°F and 35°F do not exceed the intermediate speed as defined in 210/240, minimum capacity performance as a function of ambient temperature could be approximated by interpolation between the min speed performance at 47°F ($H1_1$) and intermediate speed performance at 35°F($H2_V$). This curve could be used along with the procedural max speed curve to interpolate performance between the min and max capacity regions. This approach was evaluated using the Unit B and C data sets; it gave an HSPF within 1% of the functional value for unit B but underpredicted HSPF for Unit C by about ~6%. This conservative approach would not require further testing at additional rating points for units where min speed operation was limited to above 40°F. For more accuracy in HSPF predictions for speed controlled cases, new minimum and intermediate capacity tests could be added at 35°F and 17°F ambient temperatures. With these two new tests, more accurate minimum and intermediate/mid capacity performance curves could be determined and used along with the procedural max speed curve to calculate HSPF. With this approach, the HSPF for unit C was underpredicted by ~2%. However, for unit A, the HSPF would still be underpredicted by 14%, A similar scenario could be required for VS units which cannot run at maximum speed below certain ambient temperatures. Analogous to the above, any maximum speed control limits could also possibly be handled by a suitable modification to the standard 210/240 procedure.

9. CLOSURE

From evaluations of current VS units with high HSPF ratings, discrepancies in predicted HSPF of 7 to 22% were found by comparing the procedural versus functional HSPF values based on available manufacturer's and independently measured performance data. The average HSPF reduction found based on ORNL testing was about 8%, with individual cases ranging from 7 to 11%.

These analyses consistently indicate that the core causes of the procedural overprediction of HSPF are extrapolation of low speed performance below 47°F and speed controls that limit allowed minimum speeds based on ambient temperature. The present AHRI 210/240 test and ratings procedures do not have provisions to appropriately calculate HSPF for VS units with ambient-based minimum and maximum speed control. Further, equity in HSPF ratings between two- and variable-speed units would seem to suggest that extrapolation should not be allowed for VS units below 40°F, since it is not allowed for two-speed units. Given the strong weighting of the 27, 32, and 37°F temperature bins in the HSPF calculations, extrapolations of low speed data below 40°F ambient, as is the case with the current load line for many VS units, should be replaced by some means to more accurately represent minimum capacity in the HSPF calculations.

One potential remedy for the current situation with VS HSPF ratings is to use a higher, more representative load line. Use of the alternative heating load line described in a companion report by Rice et al. (2015) was investigated. With this load line, the differences from the procedural to the functional HSPFs dropped to ~1% for all the cases based on testing at ORNL. For the EPRI-tested case, the HSPF differences dropped from 22% to 9%. These results suggest that the existing ratings procedure can yield reasonably accurate HSPFs for current VS units if the alternative load line is substituted for the current 210/240 min DHR load line.

Substituting the alternative load line for the present 210/240 load line results in HSPF reductions for current VS units ranging from 14 to 25%, which is larger than the average 16% reduction reported by Rice et al. (2015) for single- and two-speed units. The reasons for the larger VS unit HSPF reductions are two-fold. First, use of the alternative load line significantly reduces the artificial increase in HSPF accruing from extrapolation of 47°F and 62°F min-capacity performance to lower ambient temperatures. Second, with the alternative load line, less heating capacity is delivered at the milder ambient temperatures where VS units have the highest efficiencies. In general, current VS units having little or no minimum speed controls were found to have lower procedural HSPF reductions, ranging from 14 to 18%, close to the 16% average reduction for the single- and two-speed units.

From low-ambient testing of one VS unit, we found that the fixed maximum speed assumption of the 210/240 VS ratings procedure did not hold. An optional low ambient test point of 2°F would provide a better representation of low ambient performance for such cases, as well as for all VS units that overspeed their compressors in heating mode, whether or not the maximum speed is held below 17°F. This low ambient test point could be used in place of the current maximum speed 47°F test (i.e., $H1_2$).

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