WUFI® Passive V.3.2.0.1 validation using ANSI/ASHRAE Standard 140-2017

Jasmine Garland
Student Member ASHRAE

Lisa White, CPHC®
Member ASHRAE

ABSTRACT

This report, published October 29, 2019, was prepared for the Passive House Institute US (PHIUS) and the Fraunhofer Institute for Building Physics (IBP). It is an evaluation of energy modeling methodology and analysis using WUFI® Passive V.3.2.0.1 software in comparison to test procedures described in ANSI/ASHRAE 140-2017, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Predictions generated by WUFI Passive software are evaluated against predictive benchmarks from ASHRAE 140-2017. Elaboration of software variances is provided, in addition to a comprehensive report of test procedures and results. WUFI Passive results fell well into the suggested acceptance ranges in all test cases when following Class II Procedures of ASHRAE Standard 140. When WUFI Passive is referenced in this document, it is in reference to version 3.2.0.1 which was used for all the computations described. This report is intended to be used by accrediting agencies or jurisdictions for validation or acceptance of this software.

Contents

List of Figures

List of Tables

INTRODUCTION

1.1 ASHRAE 140-2017 BACKGROUND

ASHRAE 140 is a comprehensive Standard Method of Test (SMOT) for the evaluation of building energy simulation software, with four previous release versions. The standard divides test protocol into two respective classes; *Class I Procedures*, and *Class II Procedures*. Methods for *Class I Procedures* are best suited for modeling software computing on an hourly and sub-hourly basis. *Class II Procedures* are used for WUFI Passive, Passive House Verification mode, which computes using monthly time-intervals.

The standard method of test prescribes a comparative analysis of WUFI Passive model results to the results of other validated modeling programs. This report provides a comparison to BLAST 3.0, DOE 2.1E and SRES/SUN 5.7. Comparative analysis serves validation and debugging purposes. Guidance given by ASHRAE 140-2017 establishes no formal pass/fail criteria in the evaluation of energy modeling software. However, the standard does describe statistical methods for determining accreditable acceptance ranges as described in Section 3.1.

ASHRAE Standard 140 provides a standard reporting method for documenting results and assumptions, these are recorded here in *Appendix A*. This includes a comparison of modeled results for all cases in each software, as well as differences in results between 'baseline' cases and their corresponding adjusted cases to isolate the impact of individual parameters on the results. Procedures, findings and analysis of the results are presented in the main body of the report below.

1.2 WUFI® PASSIVE V.3.2.0.1 BACKGROUND

WUFI Passive is a passive building energy modeling software developed in 2012 by the Fraunhofer Institute for Building Physics. It combines passive building energy modeling with WUFI's famed hygrothermal analysis power and was built upon the WUFI® Plus interface. The tool allows for a double assessment of the same building in the same building model – a monthly balanced based method (Passive House Verification mode), and a dynamic building simulation (WUFI Plus) used for detailed component hygrothermal assessment, comfort analysis, etc. Tier II tests, described below, used the monthly balanced-based method. The software is utilized by Certified Passive House Consultants (CPHC®) professionals in the building industry. According to PHIUS, "Fraunhofer IBP collaborated with PHIUS and Owens Corning to develop WUFI Passive using PHIUS data and expertise to produce a tool suited to North America's varying climate zones." The tool uses monthly energy balance methods following EN 13790[1] for the design and verification of buildings meeting PHIUS+ certification criteria.

1.3 CLASS II TEST PROCEDURE

Class II Procedures define 21 unique test cases, 17 of which report both annual heating and cooling loads, and 4 which report only annual heating loads. This results in 38 annual heating or cooling load outputs. The following Table 1 provides a description of differences among the test cases used for ASHRAE 140 Validation.

Table 1: ASHRAE 140 Class II Test Case Descriptions

Tier	Case Name	Description	Infiltration (ACH)	Int. heat (BTU/d)		R-Value (h ft² F/BTU)			Windows			Subfloor
				Sens.	Lat.	Walls	Ceiling	Floor	Type	Windows	Overhang	
Tier I	L100A	Base Case	0.670	56.105	12.156	12	21	14	SP	Avg. Dist.	No	Crawl
	L110A	High infiltration	1.500	56.105	12.156	12	21	14	SP	Avg. Dist.	No	Crawl
	L120A	Well insulated walls and roof	0.670	56.105	12.156	24	60	14	SP	Avg. Dist.	No	Crawl
	L130A	Double low-e windows	0.670	56.105	12.156	12	21	14	DP-LE	Avg. Dist.	No	Crawl
	L140A	Zero window area	0.670	56.105	12.156	12	21	14	N/A	N/A	No	Crawl
	L150A	All south-facing windows	0.670	56.105	12.156	12	21	14	SP	100% South	Yes	Crawl
	L155A	South facing overhangs	0.670	56.105	12.156	12	21	14	SP	100% South	No	Crawl
	L160A	East/West window orientation	0.670	56.105	12.156	12	21	14	SP	50% East / 50% West	No	Crawl
	L170A	No internal loads	0.670	56.105	12.156	12	21	14	SP	Avg. Dist.	No	Crawl
	L200A	Low efficiency construction	1.500	56.105	12.156	5	12	4	SP	Avg. Dist.	No	Crawl
	L202A	Low exterior solar absorptance	1.500	56.105	12.156	5	12	4	SP	Avg. Dist.	No	Crawl
	L302A	Uninsulated slab-on-grade	0.670	56.105	12.156	12	21	N/A	SP	Avg. Dist.	No	Slab
	L304A	Perimeter insulated slab	0.670	56.105	12.156	12	21	Edge ins.	SP	Avg. Dist.	No	Slab
	L322A	Uninsulated full basement	0.670	56.105	12.156	12	21	N/A	SP	Avg. Dist.	No	Basement
	L324A	Insulated full basement	0.670	56.105	12.156	12	21	Ins.	SP	Avg. Dist.	No	Basement
	L165A	East/West shaded windows	0.670	56.105	12.156	12	21	23	SP	Avg. Dist.	No	Crawl
Tier II	P100A	Passive solar base case	1.500	56.105	12.156	24	60	23	DP-C	100% South	No	Crawl
	P105A	South window overhangs	1.500	56.105	12.156	24	60	23	DP-C	100% South	Yes	Crawl
	P110A	Low mass version of P100	1.500	56.105	12.156	24	60	23	DP-C	100% South	No	Crawl
	P140A	Zero window area	1.500	56.105	12.156	24	60	23	DP-C	N/A	No	Crawl
	P150A	Even window distribution	1.500	56.105	12.156	24	60	23	DP-C	Avg. Distribution	No	Crawl

Class II tests begin with a baseline building represented as case L100A. The base building, 1539 sq. ft single-story house, has one conditioned zone that serves as the main

[1] EN ISO 13790 gives calculation methods for assessment of the annual energy use for space heating and cooling of a residential or non-residential building.

floor, an unconditioned attic, and a raised floor exposed to outer air conditions. Changes are applied to the baseline building incrementally, and subsequent results from each respective case are determined. The results are compared to the reference software.

Class II test procedures are divided into 'Tier I' and 'Tier II'. Tier I tests begin with the baseline building and adjust one component of the building per simulation to judge categories such as infiltration, insulation, window area, and window orientation. Adjusting these parameters in isolation allows for assessing the influence of each parameter on the annual heating and annual cooling load results. Climate data to be utilized for all cases are Colorado Springs, Colorado, for the annual heating load, and Las Vegas, Nevada for the annual cooling load. The test cases are run in both climates to record annual heating and cooling loads. One exception to this is the Tier I cases with foundation alterations, (L302A, L304A, L322A, L324A), which are only analyzed for annual heating loads, therefore utilizing only the Colorado Springs climate data set. In these cases, the exposed floor was changed to a slab-on-grade foundation type, modeled with and without insulation, followed by the addition of a conditioned basement, again modeled with and without insulation.

Tier II Tests are considered the Passive Solar Design series. These tests account for both annual heating and annual cooling loads but only utilize the Colorado Springs, Colorado, climate data. The baseline case, P100A, modeled after the well-insulated version of base case L100A, with all windows facing south, and a change in window type. Changes are incrementally made to test passive solar design modeling capabilities and techniques in consideration to window overhangs, window orientation, and thermal mass.

WUFI Passive has the capability of modeling and simulating each respective test case without alteration of respective geometries or systems using duplication of base cases to start the next iteration. All modeling required for Class II test cases can be successfully accomplished in WUFI Passive.

SIMULATION SETUP

2.1 BASE MODEL DESCRIPTIONS

To begin the energy modeling process, the respective building geometries were modeled in SketchUp and imported into WUFI Passive using a SketchUp plugin. Individual component manipulation was completed within the WUFI Passive software. To implement best practice, consistent modeling methods were applied to each geometry and modeled structure. Initially the base building: case L100A, a 27 ft x 57 ft house, was modeled as shown below:

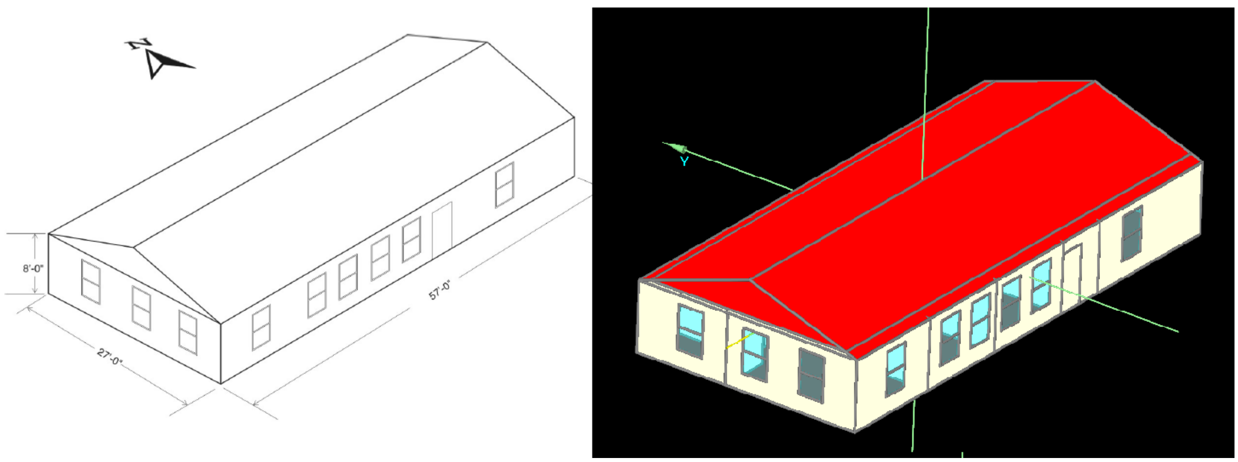

Figure 1: Base Case L100A Geometry - Standard 140 (left), WUFI Passive (right)

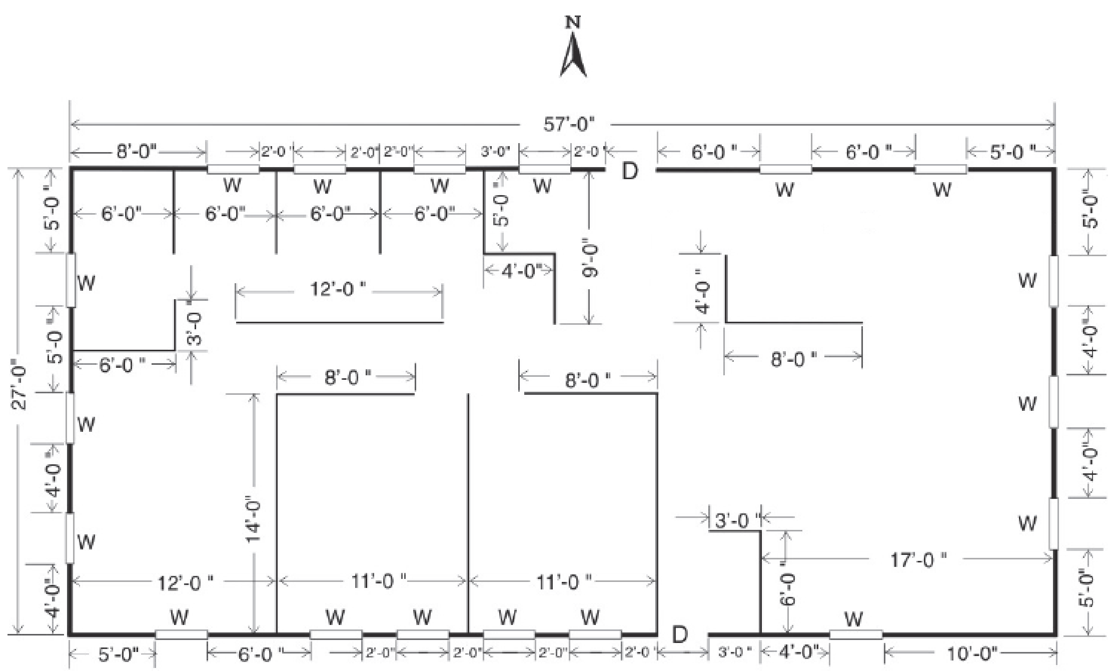

Figure 2: Base Case L100A Floor Plan

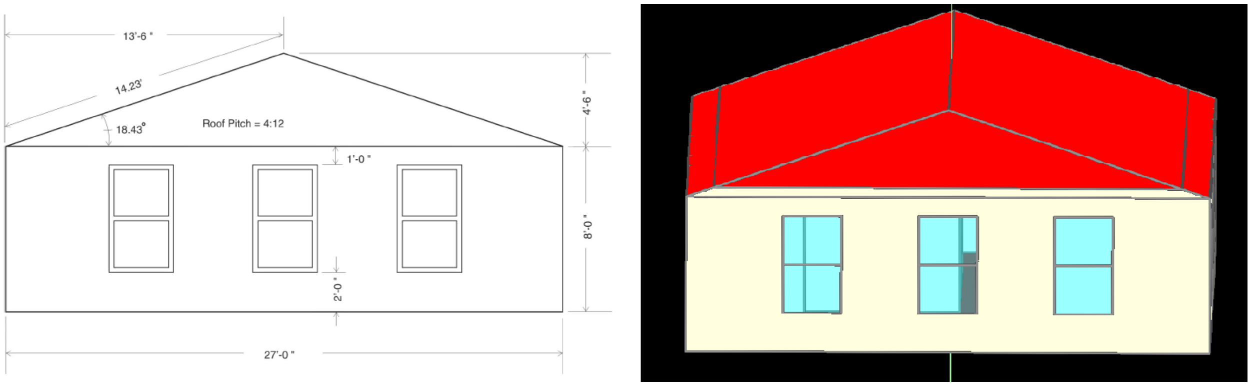

Figure 3: Base Case L100A Profile – Standard 140 (left), WUFI Passive (right)

WUFI Passive allows for the creation of 'Cases,' where a single case can be created and then duplicated to begin the next iteration. In the new case, various parameters can be adjusted as needed and provide updated results without interfering with the original case. This method was used throughout the modeling process. Incremental changes were made to the geometry in SketchUp when required as in Tier I cases: L140A, L150A, L160A, L302A, L304A, L322A, and L324A. The updated geometry was then imported into the new cases in WUFI Passive. Changes regarding infiltration, building component, and material properties were implemented within the WUFI Passive Software consistently.

The P100A baseline case for the Tier II Test Passive Solar Series uses the same footprint as L100A. Additional alterations include: all south facing windows (shown in Figure 4), a change in window type, a shift in door orientation, and additional interior thermal mass. In the next iteration of the passive solar series, case L120A, additional insulation is added to the external walls and ceiling area.

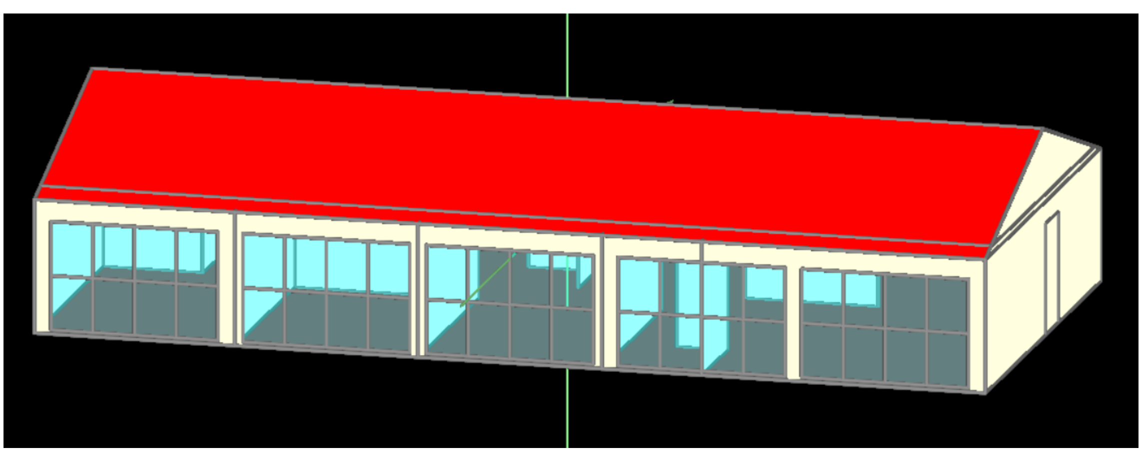

Figure 4: Passive Solar Base case P100A Window Orientation

2.2 EQUIVALENT MODELING METHODS

This section provides detail for modeling methods used in the test case series that differ but are intended to be equivalent to the modeling procedures as determined by ASHRAE. These methods were only used when the parameters specified in Standard 140 were represented slightly differently in WUFI Passive than described in the standard description. Despite this, WUFI Passive was able to simulate the effect of each parameter defined.

2.2.1 Thermal Mass

WUFI Passive 3.2.0.1 uses predetermined categories for specific heat capacity (thermal mass): lightweight, mixed, and massive. There is an option for a user defined entry that utilizes a built-in calculator. The calculator requires inputting the number of heavy surfaces per room, as the simulation tool considers both the total mass and the distribution of the mass. The WUFI Passive 3.2.01 thermal mass calculation (per unit of floor area) is shown in Equation 1 below:

$$Thermal\ Mass\ (BTU/ft^2{}^\circ F) = \left[60 + n_{heavy}\ x\ 24\right]\ x\ 0.176$$

As specified by Standard 140, the thermal mass capacity of the building is given to be 6006 BTU/°F for L100A: base case, and 22896 BTU/°F for P100A: Passive solar base. Converting these values to input in WUFI passive for specific heat capacity in BTU/ft^2°F results in numerical values of 3.9 and 14.91 BTU/ft^2°F respectively. These values were found by dividing the ASHRAE specified thermal mass capacity by the interior conditioned floor area. The values are much lower than the WUFI Passive default, as the lightweight category represents 11 BTU/ft^2°F. However, for accuracy and comparison against the reference software, the ASHRAE given values were utilized in the test results provided above.

<u>Location in Standard 140:</u> 7.2.1.3, 7.2.1.6, 7.2.3.2.2

2.2.2 Infiltration

Infiltration was specified at “natural” pressure in Standard 140, while the WUFI

Passive input for air-infiltration is at 50 pascals. However, WUFI Passive does report an estimated natural infiltration (at natural pressure) based on the 'wind protection' coefficients for the building. The test cases were assumed to have 'moderate screening,' which is the default setting. The inputs for infiltration at 50 pascals were adjusted until the reported 'Effective ACH Ambient' met the specified natural infiltration from ASHRAE 140. See Table 2 below for details.

			ASHRAE 140	WUFI Passive Result	WUFI Passive Input	
			ACH Specified	Effective ACH Ambient	Equivalent at 50Pa	Equivalent per ft² Envelope
Case	**Factor**	**Location**	**ACH**	**ACH**	**ACH50**	**CFM50/ft²**
L100A	Infiltration	Colorado Springs	0.53	0.54	7.75	0.34
L100A	Infiltration	Las Vegas	0.62	0.62	8.98	0.39
L110A	High Infiltration	Colorado Springs	1.19	1.19	17.01	0.75
L110A	High Infiltration	Las Vegas	1.38	1.38	20.10	0.87

Table 2: Equivalent Methods: Infiltration

<u>Location in Standard 140:</u> 7.2.1.7, 7.2.2.1

2.2.3 Windows

Window data provided in ASHRAE Standard 140 was not identical to the format needed for WUFI Passive. The surface films were specified separately from the glazing and frame, while in WUFI Passive they are input using a single thermal performance value for each. Therefore, the three layers (glass/frame, interior surface film, and exterior surface film) needed to be combined for a single entry. Equations 2 below were used to revise this data for input into WUFI Passive.

$$U_{glass} = \frac{1}{\frac{1}{C_g}+\frac{1}{E_g}+\frac{1}{I_g}} \qquad U_{frame} = \frac{1}{\frac{1}{C_f}+\frac{1}{E_f}+\frac{1}{I_f}} \tag{2}$$

Table 3: Equivalent Methods: Windows

ASHRAE Provided Values							Calculated Values	
Description	Conductance, net glass (COG & EOG)	Conductance, Frame	Exterior Surface Film, glass	Exterior Surface Film, frame	Interior Surface Film, glass	Interior Surface Film, frame	U-value, glass	U-value, frame
Term	Cg	Cf	Eg	Ef	Ig	If	Ug	Uf
Units	BTU/hr.ft2.F	BTU/hr.ft2.F	BTU/hr.ft2.F	BTU/hr.ft2.F	BTU/hr.ft2.F	BTU/hr.ft2.F	BTU/hr.ft2.F	BTU/hr.ft2.F
Single Pane (SP)	1.064	0.971	4.256	4.256	1.460	1.460	0.538	0.513
Double Pane Low-E (DP-L)	0.247	0.446	4.256	4.256	1.333	1.460	0.199	0.316
Double Pane Clear (DP-C)	0.516	0.492	4.226	4.226	1.397	1.460	0.346	0.3385

Location in Standard 140: 7.2.1.11, Table 7-10, Table 7-20, Table 7-51

2.2.4 Attic Infiltration

WUFI Passive does not allow for the inclusion of infiltration within an unconditioned zone. The attic has been modeled as an 'Attached Zone' with no reduction factor, which closely relates to assigning the ceiling condition to 'Outer Air.' The attached zone is assigned on the outer side of the ceiling assembly. Utilizing the attached zone for the attic, instead of assigning directly to outer conditions, removes the direct solar radiation from the exterior surface of the roof assembly.

Location in Standard 140: 7.2.1.7, 7.2.2.1

2.2.5 Basement Modeling Procedure

Cases L322A and L324A, were designated the "Basement Series," as a below grade basement was to be applied to the base case building. WUFI Passive uses a foundation interface tab, which contains built in foundation types: Heated basement (or underground floor slab), Unheated Basement, Slab on grade, Suspended floor. Using the input parameters and foundation type selected, it calculates ground temperature reduction factors. Thus, WUFI Passive automatically counts the effect of the basement assemblies being below grade.

In ASHRAE Standard 140, Table 7-41 for Case L322A specifies the total R-value of the uninsulated below-grade concrete wall as R-5.186 and Table 7-42 specifies R-40.614 for the below-grade uninsulated basement floor. Both tables include the note "*This R-value is the total air-air R-value (based on the ASHRAE overall steady-state heat transfer coefficient for a 6 ft 7 in. deep below-grade concrete floor slab) less the resistance of the* *listed interior film coefficient."* In order to not double-count the effect of the below-grade in the test case analysis, the R-value of the basement walls and slab were input in the usual manner for representing an un-insulated condition in WUFI Passive, R-0.48 and R-0.63 respectively.

Similarly, Table 7-44 specifying inputs for L324A states the above-grade concrete wall with an R-value of 10.69 while the below-grade concrete wall with R-16.31. These represent the same assembly layers. Therefore, the above-grade concrete wall R-value was used for both above and below grade conditions in order not to double-count the below grade effect. The slab R-value specified in Table 7-44 was able to be taken at face value for the test case simulation.

Location in Standard 140: 7.2.2.12

2.2.6 Shading

WUFI Passive offers two ways to model window overhangs, (1) through numerical inputs which calculates a single shading factor for the heating season and another for the cooling season, and (2) the improved method through dynamic calculation. The dynamic method would include the overhangs and other neighboring obstructions in the 3-d modeled geometry and running a shading calculation to determine monthly shading factors. To remain consistent with modeling procedures from respective reference software, and to eliminate user error, numerical inputs specified by Standard 140 were used when overhangs were added to test geometries.

This is notable because WUFI Passive has the capability to perform complex shading procedures using monthly dynamic shading calculations to determine monthly shading factors. This is generally the default/preferred method of computation by users of the software as it both improves accuracy and reduces input time. This method was not utilized for the test cases.

Location in Standard 140: 7.2.2.12

2.3 ADDITIONAL MODELING NOTES

ASHRAE 140 specifies both interior solar distribution and radiation absorptance on interior walls in Section 7.2.1.12 and that this is not a required program feature. WUFI

Passive does not have inputs for these but does account for radiation distribution in the input for specific heat capacity of the building as described in Section 2.2.1. No changes to the software source code were implemented for the evaluation.

EVALUATION CRITERIA

3.1 CALCULATING ACCEPTANCE RANGES

Standard 140 states that no formal criteria are set for the validation of the energy modeling software – accrediting agencies may determine appropriate acceptance ranges or use those provided by the standard. Annex B22 provides two procedures to determine acceptance ranges for Class II test cases: (1) establishing statistical confidence intervals, and (2) establishing a buffer zone serving as an 'economic threshold'.

For the first procedure described, the mean result of each reference software was calculated. The confidence interval was then added/subtracted to the mean to determine the maximum and minimum values in the acceptance range. A confidence interval of 93% is recommended by Standard 140 and was used for the analysis of WUFI Passive results, which equates to a confidence coefficient (t_c) of 3.576 for this sample size. However, confidence intervals between 80% and 95% are acceptable by Standard 140. The corresponding equations for calculation of maximum and minimum values from Annex B22 are shown in Figure 5.

$$L_a = X + (t_c)(s)/(N)^{1/2} \quad \text{(B22-1)}$$

$$L_b = X - (t_c)(s)/(N)^{1/2} \quad \text{(B22-2)}$$

where

L_a = maximum confidence limit for the confidence interval

L_b = minimum confidence limit for the confidence interval

X = sample mean

t_c = confidence coefficient

s = sample standard deviation = SQRT $\{SUM[(x_j - AVG(x_j))^2]/(N-1)\}$ for $j = 1$ to N, where x is a given value for the j-th sample

N = number of samples

The confidence coefficient (t_c) is determined by the sample size and the desired confidence interval. For this example, with a sample size of three ($N = 3$), t_c is calculated from Equation B22-1 or B22-2 to match the original HERS BESTEST (Appendix H)[B-27] confidence limits, resulting in the following:

$$t_c = 3.576255 \; [\text{from } t_c = 2.92 \times (3)^{1/2}/(2)^{1/2}] \quad \text{(B22-3)}$$

Figure 5: ASHRAE Standard 140 Annex B22 Confidence Interval Calculation

The second method for determining a confidence range allows for adding and subtracting 5% of the base case (case L100A) mean annual heating load to the mean of the reference software results. The justification for this method is that this equates to a negligible difference in utility cost. When the results are close together, the confidence intervals are narrow, but that should not be the source of elimination of an energy modeling program. The standard directs the use of the method that results in the largest range. All of this considered, Standard 140 states that, “Users are reminded that inclusion of this example is intended to be illustrative only and that it does not imply in any way that results from software tests are required by Standard 140 to be within any specific limits.”

3.2 CALCULATED ACCEPTANCE RANGES

A list of the calculated acceptance ranges for Annual Heating Load and Annual Cooling Load results is provided in Table 4 and Table 5.

Table 4: Class II Heating Acceptance Ranges (kBtu/yr)

Test Case	Description	BLAST 3.0	DOE 2.1E	SERIES 5.7	METHOD 1			METHOD 2		Min Conf. Interval	Max Conf. Interval
					Confidence	Min 93% Conf. Interval	Max 93% Conf. Interval	Min - 4 kBtu	Max + 4 kBtu		
L100A	Base Case	61.9	58.0	72.4	15.3	48.8	79.5	54.0	76.4	48.8	79.5
L110A	High infiltration	85.9	81.4	96.5	16.0	71.9	104.0	77.4	100.5	71.9	104.0
L120A	Well insulated walls and roof	50.3	45.1	57.8	13.2	37.8	64.3	41.1	61.8	37.8	64.3
L130A	Double low-e windows	46.3	45.8	50.0	4.7	42.7	52.1	41.8	54.0	41.8	54.0
L140A	Zero window area	49.1	47.2	52.5	5.5	44.2	55.1	43.2	56.5	43.2	56.5
L150A	All south-facing windows	54.9	49.5	64.0	15.2	41.0	71.3	45.5	68.0	41.0	71.3
L155A	South facing overhangs	57.4	52.3	66.9	15.3	43.6	74.2	48.3	70.9	43.6	74.2
L160A	East/West window orientation	62.9	58.3	73.5	16.1	48.8	81.0	54.3	77.5	48.8	81.0
L170A	No internal loads	73.1	71.6	85.5	15.7	61.1	92.4	67.6	89.5	61.1	92.4
L200A	Low efficiency construction	134.0	136.1	168.3	39.7	106.5	185.8	130.0	172.3	106.5	185.8
L202A	Low exterior solar absorptance	137.5	142.1	172.5	39.3	111.4	190.0	133.5	176.5	111.4	190.0
L302A	Uninsulated slab-on-grade	70.5	67.4	82.9	16.9	56.7	90.5	63.4	86.9	56.7	90.5
L304A	Perimeter insulated slab	60.1	56.6	69.2	13.3	48.6	75.3	52.6	73.2	48.6	75.3
L322A	Uninsulated full basement	91.7	88.3	105.9	19.3	76.0	114.6	84.3	109.9	76.0	114.6
L324A	Insulated full basement	64.9	61.1	72.6	12.0	54.2	78.2	57.1	76.6	54.2	78.2
L165A	East/West shaded windows	66.8	64.7	78.0	14.8	55.1	84.6	60.7	82.0	55.1	84.6
P100A	Passive solar base case	12.3	10.0	14.4	4.5	7.7	16.8	6.0	18.4	6.0	18.4
P105A	South window overhangs	14.6	12.1	17.0	5.0	9.5	19.6	8.1	21.0	8.1	21.0
P110A	Low mass version of P100	22.4	20.2	23.8	3.7	18.4	25.9	16.2	27.8	16.2	27.8
P140A	Zero window area	29.4	25.8	29.4	4.3	23.9	32.5	21.8	33.4	21.8	33.4
P150A	Even window distribution	25.1	22.6	28.0	5.6	19.6	30.8	18.6	32.0	18.6	32.0

Table 5: Class II Cooling Acceptance Ranges (kBtu/yr)

Test Case	Description	BLAST 3.0	DOE 2.1E	SERIES 5.7	METHOD 1			METHOD 2		Min Conf. Interval	Max Conf. Interval
					Confidence	Min 93% Conf. Interval	Max 93% Conf. Interval	Min - 4 kBtu	Max + 4 kBtu		
L100A	Base Case	54.7	60.8	59.3	6.6	64.9	51.7	50.7	64.8	50.7	64.8
L110A	High infiltration	57.7	63.8	59.3	6.5	66.8	53.7	53.7	67.8	53.7	67.8
L120A	Well insulated walls and roof	51.3	56.1	55.0	5.2	59.3	49.0	47.3	60.1	47.3	60.1
L130A	Double low-e windows	37.0	41.3	38.9	4.4	43.5	34.6	33.0	45.3	33.0	45.3
L140A	Zero window area	23.5	26.5	24.7	3.1	28.0	21.8	19.5	30.5	19.5	30.5
L150A	All south-facing windows	67.7	77.4	72.0	9.9	82.3	62.4	63.7	81.4	62.4	82.3
L155A	South facing overhangs	54.1	59.1	57.5	5.3	62.1	51.6	50.1	63.1	50.1	63.1
L160A	East/West window orientation	62.6	68.7	67.6	6.7	73.0	59.6	58.6	72.7	58.6	73.0
L170A	No internal loads	45.8	49.1	49.3	4.0	52.1	44.1	41.8	53.3	41.8	53.3
L200A	Low efficiency construction	65.7	73.1	76.7	11.6	83.4	60.3	61.7	80.7	60.3	83.4
L202A	Low exterior solar absorptance	59.6	62.2	70.6	11.8	75.9	52.3	55.6	74.6	52.3	75.9
L165A	East/West shaded windows	54.8	52.9	59.6	7.1	62.9	48.6	48.9	63.6	48.9	63.6
P100A	Passive solar base case	18.1	23.0	20.1	5.1	25.5	15.3	14.1	27.0	14.1	27.0
P105A	South window overhangs	12.0	13.6	13.5	1.9	14.9	11.1	8.0	17.6	8.0	17.6
P110A	Low mass version of P100	30.2	36.5	30.9	7.1	39.6	25.4	26.2	40.5	26.2	40.5
P140A	Zero window area	1.7	2.8	1.7	1.4	3.4	0.7	0.0	6.8	0.0	6.8
P150A	Even window distribution	12.4	15.0	14.0	2.7	16.5	11.1	8.4	19.0	8.4	19.0

Note: These acceptance ranges are theoretical values established for comparison to reference software.

RESULTS

4.1 CLASS II TEST CASE RESULTS

The result of WUFI Passive analysis against the respective reference software with corresponding confidence levels are provided below. A detailed comparison of software is provided in *Appendix A*. Things to consider for the comparative analysis are (1) if the results fall within the acceptable confidence range per individual case, and (2) if the results are consistently higher or lower than the other software.

Table 6: WUFI Passive Annual Heating Load Results (kBTU/yr)

Test Case	Description	BLAST 3.0	DOE 2.1E	SERIES 5.7	Min Conf. Interval	Max Conf. Interval	WUFI Passive Results	Within Conf. Interval?
L100A	Base Case	61.9	58.0	72.4	48.8	79.5	**55.7**	Yes
L110A	High infiltration	85.9	81.4	96.5	71.9	104.0	**77.9**	Yes
L120A	Well insulated walls and roof	50.3	45.1	57.8	37.8	64.3	**40.7**	Yes
L130A	Double low-e windows	46.3	45.8	50.0	41.8	54.0	**51.5**	Yes
L140A	Zero window area	49.1	47.2	52.5	43.2	56.5	**55.2**	Yes
L150A	All south-facing windows	54.9	49.5	64.0	41.0	71.3	**44.2**	Yes
L155A	South facing overhangs	57.4	52.3	66.9	43.6	74.2	**46.8**	Yes
L160A	East/West window orientation	62.9	58.3	73.5	48.8	81.0	**54.9**	Yes
L170A	No internal loads	73.1	71.6	85.5	61.1	92.4	**64.6**	Yes
L200A	Low efficiency construction	134.0	136.1	168.3	106.5	185.8	**150.4**	Yes
L202A	Low exterior solar absorptance	137.5	142.1	172.5	111.4	190.0	**149.9**	Yes
L302A	Uninsulated slab-on-grade	70.5	67.4	82.9	56.7	90.5	**70.4**	Yes
L304A	Perimeter insulated slab	60.1	56.6	69.2	48.6	75.3	**72.1**	Yes
L322A	Uninsulated full basement	91.7	88.3	105.9	76.0	114.6	**84.0**	Yes
L324A	Insulated full basement	64.9	61.1	72.6	54.2	78.2	**69.6**	Yes
L165A	East/West shaded windows	66.8	64.7	78.0	55.1	84.6	**58.5**	Yes
P100A	Passive solar base case	12.3	10.0	14.4	6.0	18.4	**11.0**	Yes
P105A	South window overhangs	14.6	12.1	17.0	8.1	21.0	**13.0**	Yes
P110A	Low mass version of P100	22.4	20.2	23.8	16.2	27.8	**18.6**	Yes
P140A	Zero window area	29.4	25.8	29.4	21.8	33.4	**29.0**	Yes
P150A	Even window distribution	25.1	22.6	28.0	18.6	32.0	**22.0**	Yes

Table 7: WUFI Passive Annual Cooling Load Results (kBTU/yr)

Test Case	Description	BLAST 3.0	DOE 2.1E	SERIES 5.7	Min. Confidence	Max Confidence	WUFI Passive Results	Within Conf. Interval?
L100A	Base Case	54.7	60.8	59.3	50.7	64.9	**56.0**	Yes
L110A	High infiltration	57.7	63.8	59.3	53.7	66.8	**58.8**	Yes
L120A	Well insulated walls and roof	51.3	56.1	55.0	47.4	59.3	**53.8**	Yes
L130A	Double low-e windows	37.0	41.3	38.9	33.0	43.5	**37.7**	Yes
L140A	Zero window area	23.5	26.5	24.7	19.5	28.1	**21.8**	Yes
L150A	All south-facing windows	67.7	77.4	72.0	62.4	82.3	**69.1**	Yes
L155A	South facing overhangs	54.1	59.1	57.5	50.1	62.1	**52.3**	Yes
L160A	East/West window orientation	62.6	68.7	67.6	58.6	73.0	**63.6**	Yes
L170A	No internal loads	45.8	49.1	49.3	41.8	52.1	**47.9**	Yes
L200A	Low efficiency construction	65.7	73.1	76.7	60.3	83.4	**70.8**	Yes
L202A	Low exterior solar absorptance	59.6	62.2	70.6	52.3	76.0	**70.3**	Yes
L165A	East/West shaded windows	54.8	52.9	59.6	48.6	62.9	**52.2**	Yes
P100A	Passive solar base case	18.1	23.0	20.1	14.1	25.5	**22.3**	Yes
P105A	South window overhangs	12.0	13.6	13.5	7.9	14.9	**12.3**	Yes
P110A	Low mass version of P100	30.2	36.5	30.9	25.4	39.7	**32.6**	Yes
P140A	Zero window area	1.7	2.8	1.7	0.0	3.4	**1.0**	Yes
P150A	Even window distribution	12.4	15.0	14.0	8.4	16.5	**13.8**	Yes

The WUFI Passive results are plotted on the acceptance ranges in Figure 6 and 7 below:

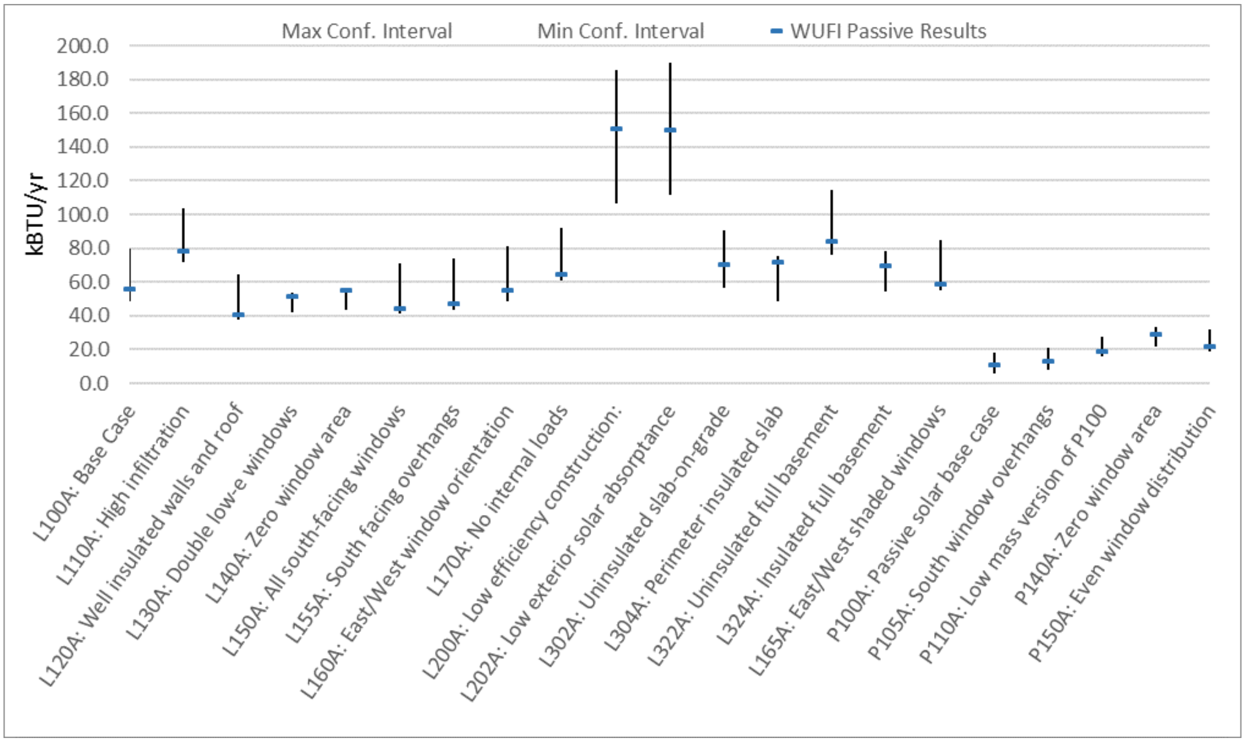

Figure 6: ASHAE 140-2017 Class II Confidence: Heating Test - Colorado Springs

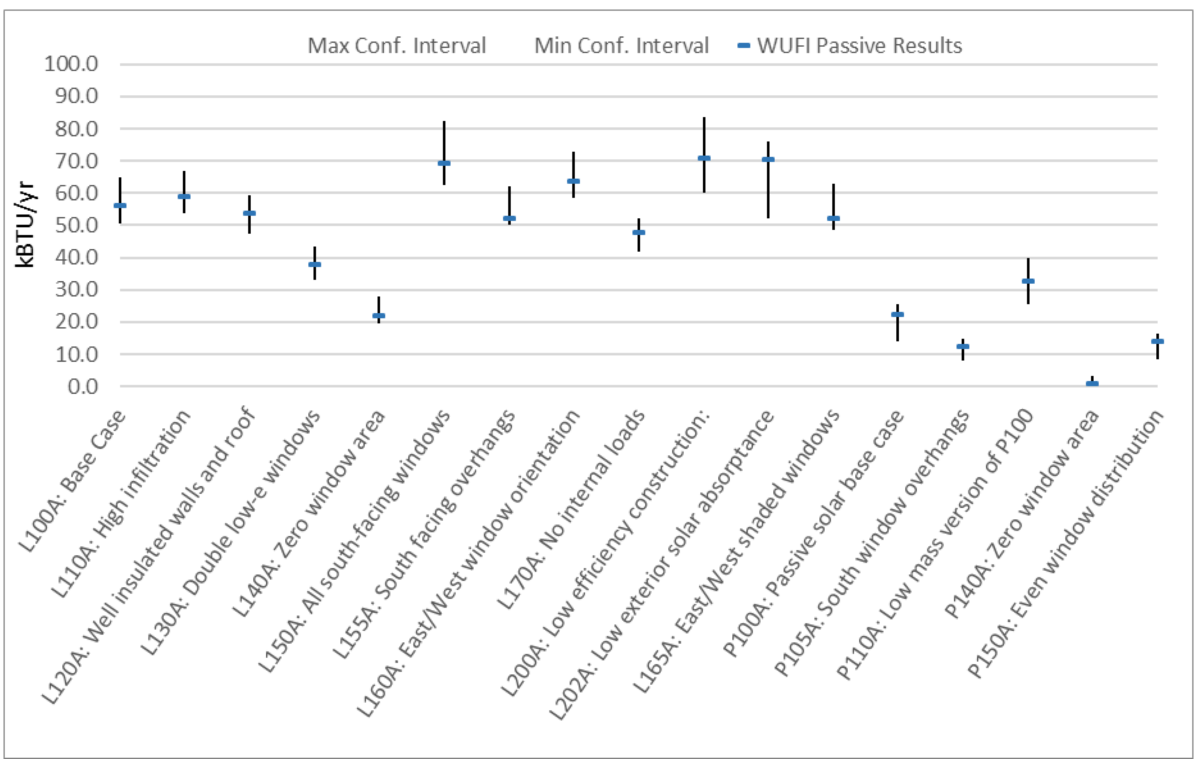

Figure 7: ASHRAE 140-2017 Class II Confidence: Cooling Test - Las Vegas

4.2 RESULTS ANALYSIS

The results of the WUFI Passive analysis fell within the specified confidence range for all 38 heating and cooling test cases. Most results fell toward the center of the confidence ranges, while a few were near the edges.

For the Annual Heating Load cases, a few were in the higher end of the confidence interval. These were the cases with the window improvement (L130A), with zero window area (L140A), and with perimeter slab insulation (L304A). For these cases, WUFI Passive predicted higher heating loads than the reference software, but still within the confidence interval. Alternatively, other Annual Heating Load cases fell into the lower end of the confidence interval where WUFI Passive predicted lower than the reference software. These cases contained well-insulated walls and roof (L120A), with all south-facing windows (L150A), south-facing overhangs (L155A), and with east/west shaded windows (L165A).

For the Annual Cooling Load cases, a few were in the lower end of the confidence interval. These cases all dealt with solar gain in some way. These were the case with zero window area (L140A), with south facing overhangs (L155A), and with east/west shaded windows (L165A). For these cases, WUFI Passive predicted lower than the reference software, but still within the confidence interval.

CONCLUSIONS

WUFI Passive results fell well into the acceptance ranges in all test cases when following *Class II Procedures* determined by ASHRAE Standard 140, testing against reference software, and applying a confidence interval.

APPENDIX A: COMPARISON OF SOFTWARE OUTPUTS

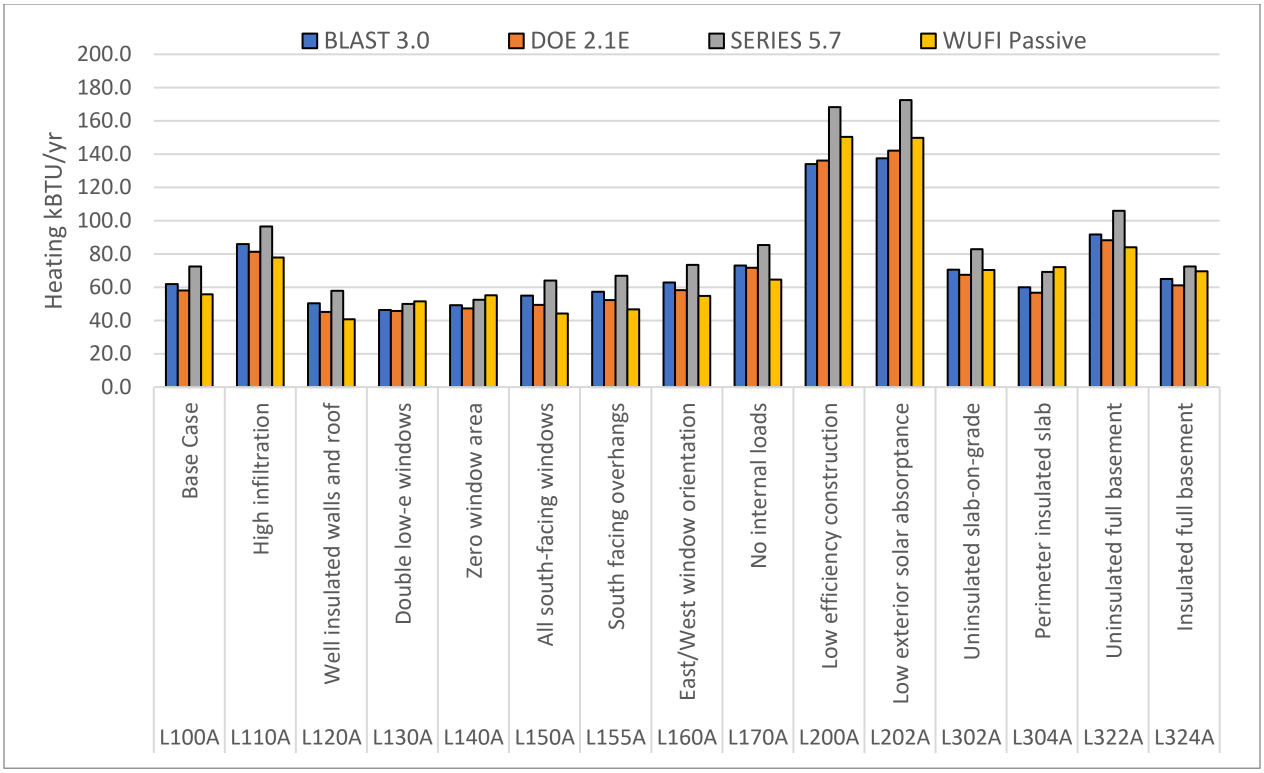

Figure 8: ASHRAE 140-2017 Class II Tier I Reference Software Comparison: Heating Test

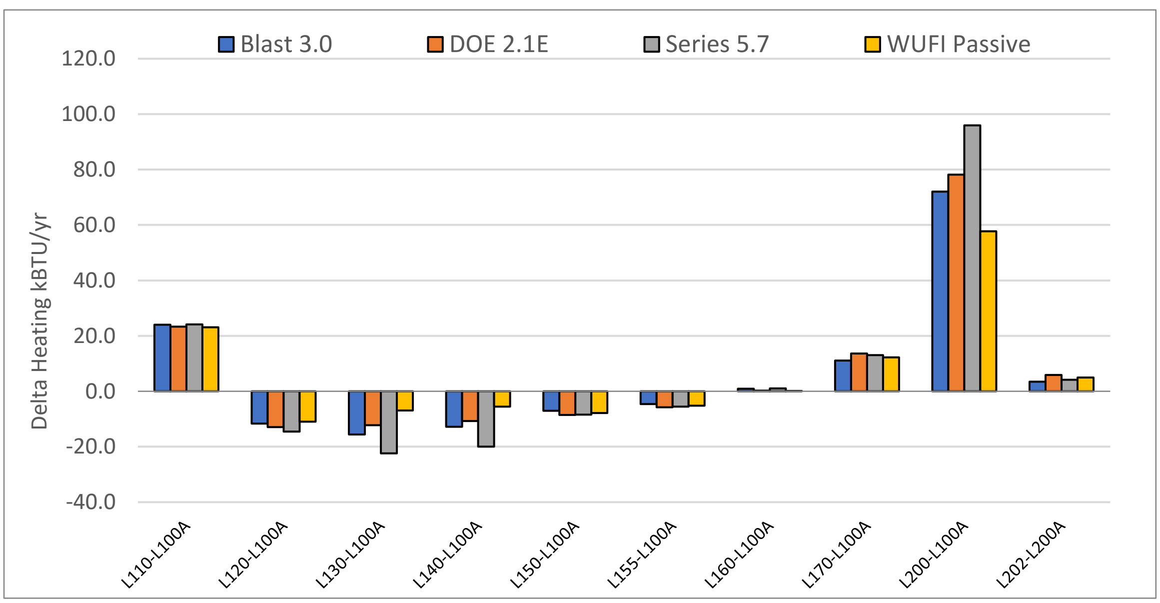

Figure 9: Class II Tier I Delta Heating Load Comparison

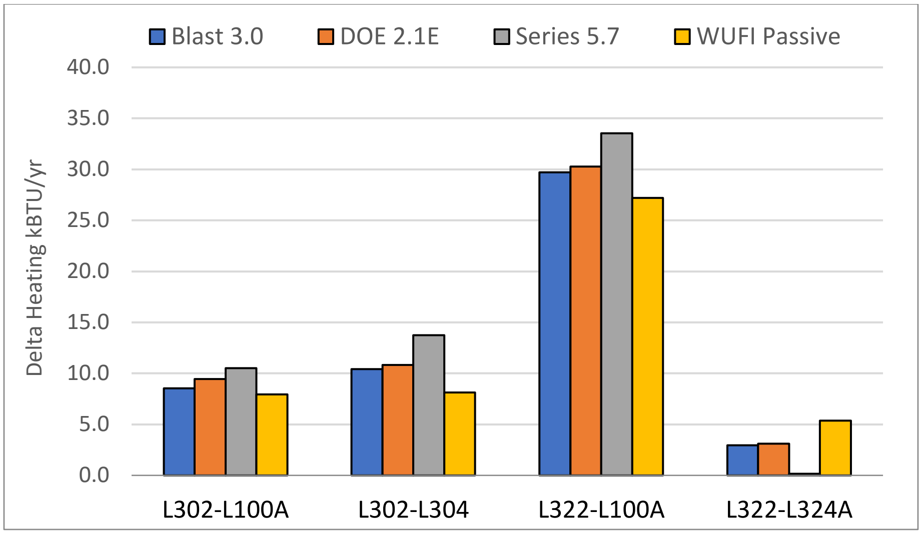

Figure 10: Class II Tier I Delta Heating Load Comparison

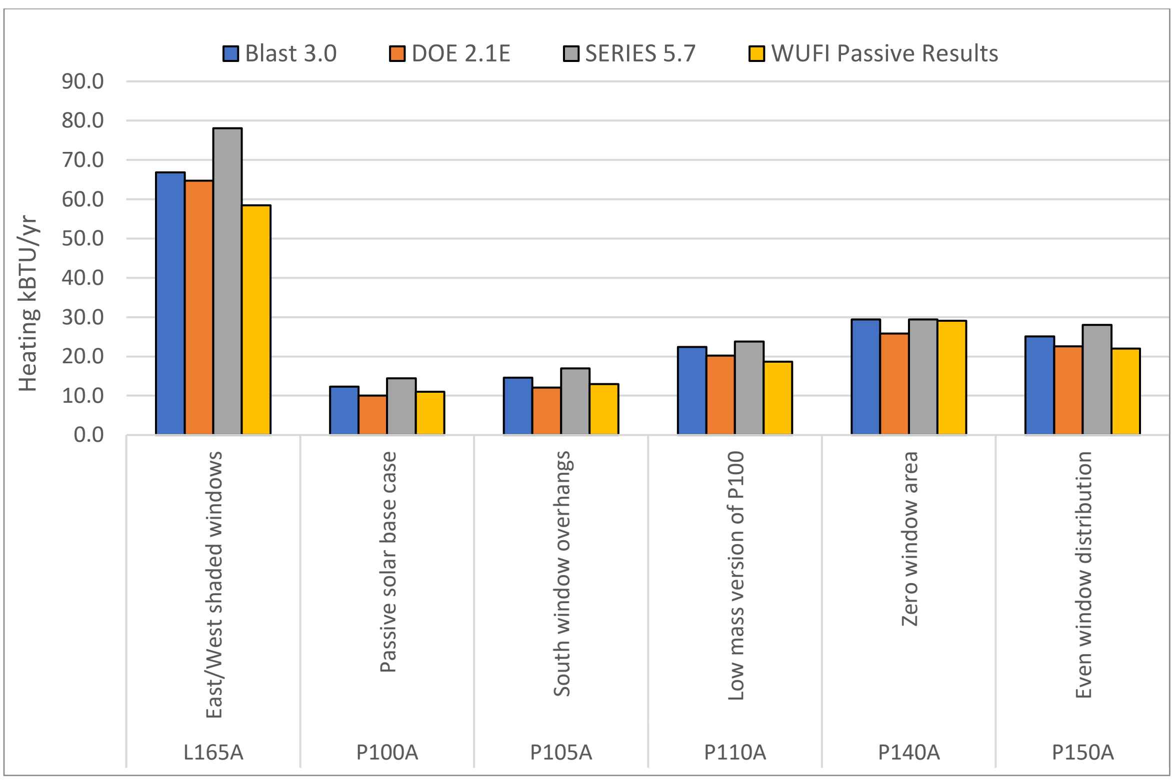

Figure 11: ASHRAE 140-2017 Class II Tier II Reference Software Comparison: Heating Test

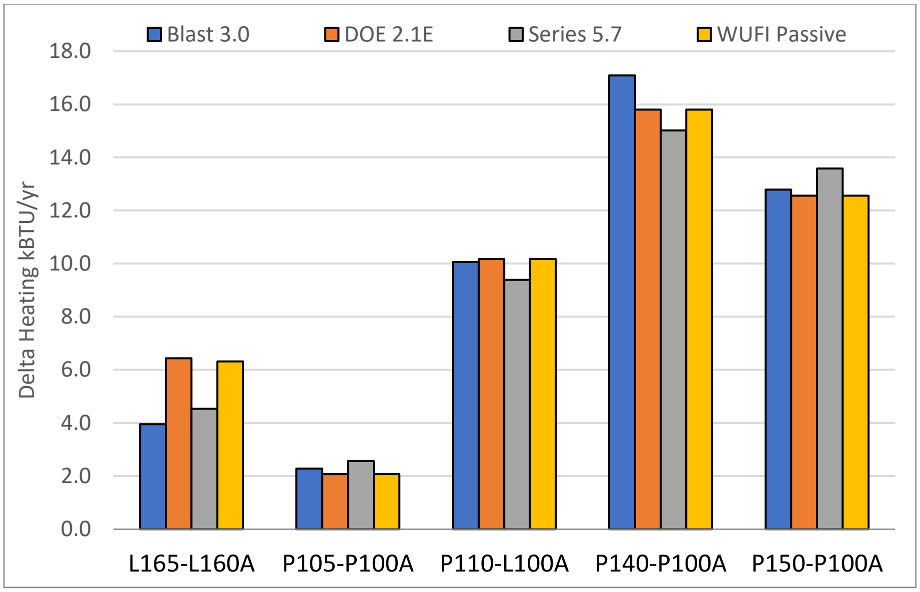

Figure 12: Class II Tier II Delta Heating Load Comparison

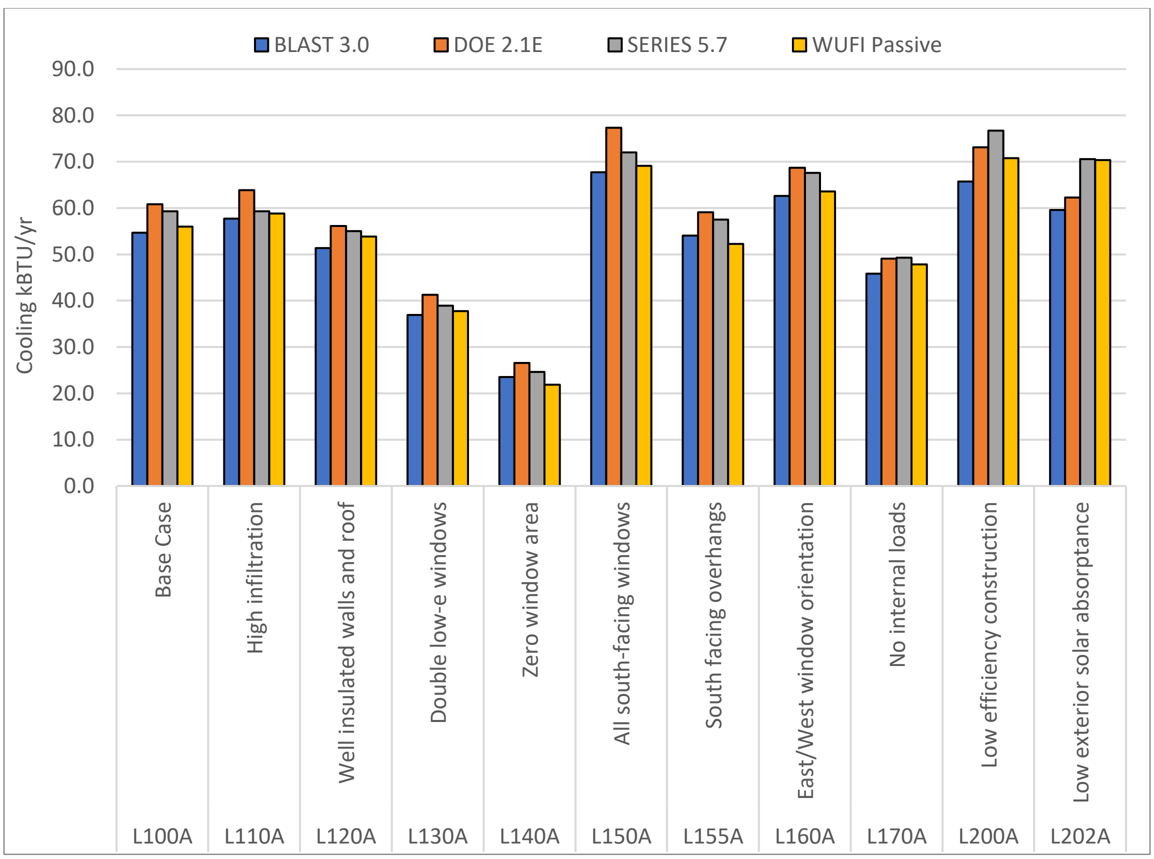

Figure 13: ASHRAE 140-2017 Class II Tier I Reference Software Comparison: Cooling Test

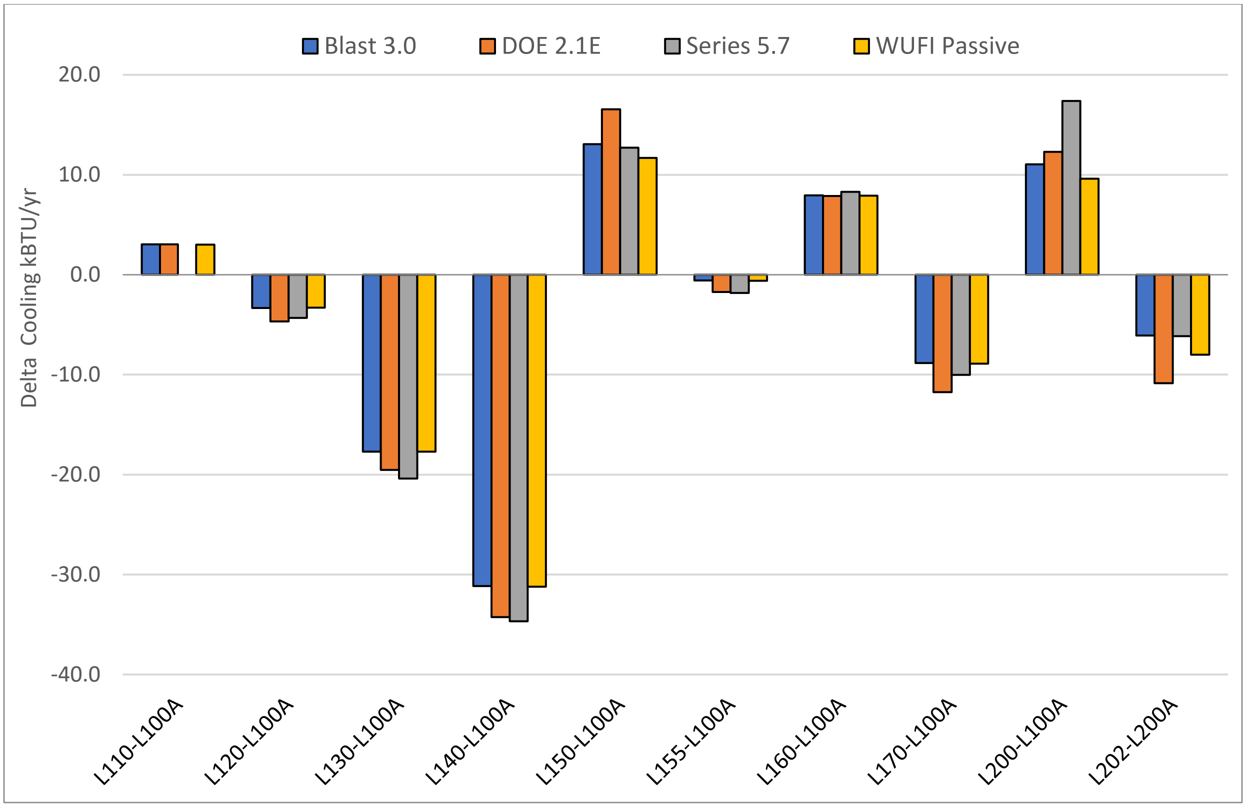

Figure 14: Class II Tier I Delta Cooling Load Comparison

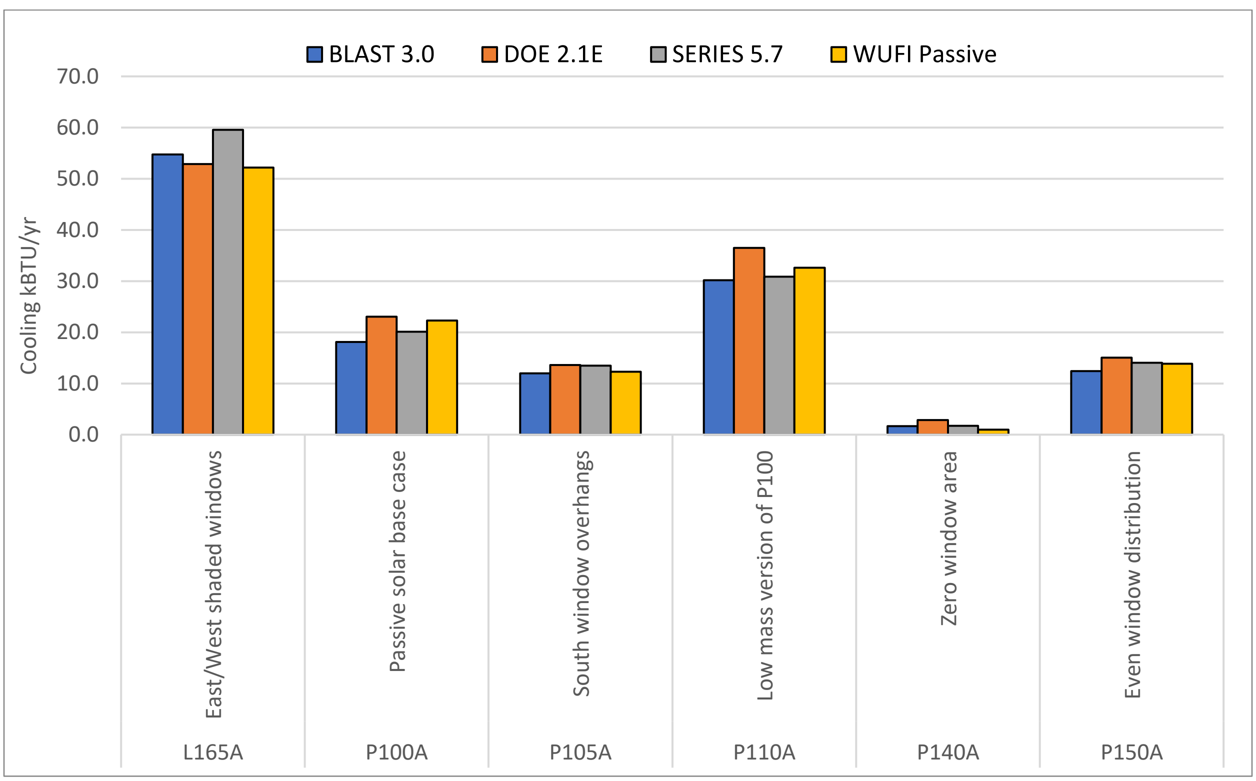

Figure 15: Class II Tier II Reference Software Comparison: Cooling Test

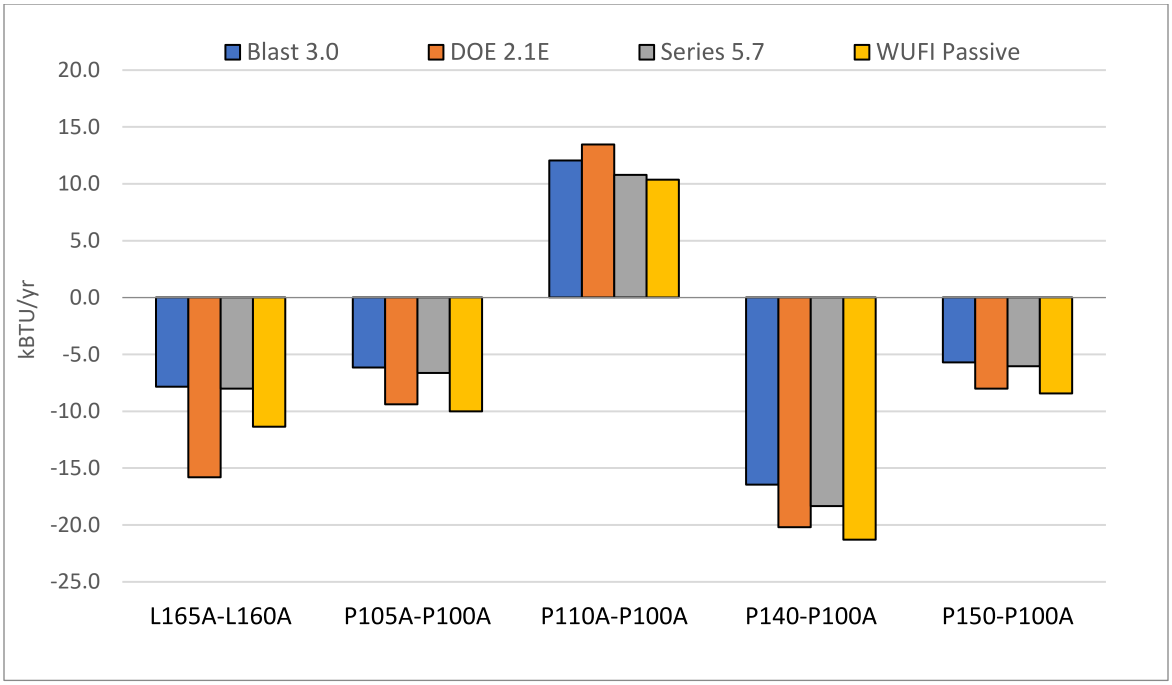

Figure 16: Class II Tier II Delta Cooling Load Comparison

APPENDIX B: WUFI PASSIVE FILE

The WUFI Passive file containing all cases can be downloaded here.