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Testing of HOT2000 version 11 in Accordance with ASHRAE Standard 140-2014

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Abstract: *HOT2000 is a key component of Canada's home energy rating, labelling, incentive programs, and code compliance. Design professionals and builders also use HOT2000 to improve residential house design. The National Energy Building Code (NEBC) requires all software used for code compliance be evaluated in accordance with ASHRAE Standard 140. After its latest major revision, the most recent version of HOT2000 Version 11.3 needed to be tested in accordance with ASHRAE Standard 140-2014. The heating energy consumption results from HOT2000 version 11.3 were mostly within the range of Std 140 reference software for both Class I and Class II test cases. Apparent differences in how HOT2000 models solar gains and makes use of these gains for a building with high thermal mass resulted in over half of HOT2000's cooling results being outside the confidence intervals. Within the context of whole house energy analysis (Class II test cases) for houses and low-rise residential buildings, HOT2000 does demonstrate consistent and acceptable energy use predictions. HOT2000 specifically is used for the whole house energy analysis.*

Keywords: *ASHRAE, Standard 140, validation, HOT2000, code compliance, energy analysis methods*

INTRODUCTION

When it was updated in 2012, the National Building Code of Canada (NBC) introduced minimum energy performance requirements for the first time, which could be met following a set of prescriptive requirements or a performance pathway. The performance pathway requires that the builder to demonstrate the house uses less energy than a reference house constructed to the prescriptive requirements. The builder may use any software tool for the performance pathway calculations, provided that the tool has been tested using the ANSI/ASHRAE Standard 140 (abbreviated as Std 140). Specifically, Sentence 9.36.5.4 (8) of the 2015 NBC requires that (NBC 2015:

> *"If a computer program is used to carry out the compliance calculations, the calculation methods employed in the energy model shall*
>
> *a) be used for both the reference and proposed houses, and*
>
> *b) be tested in accordance with ANSI/ASHRAE 140, "Evaluation of Building Energy Analysis Computer Programs.[…]"*

Natural Resources Canada (NRCan) develops, distributes and supports the HOT2000 residential energy simulation program, which is an integral part of delivering energy efficiency initiatives for new and existing houses in Canada. HOT2000 is a key component of provincial and federal energy rating, labelling and incentive programs, provides calculations for building performance code compliance, and is used by design professionals and builders to improve residential house design. Natural Resources Canada tests each major revision of HOT2000 with Std 140 to satisfy these requirements. This paper presents the results of the latest round of testing that was done on HOT2000 Version 11.3.

ANSI/ASHRAE Standard 140

Originally published in 2001, the 2014 release is the 4th edition (previous versions in 2001, 2007 and 2011). Each different edition increased the number of test cases, but otherwise stayed the same. ANSI/ASHRAE Standard 140-2014, "*Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*" (ASHRAE 2014) is a comprehensive standard method of test (SMOT) for evaluating whole building energy analysis and simulation software programs. These tests are part of an overall validation methodology. The validation tests consist of a series of carefully described sample case building plans and mechanical equipment specifications. Results from modelling the different cases with the software being tested are compared to those of reference software results and used in conjunction with diagnostic logic to determine the sources of predictive differences. ASHRAE Standard 140 classifies tests in two different classes:

Class I (Section 5) test cases – detailed diagnostic tests mainly intended for hourly and sub-hourly energy analysis programs. Class I tests are designed to test algorithms for

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building envelope, solar and internal gains and space heating, cooling and ventilation systems.

Class II (Section 7) test cases – overall diagnostic tests targeting the whole building load calculations regardless of time steps. Class II tests are geared towards simplified software for residential buildings. These test cases have been taken from the Home Energy Rating System Building Energy Simulation Test (HERS BESTEST). HERS BESTEST is a comparative validation method for evaluating building energy software used for home energy rating (Judkoff and Neymark, 1995). The 2014 version of Std 140 extends test cases for ground-coupling, for slab-on-grade, crawlspace and basement foundations.

HOT2000 Energy Analysis Program

HOT2000 is an energy simulation and design tool for low-rise residential buildings. This software is widely used across Canada to support program, policy and regulatory development and implementation. HOT2000 is a building energy simulation program that works on the basis of monthly energy balances. It uses a combination of building physics and curve-fits developed from more detailed simulation software. The limits of these curve-fits define the regions within which the program will work. HOT2000 is based on modified bin method for evaluating whole building energy analysis. Over the last 30+ years, HOT2000 has been modified, expanded and kept up-to-date. The most recent version at the time of the test was 11.3. In the past HOT2000 was tested and validated using the HERS BESTEST test cases as well to ASHRAE Std 140-2007. Class II test cases are more relevant for HOT2000, as these test cases are for evaluating the whole house energy use based on principles of a house-as-a-system's approach.

Compliance

Std 140 does not specify pass/fail criteria for evaluating an energy analysis software. Informative ANNEX B22 of the Standard provides guidance on developing an acceptance range in which the results of the tested software should fall. Using the guidance provided, the acceptance range was calculated by finding minimum and maximum confidence intervals using a tolerance of ±5% of the energy use of the base case. For example, where Case L100 is the base case for space heating, 5% of the average heating energy use modelled from the reference software is 4 million Btu (~ 4.2 GJ or 1170 kWh). To find the minimum confidence interval value, 4 million Btu (~ 4.2 GJ or 1170 kWh) is subtracted from the lowest space heating energy consumption result from the reference software for the Case in question. Similarly, to find the maximum confidence interval value, 4 million Btu is added to the highest space heating energy use from the reference software for the Case in question. Therefore, to meet this ±5% threshold, the HOT2000 results should fall between the minimum and maximum of the confidence intervals.

This range provides a reasonable threshold of economic uncertainty (ASHRAE 2014). That is, any software disagreements within ±5% of the reference results extremes for a given case, would result in relatively insignificant utility cost disagreements and therefore should not be cause for eliminating a given software tool. Annex B22 goes on to say that depending on fuel prices, climate, mortgage lending policy, and other circumstances in specific regions, it may make sense to adjust this criterion. In this paper, the confidence intervals are shown using ±5% of the base cases averages.

METHODOLOGY

The Std 140 validation exercise works by modelling a base house in the software being evaluated and comparing its predicted heating and cooling energy loads against the results of other reference software programs. One change to the house model is made at a time, and the results are compared against each relevant test case results from reference software. In addition to simply comparing the overall heating and cooling energy consumption for a given test case, comparisons are made in the change in energy consumption from one case to the other. For example, heating energy consumption is evaluated for the base house, Case L100. For the next Case, L110, the modelled infiltration rate is changed. When evaluating the results, the heating energy consumption of the house with higher ventilation rates (e.g. L110) and the difference in space heating that occurred from one case to the other are both examined.

For whole house Class II test cases, HOT2000 results are compared against those from Blast 3.0, DOE 2.1 and SRES/SUN 5.7. Heating results are calculated using a Colorado climate file, and cooling results are based on a Las Vegas weather file, with the exception of the passive solar cases where cooling is calculated using the Colorado climate. The base case house footprint is 27 ft x 57 ft (8.2 m x 17.4 m) and is depicted in Figure 2. There is a series of passive solar test cases that use the same footprint, but have only South facing windows, more thermal mass, better windows and more insulation.

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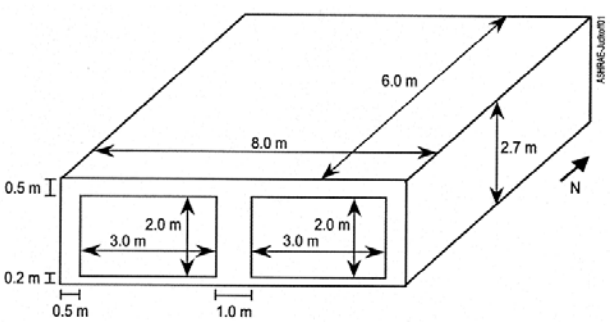
Figure 1: Diagram of base building for Cases L100A



through L324A (ASHRAE 2014).

Class I reference software include ESPr, Blast 3.0, DOE 2.1, SRES/SUN 5.7, SERIRES 1.2, S3PAE, TRNSYS, and TASE. The Class I base-building plan is a low-mass, rectangular single zone with no interior partitions (Figure 2). The low-mass basic tests (Cases 600 through 640) utilize lightweight walls, floor, and roof and test window orientation, shading devices, and setback thermostat. Similar tests are done for the high-mass basic tests (Cases 900 through 940), but utilize masonry walls and concrete slab floor.

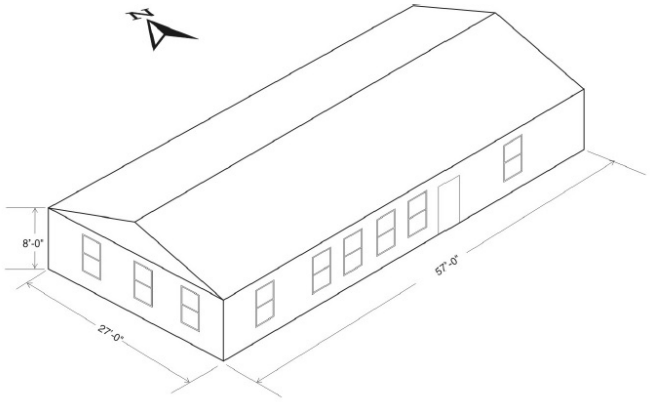


Figure 2: Diagram of zone model used for basic and in-depth test cases for Class I tests (ASHRAE 2014).

RESULTS

Whole House Energy Analysis - Class II Results

Class II test cases are geared towards whole building energy analysis and provide the overall evaluation of HOT2000.

The results of HOT2000 agreed well with those of the other software. Figure 3 and Table 1 present the results of the heating energy consumption and Figure 4 and Table 2 present the cooling results for the Class 2 test cases in relation to the respective confidence intervals. For heating, 16 of the 20 cases saw the results from HOT2000 fall within the confidence intervals, and all cases were within 10%. For sensible cooling load, 13 of the 16 cases were within the confidence intervals, with two of the three being less than 1% outside the intervals.

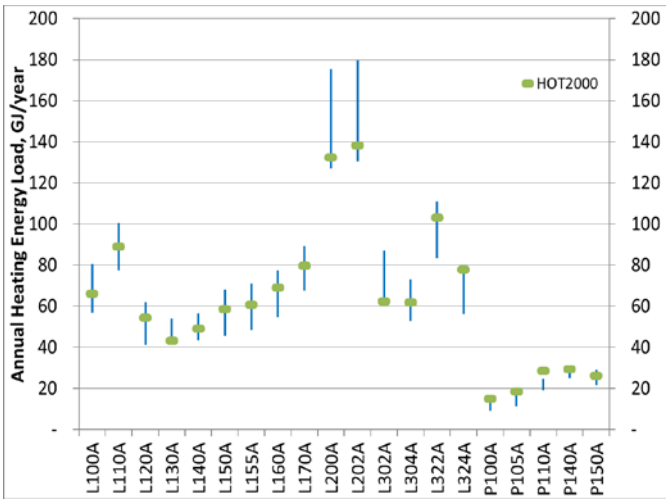


Figure 3: HOT2000 Class 2 annual heating loads compared to the range of Std 140 reference results

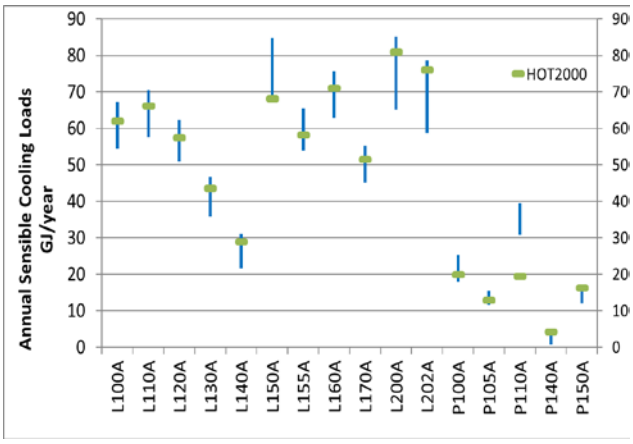


Figure 4: HOT2000 Class 2 annual sensible cooling loads compared to the range of Std 140 reference results

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Table 1: ASHRAE Standard 140 Class II Annual Heating Loads in GJ(= ~10^6 Btu/year)

Test case	Description	Min. Confidence	Max Confidence	HOT2000
L100A	Base case	57.0	80.6	65.9
L110A	High infiltration test	77.4	100.5	88.9
L120A	Well insulated walls and roc	41.1	61.8	54.2
L130A	Double low-e windows	41.8	54.0	43.3
L140A	Zero window area	43.3	56.5	49.1
L150A	All south-facing windows	45.5	68.0	58.5
L155A	South facing overhangs	48.3	70.9	60.6
L160A	East/West window orientatic	54.4	77.5	69.1
L170A	No internal loads	67.7	89.5	79.7
L200A	Low efficiency construction	127.0	175.3	132.5
L202A	Low exterior solar absorptan	130.5	179.6	138.2
L302A	Uninsulated slab-on-grade	63.4	86.9	62.3
L304A	Perimeter insulated slab	52.6	73.2	61.9
L322A	Uninsulated full basement	83.3	110.9	103.2
L324A	Insulated full basement	56.1	77.6	77.8
P100A	Passive solar base case	9.0	15.4	15.0
P105A	South window overhangs	11.1	18.0	18.5
P110A	Low mass version of P100	19.2	24.8	28.6
P140A	Zero window area	24.8	30.4	29.4
P150A	Even window distribution	21.6	29.0	26.1

Table 2: Standard 140 Class II Results – Annual Sensible Cooling Loads in GJ (= ~10^6 Btu/yr)

Test case	Description	Min Confidence	Max Confidence	HOT2000
L100A	Base case	54.5	67.3	62.0
L110A	High infiltration test	57.7	70.5	66.1
L120A	Well insulated walls and roc	51.0	62.4	57.4
L130A	Double low-e windows	35.8	46.7	43.4
L140A	Zero window area	21.7	31.2	28.8
L150A	All south-facing windows	68.3	84.8	68.1
L155A	South facing overhangs	53.9	65.5	58.1
L160A	East/West window orientatic	62.9	75.6	70.9
L170A	No internal loads	45.2	55.2	51.4
L200A	Low efficiency construction	65.1	85.2	80.8
L202A	Low exterior solar absorptan	58.7	78.7	76.0
P100A	Passive solar base case	18.1	25.3	19.8
P105A	South window overhangs	11.5	15.4	12.8
P110A	Low mass version of P100	30.8	39.5	19.3
P140A	Zero window area	0.7	4.1	4.1
P150A	Even window distribution	12.1	16.9	16.2

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Software Algorithm Tests - Class I Results

As stated, Class I results in Std 140 are detailed diagnostic tests intended for use with building energy simulation software tools having simulation time-steps of one hour or less. HOT2000 is not an hourly simulation program, and as such, a number of Class I validation tests were not appropriate for comparative purposes. However, the results of some of the test cases in Std 140 are presented with monthly or yearly heating and/or cooling energy consumption, which can be compared to HOT2000 results.

The space heating results for Class I test cases (shown in Figure 5) were even better than those from Class II. Only one result was outside the confidence intervals, and it was by only 0.4%.

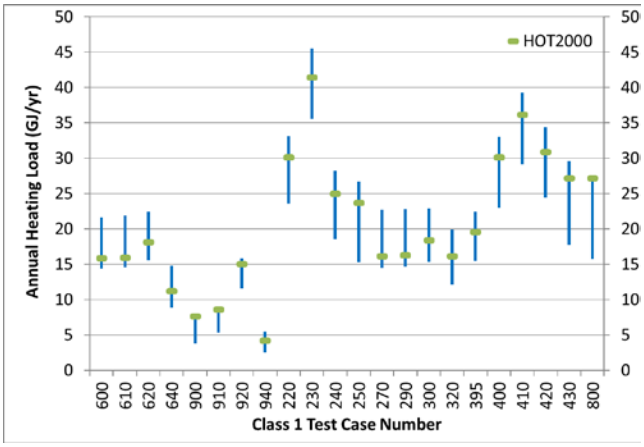

Figure 5: HOT2000 Class 1 annual heating loads compared to the range of Std 140 reference results

For cooling (Figure 6), results were not as close, with over half of the Class I space cooling results falling outside the confidence intervals.

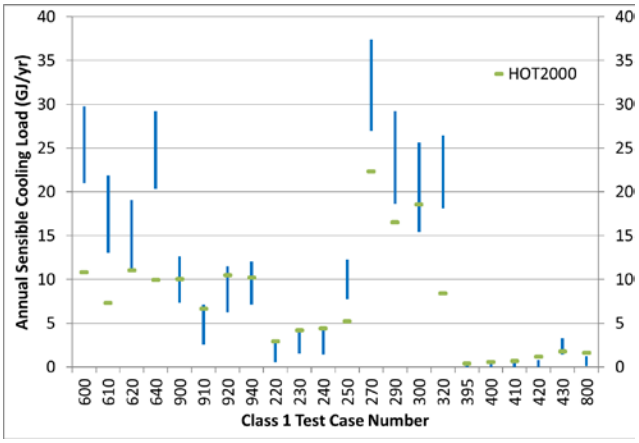

Figure 6: HOT2000 Class 1 annual sensible cooling loads compared to the range of Std 140 reference results

In the Space-Cooling Equipment Performance Tests series, HOT2000 did not perform well, being between 28% and 78% beyond the range of results of the reference software for cooling energy consumption. HOT2000 under-predicted cooling energy consumption in all cases except for the part load test cases (CE130 and CE140) where it over-predicted consumption. It is likely that the larger differences in calculated cooling energy consumption are in part due to how HOT2000 evaluates latent cooling loads. In addition, the cooling loads used in the majority of the Space-Cooling Equipment Performance Tests series are much higher than the loads associated with houses, and can be beyond the range of the equations developed for the HOT2000 cooling load calculations.

All of the Space-Heating Equipment Performance Tests were within ±5% of the results of the reference software.

DISCUSSION

Trends in the Results

Evaluation of Class I (algorithms) and Class II (whole house) tests showed somewhat different trends. HOT2000 showed better results for the whole house energy analysis (Class II tests) for space heating and space cooling loads. Space heating algorithms (Class I test cases) of HOT2000 meet the acceptance criteria; however, the space cooling load predictions are substantially lower when compared to hourly based models.

As presented, the HOT2000 annual heating load results were mostly all within the range of results from the Std 140 reference software results. The only two cases where HOT2000's results were beyond 5% were for Case L302A, the uninsulated slab-on-grade, where HOT2000's results were 6.9% above the confidence intervals, and Case P110A, which is a passive solar case with low thermal mass, where HOT2000's results were 9.3% above the confidence intervals.

Slab on Grade Results

As explained, when comparing results of HOT2000 to those of the reference software, both the overall heating and cooling energy calculated, as well as the difference in energy use between cases needs to be examined. The modelled slab-on-grade heating results were within 7% of those of other programs for individual cases, however, the differences between the uninsulated slab-on-grade case (L302) compared to the open crawlspace (shown as L302-L100 in Fig. 7) and to the perimeter insulated slab-on-grade (shown as L302-L304 in Fig. 7) followed a different trend in HOT2000 compared to the other programs. The heating energy consumption in HOT2000 was lower for the slab-on-grade compared to the open crawlspace (L100), whereas

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it was the opposite for the other three programs. Adding perimeter insulation around the slab-on-grade had a similar impact in the reference software of saving roughly 10 million Btus (10.5 GJ) whereas it only generated a marginal 0.4 million Btu (0.42 GJ) savings in HOT2000.

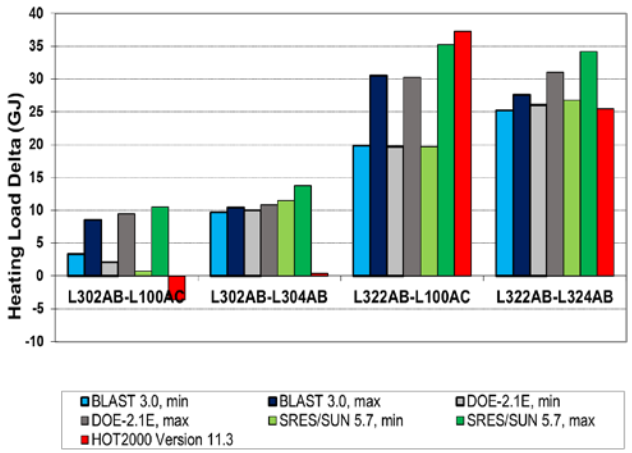

Figure 7: Differences in annual heating load for impacts of foundations

It was not possible to model all the foundation cases specified in Std 140 in HOT2000. The manual lays out two methods for modeling the heat loss: the ASHRAE method and a soil coefficient method. The latter method models the soil as a large amount of mass in contact with ambient air. In other words, a U-value is assigned to the soil and it is modeled as an above grade component with no thermal mass. Both of these methods assume that the heat loss is driven by the ambient air temperature and ignore the heat loss to the deep ground.

HOT2000 uses the BASESIMP heat loss method to model foundations. This is a detailed model which takes into account seasonal soil temperature variations and heat loss to both the deep ground and the surface (Beausoleil-Morrison, 1999). It is a regression-based algorithm developed from thousands of parametric finite-element simulations. This method has been validated against real houses and was found to give accurate results..

All South Facing Windows

The majority of the cases where cooling loads were outside the confidence intervals have all-south facing windows. The exception being cooling loads for the passive solar cases for Class I (high mass with south facing windows) that were all within the confidence intervals. However, this is likely a combination of the lower cooling load associated with all south-facing windows being counter-balanced by the higher cooling load associated with the thermal mass.

Figure 8 presents the results of the heating and sensible cooling loads for cases with even window distribution, minus the results calculated with all-south facing windows (L100-L150 for the base case and P150-P100 for passive solar).

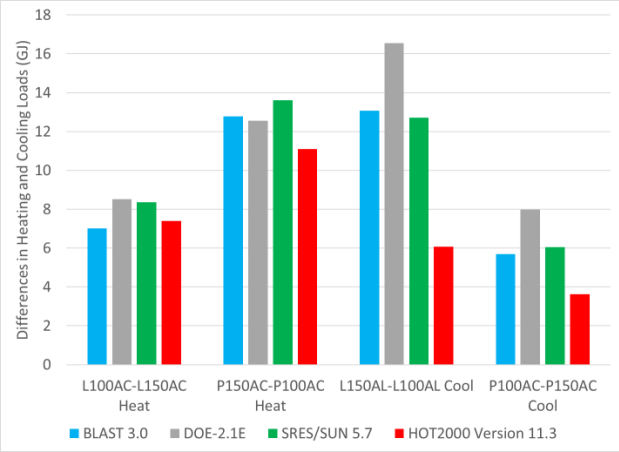

Figure 8: Class 1 – Differences in annual heating and sensible cooling loads with different window distributions

For heating, in a less insulated building with no thermal mass, going from an even window distribution (L100) to all south-facing (L150) reduces heating loads by 7.0 million Btu (7.4 GJ) or 11.2% in HOT2000 compared to an average of 8.0 million Btu (8.4 GJ) or 12.5% in the other software. For the more insulated, more massive building, going from an even window distribution (P150) to all south-facing windows (P100) decreases heating loads by 10.5 million Btu (11.1 GJ) or 42.5% in HOT2000 compared to 13.0 million Btu (13.7 GJ) or 51.6% in the other software.

For cooling, in a less insulated building with no thermal mass, going from an even window distribution (L100) to all south-facing (L150) increases cooling loads by 5.8 million Btu (6.1 GJ) or 9.9% in HOT2000 compared to an average of 14.1 million Btu (14.9 GJ) or 24.2% in the other software. For the more insulated, more massive building, going from an even window distribution (P150) to all south-facing windows (P100) increases cooling loads by 3.4 million Btu (3.6 GJ) or 22.1% in HOT2000 compared to an average of 6.6 million Btu (7.0 GJ) or 47.8% in the other software.

Thermal Mass and Cooling

Figure 9 shows differences in annual heating and sensible cooling loads for cases with (P100) and without (P110) thermal mass. For space heating, eliminating the thermal mass resulted in a roughly 30% higher increase in space heating for HOT2000 compared to the reference software,

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which indicates that thermal mass had a higher impact in reducing space heating load in HOT2000 compared to the other software. The impact of thermal mass on cooling load in HOT2000 does not follow the same trend as the other software. As in the case of the other software, thermal mass can help reduce cooling loads by tempering the rise in indoor temperatures associated with solar gains. Essentially, it spreads out the impact of solar gains on indoor temperatures, shifting some of the loads to the evening. Although it will increase the indoor air temperature, in some cases it will still be below the cooling setpoint temperature, thus reducing annual cooling loads. Figure 9 shows that while cooling loads are on an average 12 million Btus (12.7 GJ) or 59.4% higher without thermal mass in the other software, they are 0.5 million Btus (0.5 GJ) or 2.7% lower in HOT2000.

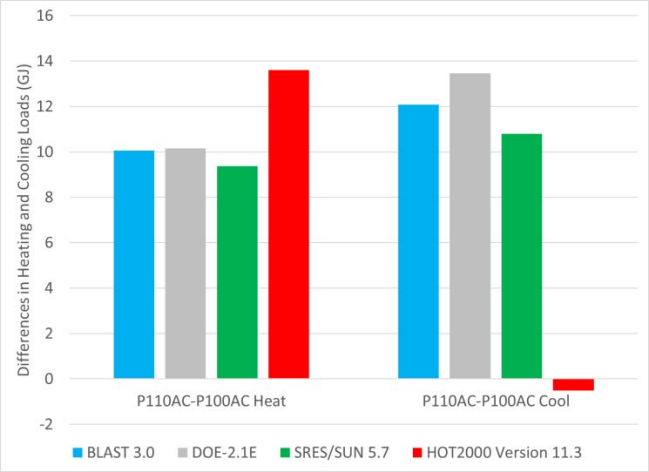

Figure 9: Differences in annual heating and sensible cooling loads for cases with and without thermal mass.

Improvements in HOT2000

Previous versions of HOT2000 have been tested using Std 140. Haltrecht and Fraser (1997) tested HOT2000 version 7.15 using HERS BESTEST, which is now defined as Class II tests in Std 140. The space heating results using HOT2000 version 11.3 are similar to those of the 1997 tests with improvements in results for cases L322 and L324 (uninsulated, and insulated full basements).

Since version 7.15, HOT2000's basement model has been updated, and now has results that are within the confidence intervals instead of being above it. The sensible cooling load results from Version 11.3 are also much better than they were. Of the 16 cases tested by Haltrecht and Fraser, only 6 were within the results obtained from the reference software compared to 10 with version 11.3. The one test case where the cooling results did not improve is for case P110 (passive solar case with no thermal mass) where version 7.15 calculated cooling loads that were 23.6% lower than the confidence interval compared to 37.3% lower for version 11.3.

Cooper (2011) tested HOT2000 version 10.51 using the Class I tests of Std 140. Results for space heating loads from version 11.3 showed a marked improvement compared to previous version 10.51. Of the eight cases that were outside the confidence intervals with version 10.51, only one remained with version 11.3 (Case 910 – South windows with overhangs). Even that one case show good improvement; with version 10.51 case 910 was 33.6% above the confidence intervals, while it was only 0.4% above the confidence interval for version 11.3.

The cooling results for version 11.3 were slightly better than those of version 10.51 but the number of cases outside the confidence interval is similar between both versions.

Limitations of ASHRAE Standard 140

Cooper (2011) questioned whether the test cases and weather data employed in Std 140 were representative of Canadian conditions. He pointed out that HOT2000 was developed as a tool to evaluate Canadian homes, using a combination of curve-fits and detailed building physics. The curve fits were derived using an hour-by-hour computer simulation with actual weather data for five Canadian locations. The weather data used for test cases in Std 140 is not representative of Canadian climate. Solar heat gains in cases with south windows will be at the limit (or beyond) what HOT2000 is designed to simulate due to the cases having very high window area (over 20% of the floor area) and the weather file having winter insolation two to three times what is typical for Canada.

Haltrecht and Fraser questioned whether the Std 140 test cases were sufficient. There are some important elements of residential energy consumption that are not being tested with the current test cases. For example, Std 140 provides a set infiltration rate to model and does not actually test a program's capability of predicting infiltration. This is an important aspect which should be tested in a program since infiltration can account for 16% to 35% of the heating energy requirement in existing houses in Canada (Scanada, 1996).

FURTHER FIELD TESTING OF HOT2000

The real testing of energy simulation program should include field validation of overall energy use calculations. Currently, we are conducting field evaluation of 35 homes across Canada ranging from pre-1990 to current practice to very efficient net-zero energy performance levels. The field evaluation will include assessment of houses, HOT2000 modelling, measured utility data, weather

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normalization and well-proven reconciliation methods. The field testing results should be available by summer of 2018.

IMPLICATIONS TO HOUSING PROGRAMS

The ASHRAE Std 140-2014 testing of HOT2000 ver 11 showed energy use predictions within the ±5% for whole house (Class II) test cases. HOT2000 is mainly used for whole house energy analysis of low-rise residential houses (NBC Part IX 2015). The focus of energy analyses is on predictions of space heating, ventilation and domestic hot water energy use. Cooling energy requirements in Canadian climates account for much lower portion of overall annual energy use – in the range of 3% in maritimes, prairies and northern climates to a maximum 8% in southern Ontario climates. The results of Std 140 Class II test cases certainly raise the confidence level, consistency and dependability of HOT2000 energy use predictions for the delivery of Canadian housing programs.

CONCLUSION

HOT2000 version 11.3 heating results were mostly within the range of Std 140 reference software for both Class I and Class II tests.

The combination of differences between the solar gains and thermal mass were more pronounced in the cooling load calculations, which resulted in HOT2000 being outside the confidence intervals in over half of the modelled cases.

Overall, HOT2000 predictions for whole house energy use, for most of Std 140 test cases were within acceptable ranges.

ACKNOWLEDGEMENT

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