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Revised Heating Load Line Analysis: Addendum to ORNL/TM-2015/281

C. Keith Rice
Bo Shen
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July 2016

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Energy and Transportation Science Division
Building Technologies Program

REVISED HEATING LOAD LINE ANALYSIS: ADDENDUM TO ORNL/TM-2015/281*

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CONTENTS

LIST OF FIGURES v
LIST OF TABLES v
ABBREVIATED TERMS vii
ACKNOWLEDGMENTS ix
1. BACKGROUND 1
2. BASIS FOR REVISED HLL ANALYSIS 1
    2.1 RESIZING APPROACH 1
3. RESULTS OF REVISED HLL ANALYSIS 4
    3.1 IMPACT ON HEATING LOAD SLOPE FACTORS OF REMOVING MECHANICAL VENTILATION 4
    3.2 IMPACT ON HEATING LOAD SLOPE FACTORS OF HEAT PUMP SIZING REVISION 6
4. EFFECTS ON HSPF RATINGS LEVELS—SINGLE- AND TWO-CAPACITY UNITS 8
5. EFFECTS ON HSPF RATINGS LEVELS—VARIABLE-SPEED UNITS 11
6. EFFECTS OF A LOWER HLL SLOPE FACTOR ON VS HSPF DIFFERENCES BETWEEN PROCEDURAL CALCULATIONS AND FUNCTIONAL OPERATION 12
7. SUMMARY OF FINDINGS FROM REVISED ANALYSIS 13
8. REFERENCES 14

LIST OF FIGURES

Figure 1. Hourly, binned, and design cooling load rates for IECC 2006 prototype residential house in Indianapolis, Indiana, without mechanical ventilation. 2
Figure 2. Comparison of EnergyPlus binned cooling load curve and linearization to AHRI load line for the adjusted rated unit size. 3
Figure 3. Regional heating load slope factors: E+ autosizing; with and without mechanical ventilation. 5
Figure 4. Regional zero-heating-load ambient temperatures with and without mechanical ventilation. 5
Figure 5. Regional zero-heating-load ambient temperatures: SNOPR with mechanical ventilation and "revised" without. 6
Figure 6. Regional heating load slope factors: E+ autosizing and adjusted sizing; without mechanical ventilation. 6
Figure 7. Rounded regional heating load slope factors. 7
Figure 8. Reductions in rated HSPF from alternative heating load line with a 1.15 slope factor versus $Q_h(17)/Q_c(95)$ ratio for single- and two-capacity heat pumps 10
Figure 9. Reductions in rated HSPF from alternative heating load line with a 1.15 slope factor versus $Q_h(17)/Q_c(95)$ ratio for VS units with and without ambient limits on minimum speeds. 12

LIST OF TABLES

Table 1. Summary of locations and house construction types modeled per IECC 2006 code in EnergyPlus[a] and rated cooling capacity sizes selected[b] 3
Table 2. Seasonal heating load change factors by region from current DHR_{min} loads for alternative slope factors and revised zero load ambients and heating load hours 8
Table 3. HSPF ratings changes in DOE Region IV using the alternative heating load line with 1.15 slope factor for different sizing and heat pump types 9
Table 4. Relative HSPF ratings changes from standard to northern climate application for current and alternative heating load lines 10

ABBREVIATED TERMS

AC	air conditioning
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
COP	coefficient of performance
DB	dry bulb temperature
DHR_{min}	minimum design heating requirement
DOE	US Department of Energy
E+	EnergyPlus
F/D	frosting/defrosting
HLL	heating load line
HP	heat pump
HSPF	heating seasonal performance factor
IECC	International Energy Conservation Code
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RH	relative humidity
SEER	Seasonal Energy Efficiency Ratio
SNOPR	supplementary notice of proposed rulemaking
VS	variable-speed
WB	wet bulb temperature

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1. BACKGROUND

In the original Oak Ridge National Laboratory (ORNL) heating load line (HLL) analysis (Rice et al. 2015a), we concluded that a more representative HLL for heating seasonal performance factor (HSPF) calculations would have a steeper, 1.3 slope factor and a lower outdoor zero-load ambient temperature than the current 65°F value, varying from about 55°F in the US Department of Energy (DOE) Climate Regions IV and V (AHRI 2008) and increasing in milder climates to as high as 60°F in DOE Region I. This analysis was based on DOE Prototype Residential House input files for EnergyPlus (E+) (Taylor et al. 2012, DOE 2014) for the International Energy Conservation Code 2006 level (IECC 2006) in selected US locations and used E+ autosizing of the air-source heat pumps based on design cooling conditions.

On further review of this analysis during and after the DOE Central Air-Conditioning (AC) and Heat-Pump Working Group meetings over the fall of 2015 (DOE 2015a), we identified two areas where adjustments to the analysis were found to be appropriate.

2. BASIS FOR REVISED HLL ANALYSIS

ORNL identified two areas of potential modification to address.

- First, the Prototype Residential House input files for IECC 2006 code level were found to include continuous mechanical ventilation, which is not a requirement of the IECC 2006 code. On review of this finding with the DOE Residential Central AC/Heat Pump Standards team, it was determined that the typical house in the 2021–2023 time frame would not have continuous ventilation.

- Second, the heat pump sizing approach was reconsidered. Because the alternative HLL was formulated as a function of the unit's rated cooling capacity, the heating load slope factor is influenced directly by the assumptions regarding the sizing of the unit. In the original analysis, E+ autosized unit values were used. On further review, this approach was found to give units that were undersized by ~8% on average below that which would be required to meet all of the cooling season hourly loads, i.e. the equipment cooling capacity was undersized relative to the maximum hourly cooling demands . In the revised approach, the unit sizes were increased to meet all of the hourly cooling loads. In DOE Climate Region V, a further 10% oversizing is also applied to (1) bring the AHRI Standard 210/240 cooling load line used in Seasonal Energy Efficiency Ratio (SEER) ratings (AHRI 2008) into closer alignment with the E+ average cooling load line and (2) reduce supplemental electric resistance heat use in this colder climate.

2.1 RESIZING APPROACH

The indicated undersizing was determined by comparing the E+ design cooling load at the 75°F indoor set point condition to the hourly cooling loads. (In the E+ autosizing approach, the design cooling capacity requirement is set to equal the design cooling load.) An example of this comparison is shown in Figure 1 for Indianapolis for the 2006 IECC house with mechanical ventilation turned off. While the E+ design load is seen to be higher than the average binned load, it is seen to be slightly lower than that required to meet all of the hourly loads, as shown with the resulting equipment capacity at design conditions given by the dashed red line in Figure 1. By adjusting the design load upward by 8%, as shown in Figure 1, we are in turn requiring a higher equipment capacity of the same adjustment factor, shown by the dashed purple line when operating at the indoor set point and relative humidity (RH) conditions, that will meet all the hourly cooling loads (accounting for the gradual drop in cooling capacity output of the heat pump with increasing ambient). Also, the ambient at which the calculated E+ design day load is a maximum in Figure 1 is lower than the 0.4% design temperature used in the E+ design day calculations (which is the maximum ambient temperature for 99.6% of the time over the cooling season). This is because the thermal inertia of the house shifts the peak cooling load to a later time in the day than the peak ambient temperature.

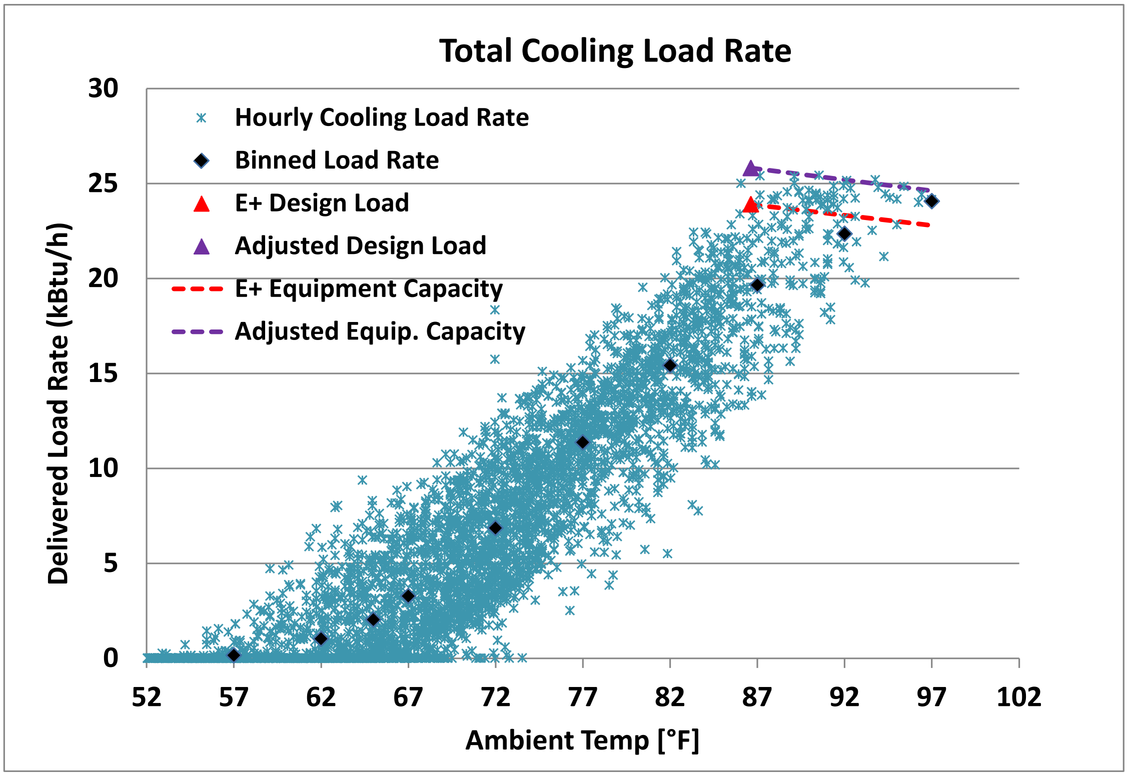

Figure 1. Hourly, binned, and design cooling load rates for IECC 2006 prototype residential house in Indianapolis, Indiana, without mechanical ventilation.

The revised approach involves selection of heat pump cooling capacity (aka sizing of the unit) such that the equipment capacity (purple dotted line in Figure 1) meets or exceeds all of the E^+-generated hourly cooling load/ambient temperature point(s) (blue stars in Figure 1). This approach also results in a heat pump capacity in Region IV that, at 95°F ambient temperature, is about 10% larger than the average linearized cooling load, which is consistent with the AHRI 210/240 assumption for cooling unit sizing built into the SEER calculations (AHRI 2008). This is shown in Figure 2, where the AHRI load line (shown by the green line) calculated for the adjusted rated capacity (green diamond) is close to the average binned load lines (actual or linearized). Both the E+ rated size and the adjusted rated size are shown in Figure 2, along with the E+ original and adjusted design loads. The rated sizes are based on return air conditions of 80/67°F DB/WB(dry- and wet-bulb temperature) and a 95°F ambient while the design load and the load lines are based on 75°F DB and ~50% RH (relative humidity) return air conditions and ~87°F ambient. As such, the rated unit sizes (for both E+ autosizing and adjusted sizing) are slightly higher than the E+ design load and the adjusted design load, respectively, because the return air difference increases rated capacity more than the higher ambient lowers capacity. In summary, the revised sizing approach meets all of the hourly cooling loads and is more consistent with the AHRI 210/240 cooling unit sizing assumption relative to the average (binned) cooling loads.

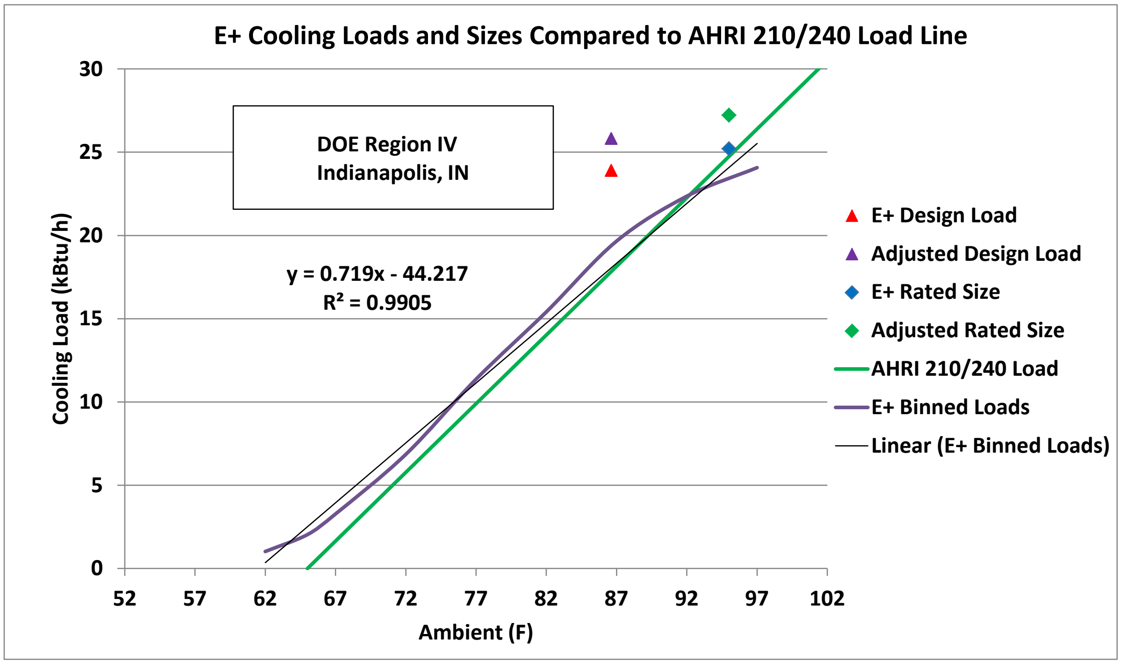

Figure 2. Comparison of EnergyPlus binned cooling load curve and linearization to AHRI load line for the adjusted rated unit size.

Further changes to the region-by-region loads analysis were the additions of one more Region II location of Charleston, South Carolina; another Region III location of Memphis, Tennessee; and two more Region V locations of Lansing, Michigan, and Albany, New York. The original higher-elevation Region V location of Eagle County, Colorado, was dropped as being less representative due to the higher solar contributions, which gave a somewhat lower zero heating load ambient (~50°F). A summary of the locations included for Regions I–VI, foundation type, E+ cooling autosizes, and adjusted sizes (with all cooling capacities provided based on standard rating conditions) are given in Table 1 for the IECC 2006 code houses without mechanical ventilation. By comparison, the original E+ sizes with mechanical ventilation were 0.2 tons higher than the autosized values in Table 1 for most locations. Exceptions were 0.1 tons higher for Omaha, Nebraska; Lansing, Michigan; and Portland, Oregon; and 0.4 tons higher for Minneapolis, Minnesota.

Table 1. Summary of locations and house construction types modeled per IECC 2006 code in EnergyPlus[a] and rated cooling capacity sizes selected[b]

Location	House type	E+ cooling autosize (tons)	Adjusted cooling size (tons)
	DOE Region I		
Tampa, Florida	Slab	2.5	2.68
	DOE Region II		
Charleston, South Carolina	Slab	2.5	2.7
Fort Worth, Texas	Slab	2.7	2.94
	DOE Region III		
Atlanta, Georgia	Slab	2.3	2.44
Memphis, Tennessee	Slab	2.5	2.68
Oklahoma City, Oklahoma	Slab	2.6	2.83

Table 1. (continued)

Location	House type	E+ cooling autosize (tons)	Adjusted cooling size (tons)
DOE Region IV			
Indianapolis, Indiana	Heated basement	2.1	2.27
Peoria, Illinois	Heated basement	2.2	2.38
Philadelphia, Pennsylvania	Heated basement	2.3	2.44
Omaha, Nebraska	Heated basement	2.4	2.62
DOE Region V			
Albany, New York	Unheated basement	1.8	1.94 (2.14 [c])
Lansing, Michigan	Heated basement	2.0	2.20 (2.42 [c])
Minneapolis, Minnesota	Heated basement	2.0	2.18 (2.40 [c])
DOE Region VI			
Portland, Oregon	Crawl space	1.8	2.02

[a] EnergyPlus V8.1 results, no mech.l ventilation, 2400 ft^2 conditioned space on main and second floors
[b] House load set points: cooling = 75°F; heating = 70°F
[c] With 10% further oversizing

3. RESULTS OF REVISED HLL ANALYSIS

Removing mechanical ventilation from the E+ space-conditioning loads model lowered the values of both the zero-heating-load ambient temperature and the heating load slope factor. The change related to unit sizing affected only the heating load slope factor. Revised sets of heating load slope factors were calculated, first incorporating just the removal of mechanical ventilation, and second adding also the change in heat pump sizing. This was done so that the individual impacts on slope factor of the two analysis changes could be determined.

3.1 IMPACT ON HEATING LOAD SLOPE FACTORS OF REMOVING MECHANICAL VENTILATION

First, the heating load slope factors and zero-heating-load ambient temperatures for each region were recalculated for the E+ IECC 2006 houses with mechanical ventilation turned off, based on E+ unit autosizing that was used in the initial analysis. This lowered the average Region IV slope factor from 1.31 to 1.24, while the average over all six regions dropped from 1.32 to 1.26. These results are shown in Figure 3.

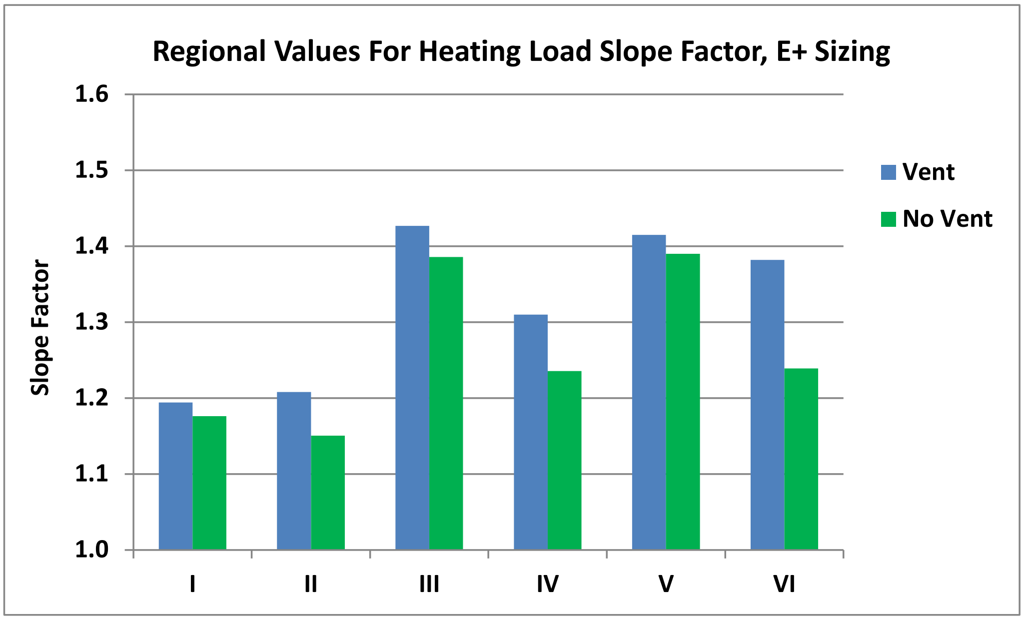

Figure 3. Regional heating load slope factors: E+ autosizing; with and without mechanical ventilation.

The zero-heating-load ambient temperatures in the revised analysis dropped by approximately 1°F for all regions except for a 2°F drop in Region I. The new results with no mechanical ventilation are compared with the values with mechanical ventilation in Figure 4.

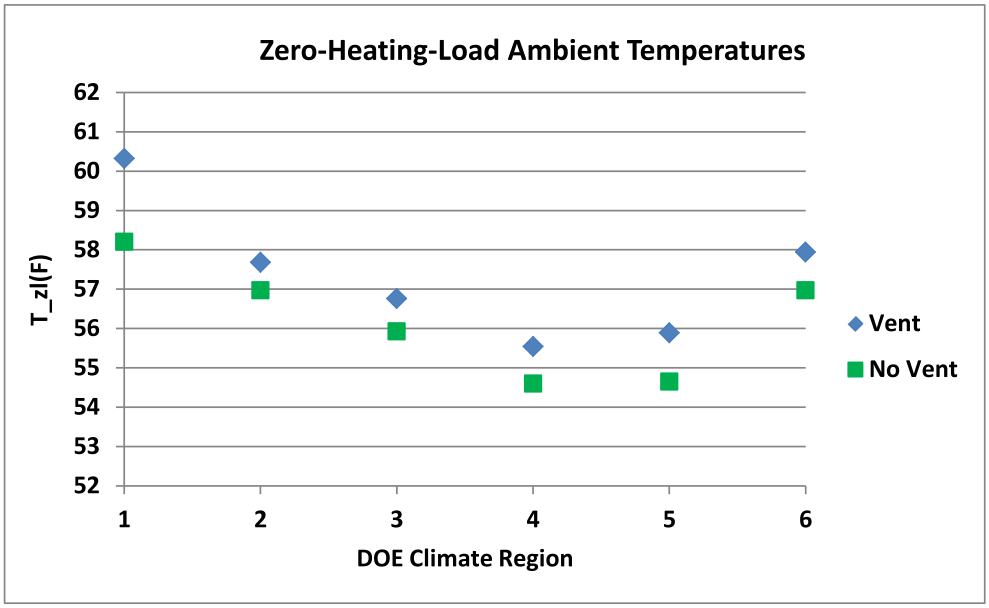

Figure 4. Regional zero-heating-load ambient temperatures with and without mechanical ventilation.

In Figure 5 the new values (rounded to the nearest integer value) are compared with those proposed by DOE in the supplementary notice of proposed rulemaking (SNOPR) published on November 9, 2015 (DOE 2015b). The Region IV values remain at 55°F as in the SNOPR because the original average value with mechanical ventilation (55.5°F) dropped to 54.6°F, and both round to 55°F. For Region V, with the addition of two new locations post SNOPR, the average values with mechanical ventilation increased to 55.9°F, dropping back to 54.7°F with no ventilation.

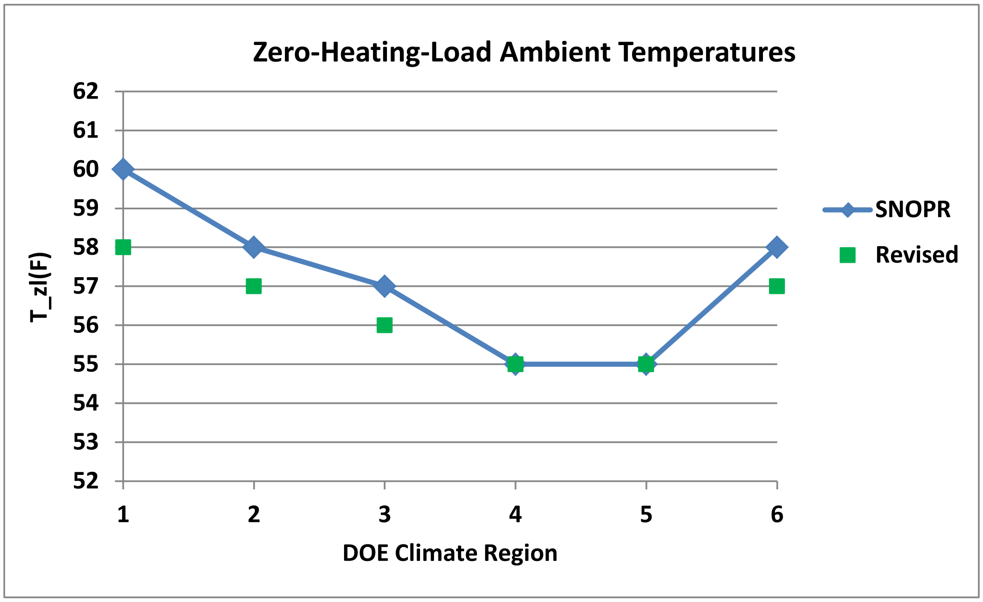

Figure 5. Regional zero-heating-load ambient temperatures: SNOPR with mechanical ventilation and "revised" without.

3.2 IMPACT ON HEATING LOAD SLOPE FACTORS OF HEAT PUMP SIZING REVISION

With the units resized to meet all of the hourly cooling loads, the averaged Region IV slope factor dropped from 1.24 to 1.15 while the average slope factor over all regions dropped from 1.26 to 1.16. Figure 6 shows regional slope factors with E+ autosizing and adjusted E+ sizing.

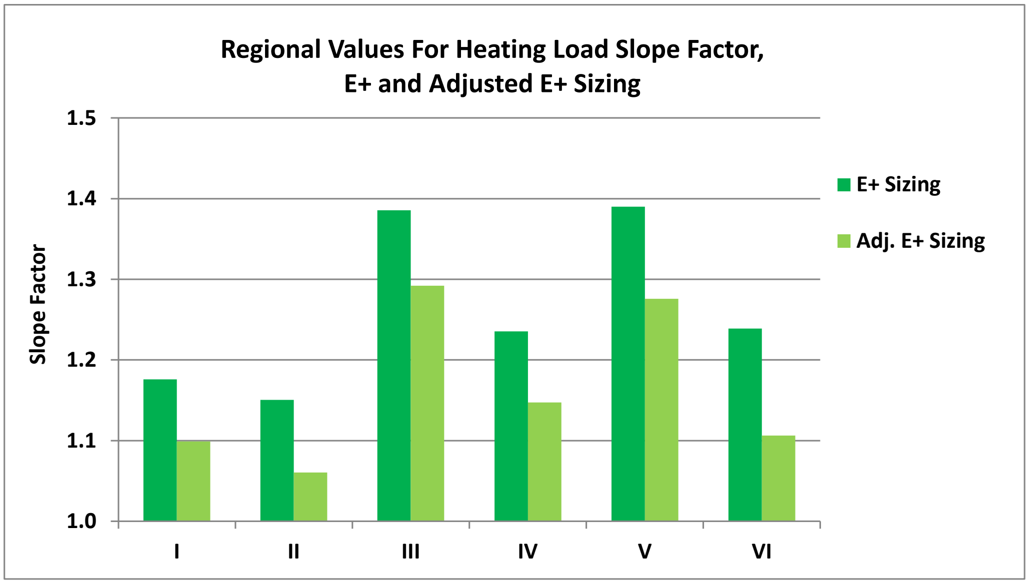

Figure 6. Regional heating load slope factors: E+ autosizing and adjusted sizing; without mechanical ventilation.

However, given the range of slope factor values from a low of 1.06 in Region II to a high of 1.29 in Region III, a variable slope factor by region provides the closest agreement in seasonal heating loads with the E+ results over all six climate regions. In this case, rounding to the nearest 0.05 could be considered for convenience, giving slope factors of 1.1, 1.05, 1.3, 1.15, 1.3, and 1.1 for DOE Climate Regions I to VI, respectively.

Another sizing adjustment was analyzed for Region V to include a further 10% oversizing for cold climate applications. This provides a closer matching of the AHRI cooling load lines with the binned cooling load lines for the three Region V locations determined from E+ simulations. Without this adjustment, the resulting AHRI cooling load line is lower than the E+ load line in Region V. With this size increase, the slope factor for Region V drops from a rounded value of 1.3 to 1.15, the same as for Region IV.

In Figure 7, the rounded slope factors from the revised analysis with the extra Region V oversizing are compared to the values proposed in the SNOPR. A variable slope factor by region will give the most consistent seasonal heating load with E+ results; however, the 1.15 factor could be used to represent an average over all regions if a single slope factor is needed.

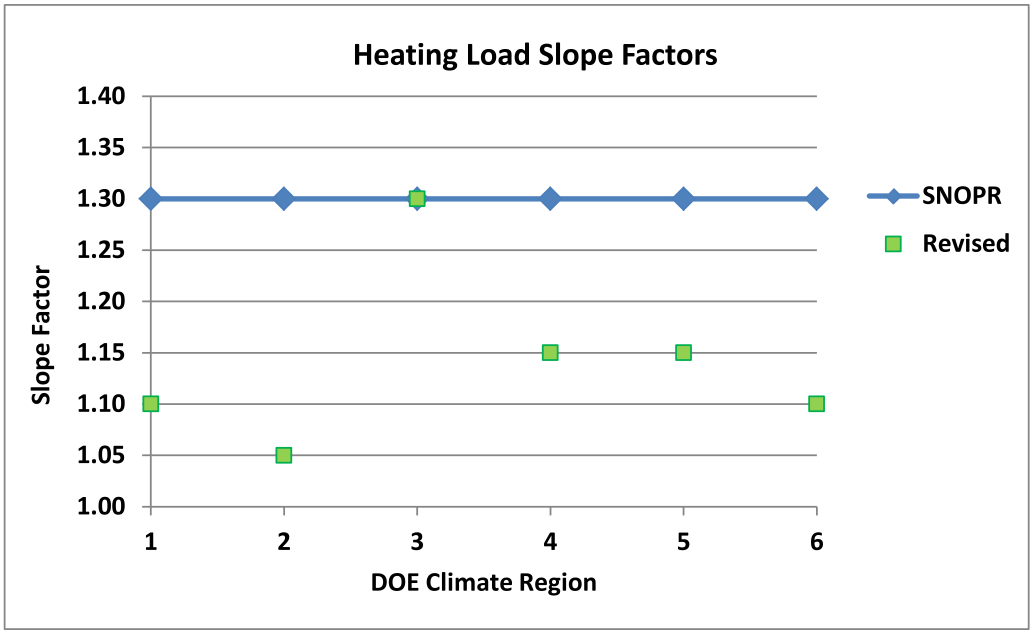

Figure 7. Rounded regional heating load slope factors.

Table 2 shows the change in seasonal heating loads from the current procedure using the minimum design heating requirement (DHR_{min}) loads to those with the alternative revised load lines. In other words, the "seasonal heating load change factors" are defined as the seasonal heating loads derived using the current procedure in AHRI 210/240 and the load lines developed in this revised analysis, divided by the seasonal heating loads calculated using the current procedure in AHRI 210/240 and the minimum design heating requirement (DHR_{min}) load lines. In some cases, the seasonal loads are lower (change factor less than one); this is where the lower zero-load ambient has a larger cumulative effect than the increase in the heating load slope factor. In other cases, the seasonal loads are higher (change factor greater than one). Change factors are shown in Table 2 using the revised zero-load-ambient temperatures and resultant new heating load hours with two options, regional or national average values, for the heating load slope factor. The percentage differences in seasonal load between the regional factors and the average national value are also shown in Table 2. The largest error in using a national average slope factor is in Region III, where the seasonal heating load is underpredicted by 11.5%. The next-largest difference, with an overprediction of 9.5%, is in Region II.

Table 2. Seasonal heating load change factors by region from current $\mathrm{DHR}_{\min}$ loads for alternative slope factors and revised zero load ambients and heating load hours

DOE climate regions	I	II	III	IV	V	VI
Zero-heating-load ambients ***(Fig. 5 green squares)***	**58**	**57**	**56**	**55**	**55**	**57**
Heating load hours	**493**	**857**	**1247**	**1701**	**2202**	**1842**
Regional heating load slope factors ***(Fig. 7 green squares)***	**1.1**	**1.05**	**1.3**	**1.15**	**1.15**	**1.1**
Seasonal heating load change factor	0.797	0.851	1.150	1.129	1.555	0.852
Avg. national heating load slope factor ***(if a single slope factor is needed)***	**1.15**	**1.15**	**1.15**	**1.15**	**1.15**	**1.15**
Seasonal heating load change factor	0.833	0.932	1.018	1.129	1.555	0.890
Load difference: national vs. regional factors (%)	4.5	9.5	–11.5	0.0	0.0	4.5

In summary, the revised analysis results in no change in the zero-load ambient temperatures for Regions IV and V and a 1°F to 2°F decrease of the zero-load ambient temperatures for the other four DOE climate regions. This also results in changes to the heating load hours for those regions as listed in Table 2. The HLL slope factors were lowered from the original analysis with the 1.30 factor to 1.15 in Regions IV and V. The revised analysis suggests that a variable HLL slope factor might be appropriate for the other four DOE climate regions, ranging from 1.05 in Region II to 1.3 in Region III, as shown in Figure 7. Table 2 shows the impact on seasonal heating load calculations (proportional to seasonal heating energy costs) of selecting slope factors based on regional values or using a national average slope factor. There is no impact on these calculations for Regions IV and V because the heating slope factors would be 1.15 for either approach. The predicted seasonal heating energy costs will also be affected by the changes in HSPF ratings from regional HLL slope factors different from 1.15, so the differences in percentages of seasonal heating energy cost using a 1.15 national average will be up to a few percentage points larger (both positive and negative), for regions other than IV and V, than those indicated by the load difference percentages shown in Table 2.

4. EFFECTS ON HSPF RATINGS LEVELS—SINGLE- AND TWO-CAPACITY UNITS

In Table 3, the effects on HSPF ratings of a 1.15 heating load slope factor and 55°F zero-load-ambient are shown for single- and two-capacity units in DOE Climate Region IV. In standard application (i.e., without lockout of high-stage cooling, as for a northern climate heat pump), the reduction in HSPF averages 12.6% for the single-capacity units evaluated, for the two-capacity units evaluated, and for the entire collection of single-capacity and two-capacity units evaluated. This compares with an average 16% reduction for the 1.3 slope factor indicated in the analysis described in the original HLL report (Rice et al. 2015a). For northern climate applications, where the cooling operation is limited to low-stage operation and the heat pump unit is sized accordingly, the HSPF reduction is only 6%, as compared to 7.3% with the 1.3 slope factor in the original report.

Table 3. HSPF ratings changes in DOE Region IV using the alternative heating load line with 1.15 slope factor for different sizing and heat pump types

Tested heat pump type	HSPF change (%)	Unit characteristics
Standard application, one capacity		
2 ton	–11.4	Lower F/D loss
4 ton	–13.7	Higher F/D loss
Standard application, two capacity		
3 ton, two stage	–13.3	No low-stage operation at < 40°F
3 ton, dual compressor	–13.9	Higher low-stage COP
5 ton, two stage	–10.5	Lower low-stage COP
Average change	**–12.6**	
Northern climate application		
3 ton, two stage	–9.1	No low-stage operation at < 40°F
3 ton, dual compressor	–3.2	Higher-low-stage COP
5 ton, two stage	–5.6	Lower-low stage COP
Average change	**–6.0**	

COP: coefficient of performance
F/D: frosting/defrosting
HSPF: heating seasonal performance factor

As noted in the original report (Rice et al. 2015a), the effects of the alternative HLL on rated HSPF correlates well with the ratio of rated heating capacity at 17°F ambient, $Q_h(17)$, divided by rated cooling capacity at 95°F ambient, $Q_c(95)$, as shown in Figure 8. This is a way to quickly estimate the effect of the alternative load line on specific single- and two-speed heat pumps. The three rightmost data points are the lower HSPF reductions for the northern climate application units, with the dual compressor (i.e., tandem) case having the lowest loss. For two-capacity units, other characteristics such as the ambient limits on the low-capacity operation and relative COPs of the low- to high-capacity modes of operation can also affect the degree of HSPF reduction.

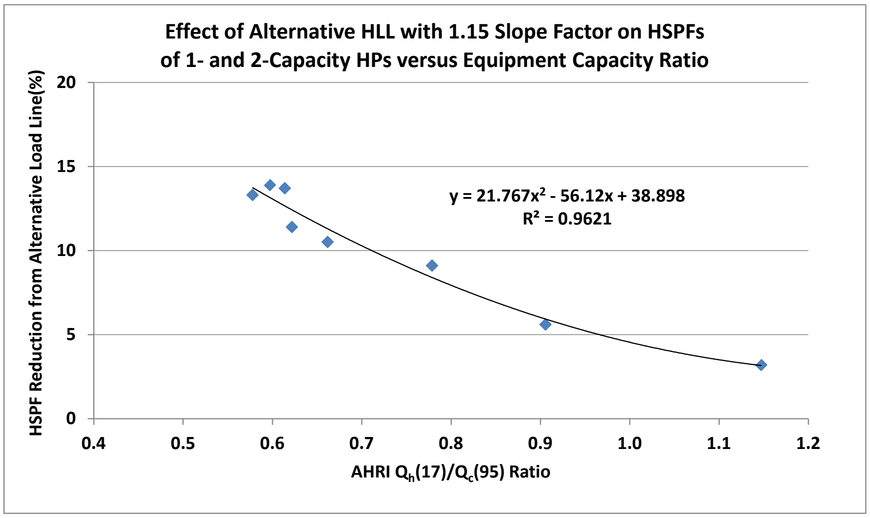

Figure 8. Reductions in rated HSPF from alternative heating load line with a 1.15 slope factor versus $Q_h(17)/Q_c(95)$ ratio for single- and two-capacity heat pumps

As noted in the original report (Rice et al. 2015a), use of a higher HLL leads to a significant relative increase in rated HSPF for northern-climate heat pump designs, in contrast to the negligible HSPF boost for such designs using the current rating procedure. In Table 4, we show the changes in relative HSPF ratings between standard and northern climate application of the same two-capacity units, first with the AHRI 210/240 minimum load line and then with the alternative load line having a 1.15 slope factor and lower zero-load-ambient. Relative to the standard two-capacity application, use of the alternative load line with northern climate sizing gives 5.4% to 11.6% higher HSPF values, averaging 8.2%, more as one would expect, rather than the minimal 0 to 2.7% changes, averaging 0.6%, obtained with the current load line approach. This change translates to a relative HSPF increase of 0.74 Btu/W-h for a baseline 9.0 HSPF unit (i.e., northern climate sizing would increase HSPF from 9 to 9.74). Note that the dual compressor case, where the rated cooling capacity is ~ half that in standard application, has the largest gain compared to two-stage northern climate sizing where the rated cooling capacity is ~ two-thirds of that in standard application.

Table 4. Relative HSPF ratings changes from standard to northern climate application for current and alternative heating load lines

Heat pump type	HSPF change (%)	
	AHRI 210/240 load	Alternative 1.15 load line
3 ton, two stage	2.70	7.62
3 ton, dual compressor	–0.76	11.6
5 ton, two stage	–0.03	5.35
Average change	**0.64**	**8.18**

AHRI: Air-Conditioning, Heating, and Refrigeration Institute
HSPF: heating seasonal performance factor

With regard to the listed heating season operating costs in the AHRI directory (AHRI 2016), use of the alternative load line would result in an average 29% increase in such costs. This is the result of the 12.9% increase in the delivered heating season load, as indicated in Table 2, combined with the average decrease in the HSPF of 12.6% from Table 3. This higher level of predicted energy use and operating costs would result in shorter paybacks for heat pumps that deliver improved heating performance. In comparison, heating season operating costs increase ~65% with use of an HLL halfway between the AHRI 210/240 minimum and maximum load lines, as compared with use of the min load line used in the current rating procedure. This is more than twice the average 29% increase with the revised alternative load line.

In DOE Climate Region V, the predicted heating season operating costs would average 90% higher with the alternative load line for standard heat pump designs. This finding is based on the 55.5% increase in delivered heating season load, as shown in Table 2, and an average HSPF decrease of 18% in Region V for the five units of Table 3 in standard application. This almost doubling of predicted heating costs for standard heat pumps in Region V should improve the business case for northern climate or other heat pump designs that deliver improved heating performance.

Heating season operating costs for the other four DOE climate regions using the revised alternative load line can be calculated using the equations in Appendix B of Rice et al. 2015a and the parameters summarized in Table 2 of this report. The HSPFs calculated for the different regions using the regional zero-load ambient temperatures and regional heating load slope factors vary from the HSPF calculated for Region IV by +31%, +27%, +18%, -21%, and +30% for Region I, II, III, V, and VI, respectively. These regional HSPF differences are about 50% larger than those with the current load line approach, mainly because the effects of the higher load line are not as significant in the milder climates and so the drop in HSPF is less; a similar effect is seen in Region V, where the increase in heating load has a stronger effect on HSPF than is currently the case.

5. EFFECTS ON HSPF RATINGS LEVELS—VARIABLE-SPEED UNITS

The HSPF reductions for variable-speed (VS) units when using the alternative Region IV load line as compared with currently rated HSPFs are shown in Figure 9; as in Figure 8, these reductions are shown versus the ratio of rated heating capacity at 17°F, $Q_h(17)$, divided by rated cooling capacity at 95°F, $Q_c(95)$. The figure separately shows the HSPF reduction for heat pumps that limit minimum-speed operation (i.e., increase the lowest speeds allowed) below 47°F and those that do not. 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 alternative load line, which has higher heating loads for most heating season hours than the current test procedure. This benefit is much more pronounced for VS units that do not limit minimum speed operation below 47°F ambient, which is consistent with results reported by Rice et al. 2015b for the alternative load line using the 1.3 slope factor.

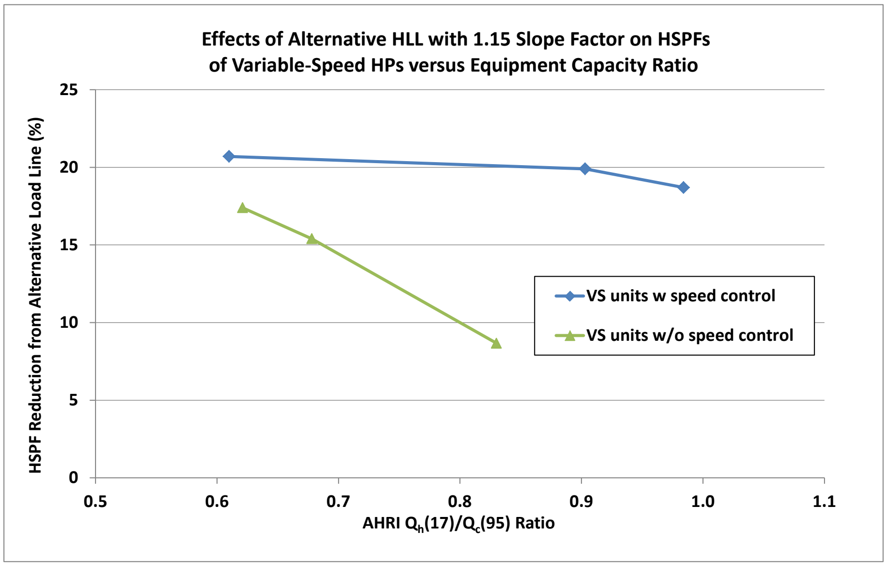

Figure 9. Reductions in rated HSPF from alternative heating load line with a 1.15 slope factor versus $Q_h(17)/Q_c(95)$ ratio for VS units with and without ambient limits on minimum speeds.

Substituting the revised alternative load line described in this addendum for the DHR_{min} load line results in HSPF reductions for current VS units ranging from 9% to 21%, which is generally larger than the average 12.6% reduction for single- and two-capacity units. There are two reasons for the larger VS unit HSPF reduction. First, use of the alternative load line significantly reduces the artificial increase in HSPF accruing from extrapolation of 47°F and 62°F minimum speed performance to lower ambient temperatures for VS units that limit minimum speed operation below 47°F, as reported by Rice et al. (2015b). Second, with the alternative load line, less heating capacity is delivered at the milder ambient temperatures, where VS units operating at low speeds have the highest efficiencies. In general, current VS units having little or no minimum speed limitations below 47°F ambient were found to have lower HSPF reductions, ranging between 9% and 17%, bracketing the 12.6% average for the single- and two-speed units in standard application. Those VS units without minimum speed constraints below 47F ambient and having more overspeed capability at lower ambients, i.e. higher $Q_h(17)$ / $Q_c(95)$ ratios have the lowest HSPF reductions in Figure 9, which are close to those shown in Table 3 and Figure 8 for northern climate two-stage heat pump applications at similar $Q_h(17)$ / $Q_c(95)$ ratios.

6. EFFECTS OF A LOWER HLL SLOPE FACTOR ON VS HSPF DIFFERENCES BETWEEN PROCEDURAL CALCULATIONS AND FUNCTIONAL OPERATION

Using available performance data sets (Rice et al. 2015b) for VS heat pumps that limit minimum speed operation below 47°F ambient, we evaluated the effect of a 1.15 HLL slope factor on the differences between procedural and functional calculations of HSPF. Previously (Rice et al. 2015b), use of a 1.3 HLL slope factor was found to reduce to less than 1%, in three of the four cases evaluated, the differences between the procedural HSPF calculation (per AHRI 210/240 procedure but with a higher HLL) as compared to HSPF calculations using more detailed test data sets that more fully captured the functional (as controlled) operation of these units. This was in contrast to the rather significant HSPF differences found in that report for such units when using the current (much lower) HLL used for HSPF rating calculations in AHRI 210/240.

A reduction in the alternative HLL slope factor from 1.3 to 1.15 increases the differences between procedural and functional HSPF values for these VS units. For three of the four VS units evaluated in the previous study (Rice et al. 2015b), the lowering of the HLL slope factor from 1.3 to 1.15 increases the procedural/functional HSPF difference from negative 1% (or less) to positive 1.1% (or less) for two of the units and positive 3% for the third. For the fourth unit analyzed in that report, a VS unit tested by Hunt (2013), which also limited minimum speed operation below 47°F ambient, the original procedural overprediction increases from 9.5% to over 14% as the HLL slope factor in Region IV is lowered from 1.3 to 1.15.

The results for the unit tested by Hunt (2013) were atypical. The larger error was found to be because the extrapolation of the minimum speed performance to ambients below 47°F gives an increasing COP with lower ambient, which results in the largest COP overpredictions from lower HLLs. This minimum speed trend also flattens the slope of the intermediate-speed COP versus ambient, adding more COP overpredictions between minimum and maximum speeds. To more accurately predict HSPF for such a unit, improved performance representations at minimum capacity operation below 47°F and at intermediate speeds at ambients below 35°F would be needed. In lieu of this, an option could be to apply a default HSPF penalty to the calculated HSPF for such VS units with an increasing COP extrapolation below 47°F at minimum speed.

With the above exception, the use of the lower 1.15 slope factor still limits to a fairly low level the difference between the procedural and functional HSPFs for VS designs that increase the minimum compressor speeds at ambients below 47°F. However, use of lower heating load slope factors than 1.15 for HSPF rating of minimum-speed-limited VS units should include some consideration for derating the calculated HSPFs for the inherent COP overpredictions from the fixed minimum speed assumption in the HSPF ratings procedure.

7. SUMMARY OF FINDINGS FROM REVISED ANALYSIS

The original HLL analysis was modified to incorporate two adjustments of (1) removing mechanical ventilation and (2) resizing the heat pump units based on new criteria. This resulted in a lowering of the HLL slope factor from the originally rounded 1.3 level to 1.15 in DOE Region IV and V while leaving unchanged the zero-load ambient at a rounded value of 55°F. For the other four DOE regions, the zero-load ambients dropped by 1°F to 2°F from those found earlier, and the rounded HLL slope factors ranged from 1.05 to 1.3. The average rounded HLL slope factor over all six DOE regions is 1.15.

Effects of the revised slope factor on rated HSPFs (Region IV) for single- and two-capacity units dropped from 16% in the original work to 12.6% in this report. For VS units, the HSPF reductions of 14% to 25% in the original report were lowered to a range of 9% to 21%. As in the original report, for VS units that do not limit minimum speed operation below 47°F ambient, the average HSPF reduction for the cases evaluated is approximately the same as for single- and two-capacity units.

For VS units that do limit minimum speed operation below 47°F ambient, the lower 1.15 slope factor of this report generally results in small overpredictions of rated HSPF by 1% to 3% compared to functional HSPF. An exception is minimum-speed-limited VS units where the minimum speed COP at 47°F is higher than that at 62°F; one such unit was found to have an HSPF overprediction of over 14% with the 1.15 HLL slope factor level. For such VS exceptions, a default HSPF penalty should be considered. For the more typical VS units that limit minimum speed operation, use of a 1.15 slope factor for rated HSPF was found to still acceptably limit the HSPF error. If slope factors lower than 1.15 are used for HSPF ratings, some means should be considered to appropriately derate the HSPFs for VS units that limit minimum-speed operation below 47°F ambient.

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