EXPERIENCE TESTING ENERGYPLUS WITH THE IEA HVAC BESTEST E300-E545 SERIES AND IEA HVAC BESTEST FUEL-FIRED FURNACE SERIES

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ABSTRACT

The EnergyPlus building energy simulation software has been tested using the IEA HVAC BESTEST E300-E545 series of tests and the IEA HVAC BESTEST Fuel-Fired test series. The first is a series of comparative tests for a single-zone DX cooling system which tests a program's ability to model hourly loads over an expanded range of performance conditions for various air mixing, infiltration, thermostat set-up, overload conditions, and various economizer control schemes. The second is a series of analytical/semi-analytical comparative tests for a single-zone fuel-fired furnace which tests a program's ability to model steady state performance, varying outdoor and indoor conditions, and circulating and draft fan operation.

Each of these HVAC BESTEST series were used to test EnergyPlus prior to new public releases. The application of these tests proved to be very useful in several ways: a) revealed algorithmic errors which were fixed, b) revealed algorithmic shortcomings which were improved or eliminated through the use of more rigorous calculations for certain components, and c) caught newly introduced bugs before public release of updates.

INTRODUCTION

Formal independent testing has been an integral component in the development of EnergyPlus, a building energy simulation program with the latest release by the U.S. Department of Energy in April 2006 (EnergyPlus 2006). Comprehensive testing of building energy analysis software is a difficult task given the infinite combinations of inputs that may be entered and the difficulties in establishing truth standards for all but the simplest cases. Testing has been guided by a comprehensive test plan which includes the following types of tests:

- Analytical tests which compare against analytical solutions,
- Comparative tests which compare against other software,
- Sensitivity tests which compare small input changes versus a baseline run,
- Range tests which exercise the program over wide ranges of input values, and
- Empirical tests which compare against experimental data.

HVAC system tests include both steady-state cases and cases with time-varying loads and weather conditions. Steady-state tests are valuable to confirm the basic physics of the simulation models. Time-varying cases exercise HVAC system simulations over a broader range of operating conditions.

Published test suites which include reference results have been applied as much as possible in order to take advantage of the efforts of others to develop well-defined, reproducible tests. Through the efforts of the International Energy Agency (IEA) and their Solar Heating and Cooling Programme (SHC), Task 22 – Building Energy Analysis Tools, several test suites were developed to test the ability of building energy analysis programs to model the performance of HVAC equipment. Two of these test suites as described below were used by EnergyPlus and other whole building energy analysis programs to perform analytical tests and/or comparative tests. The testing procedures and results of applying these procedures are presented in the following referenced reports listed at the end of this technical paper: Neymark and Judkoff 2004 and Purdy and Beausoleil-Morrison 2003.

The results obtained by EnergyPlus with both of these test suites are briefly described in this technical paper. Complete reports presenting the results of all EnergyPlus tests are posted on the EnergyPlus web site (Henninger and Witte 2006a and 2006b).

HVAC BESTEST CASES E300 – E545

HVAC BESTEST Cases E300-E545 test a program's modeling capabilities on the air-side of the coil in hourly context over an expanded range of performance conditions. These cases also test the ability to model outside air mixing, infiltration, thermostat set-up, overload conditions, and various economizer control schemes. The cases are grouped as follows:

- Case E300 – Base Case
- Additional E300 Series Cases – Cases E310, E320, E330, E340, E350 and E360
- Economizer Series (E400 series) Cases – E400, E410, E420, E430 and E440
- No Outside Air Series (E500 series) Cases – E500, E510, E520, E522, E525, E530, E540 and E545.

Test Descriptions

Base Case Building and Mechanical System (Case E300)

The basic test building is a square 196 m^2 single zone (14 m wide x 14 m long x 3 m high) with no interior partitions and no windows. The building is intended as a near-adiabatic cell with cooling load driven by user specified internal gains, infiltration and outside air. For further details refer to Section 1.3 of the HVAC BESTEST report (Neymark and Judkoff 2004).

The mechanical system is a simple unitary vapor compression cooling system with air cooled condenser and indoor evaporator coil, 100% convective air system, single speed, draw-through air distribution fan, indoor and outdoor fans cycle on/off with compressor, no cylinder unloading, no hot gas bypass, crankcase heater and other auxiliary energy are 0. There is a non-proportional-type thermostat, heat always off, cooling on if zone air temperature >25.0°C and heat extraction rate is assumed to equal the maximum capacity of the equipment for the hour's environmental conditions. For further specifications and the equipment's full-load and part-load performance, see Section 1.3.1.4 of the HVAC BESTEST report (Neymark and Judkoff 2004).

Other Test Cases

Using this base case test building and mechanical cooling equipment the following test cases which carefully change one test parameter at a time were performed with EnergyPlus:

Case E300 – Base case with 15% outside air
Case E310 – Case E300 with high latent load
Case E320 – Case E300 with high infiltration rate
Case E330 – Case E300 with high outside air rate
Case E340 – Case E300 with infiltration/outside air
Case E350 – Case E300 with thermostat set-up
Case E360 – Case E300 with undersized equipment
Case E400 – Case E300 with economizer with temperature control
Case E410 – Case E400 with economizer with compressor lockout
Case E420 – Case E400 with economizer with outdoor temperature limit = 20°C
Case E430 – Case E400 with economizer with enthalpy limit
Case E440 – Case E430 with economizer with outdoor enthalpy limit
Case E500 – Case E300 with 0% outside air
Case E510 – Case E500 with high part load ratio
Case E520 – Case E500 with low entering dry bulb (EDB) temperature = 15°C
Case E522 – Case E520 with low EDB = 20°C
Case E525 – Case E520 with high EDB = 35°C
Case E530 – Case E500 with dry coil
Case E540 – Case E530 with dry coil, low EDB = 15°C
Case E545 – Case E540 with dry coil, high EDB = 35°C

Weather Data

A TMY2 format weather data file (NEW-ORL.TM2) provided with the test suite was used to perform hourly annual simulations for each test case.

EnergyPlus Modeling and Methodology Issues

With nearly any published test suite, issues and choices arise when modeling the tests with a specific software package. The issues that arose with using EnergyPlus are summarized below.

Building Envelope Construction

The specification for the building envelope required that the exterior walls, roof and floor be made up of one opaque layer of insulation (R=325 m^2-K/W) with differing radiative properties for the interior surface and exterior surface. To allow the surface radiative properties to be set at different values, the exterior wall, roof and floor had to be simulated as two insulation layers, each with R=162.5 m^2-K/W.

HVAC System

For modeling of the simple unitary vapor compression cooling system, the EnergyPlus Unitary Air-to-Air Heat Pump model was utilized. The Heat Pump model was the only DX cooling system available in EnergyPlus which allowed both a draw-thru fan configuration and an economizer. Since cooling only was required during the simulation, the heat pump controls were set to prevent operation of the heat pump in the heating mode.

Compressor and Condenser Fan Breakout

The rated COP required as input by the EnergyPlus DX coil model requires that the input power be the combined power for the compressor and condenser fans. As such, there are no separate input variables or output variables available for the compressor or condenser fan. The only output variable available for reporting in EnergyPlus is the DX coil electricity consumption which includes compressor plus condenser fan.

Results of Testing

As one of several participants during the period when the HVAC BESTEST E300-E545 specification was being developed, the EnergyPlus development team had opportunity to compare their results with the results of five other programs. Examination of results and comparison of results with other programs allowed for identification of several deficiencies which were then corrected to achieve the temperature and humidity control desired and give better agreement with other programs.

Space Temperature Out of Control

During the early rounds of testing with EnergyPlus version 1.0.2.004 when results from other programs were not yet available, it was noticed that the space temperature was not always maintained at 25°C in cases E300 (base case) and E310 (high latent loads). There were hours during periods of low or no internal loads when the air-conditioner did not cycle on to provide cooling and subsequently the space temperature rose to as high as 30°C. An error was discovered with calculating outlet conditions from the cooling coil when dry conditions occurred. Subsequent code changes corrected this problem which then allowed space set point temperatures to be maintained. While resolving this problem it was also decided to revise the calculation for the humidity ratio leaving the cooling coil. In the psychrometric routines the heat of vaporization (h_{fg}) function for converting a zone latent load into a load in the HVAC system was replaced with the h_g function (enthalpy of saturated water vapor) as per ASHRAE equations. This change occurred in EnergyPlus version 1.0.3.007.

Weather Data Interpolation

EnergyPlus has the capability to perform sub-hourly time step simulations. For HVAC BESTEST cases E300-E545 a TIMESTEP = 4 was used which means that the simulation was performed for 15 minute time increments each hour. This approach then requires that the hourly weather be interpolated to get weather for each 15 minute increment. When comparing EnergyPlus version 1.0.3.005 results to that for other programs, it was discovered that the EnergyPlus outdoor dry bulb temperature was one hour out of phase with some of the other programs. Detailed examination of these results as well as results from other test suites resulted in subsequent improvements to the interpolation procedure.

Low Space Humidity Levels

Initial simulations with EnergyPlus version 1.0.3.005 for cases E530, E540 and E545 (all dry coil cases) resulted in very low humidity levels in the space. This situation was due to EnergyPlus' initialization methodology and was alleviated by introducing a small amount of infiltration during the first week of the simulation. Even though EnergyPlus initializes all nodes to the outdoor humidity ratio at the beginning of the simulation, conditions during the simulation warmup days overdry the zone for these cases. Without the infiltration during the first week, there is no source of moisture to overcome the overdrying and establish the desired equilibrium. For cases E530, E540 and E545, a constant infiltration load of 1.0 m3/s was turned on for January 1 through January 7 and then turned off. This problem occurred only because these test cases are unrealistic because there were no sources of moisture. Simulation of actual buildings will normally have moisture introduced by infiltration, ventilation air and internal gains such as people.

Space Humidity Ratio Algorithm

During later rounds of testing a comparison of EnergyPlus results to the results of other programs indicated that the maximum space humidity ratios for Cases E500 through E545 were high. Further investigation into the problem indicated that these maximum values were actually happening one to two hours after the internal loads and HVAC system had been scheduled off. This was occurring because of the way the moisture balance algorithm had been set up. Internal loads during each time step of the simulation in EnergyPlus were being accounted for after the HVAC system simulation. With EnergyPlus version 1.1.0.004 and subsequent releases the space internal loads are now accounted for before the system simulation. This brought the EnergyPlus results more in line with the results of the other programs.

Figures 1 and 2 show selected results for various versions of EnergyPlus as some of these issues were addressed and corrected. Figure 3 illustrates the range of results that were obtained with various whole building energy analysis programs and was taken from Neymark and Judkoff 2004.

HVAC BESTEST FUEL-FIRED FURNACE CASES 1A – 2C

The HVAC BESTEST Fuel-Fired Furnace test suite provides an analytical verification and comparative diagnostic procedure for testing the ability of whole building simulation programs to model the performance of fuel-fired furnaces. Specific cases are designed to test a program with respect to the following components: furnace steady-state efficiency, furnace part load ratio, outdoor temperature, indoor set point temperature, circulating fan operation and draft fan operation.

Test Descriptions

Base Case Building and Mechanical System (Case 1a)

The basic test building is a rectangular 48 m^2 single zone (8 m wide x 6 m long x 2.7 m high) with no interior partitions and no windows. The building is intended as a near-adiabatic cell with energy transfer through a single surface to drive the heating loads. Energy is transferred to the outdoors through the roof. For further details about the building envelope refer to Section 2.1 of the HVAC BESTEST Fuel-Fired Furnace report (Purdy and Beausoleil-Morrison 2003).

The mechanical system is a simple sealed combustion, fuel-fired, convective heating system with the following characteristics:

- Heating capacity: 10,000 W
- Indoor fan power: 200 W
- Draft fan power: 50 W
- Full load efficiency: 80%
- No pilot light
- No air or thermal losses from distribution ducts
- Combustion air drawn directly from outdoors.

There is a non-proportional type thermostat, cooling always off, heating on if zone air temperature <20.0 °C. For further specifications and the equipment's full-load and part-load performance, see Section 2.2 of Purdy and Beausoleil-Morrison 2003.

Other Test Cases

Using this base case test building and mechanical heating equipment the following eleven test cases were performed with EnergyPlus:

Case 1a – Base case
Case 1b – Efficiency test
Case 1c – Simple part load test
Case 1d – No load test
Case 1e – Complex part load test
Case 1f – Circulating fan test
Case 1g – Cycling circulating fan test
Case 1h – Draft fan test
Case 2a – Realistic weather
Case 2b – Setback thermostat
Case 2c – Undersized furnace

Weather Data

A set of five weather files in WYEC2 format are provided with the test suite, each containing three months of hourly weather data (January 1^{st} – March 31^{st}).

- Constant outdoor temperature of -30°C (used with Cases 1a and 1b)
- Constant outdoor temperature of 0°C (Case 1c)
- Constant outdoor temperature of 20°C (Case 1d)
- Varying sinusoidal outdoor temperature over each 24-hour period from -20°C to +20°C (Cases 1e – 1h)
- Realistic varying weather from a cold winter location (Cases 2a – 2c).

EnergyPlus Modeling and Methodology Issues

During the development of EnergyPlus models for the eleven test cases described above and during subsequent rounds of simulations and comparing test results to the analytical results and results of other programs, various issues arose or changes to the simulation code were required to improve the accuracy of EnergyPlus results. Some of these issues and changes are discussed below.

Surface Convection Coefficients

The specification for the building envelope requires that the exterior walls and floor are made up of one opaque layer of insulation (R=100 m^2-K/W) to approach an almost adiabatic condition while the roof was constructed of opaque layer with an R=0.14 m^2-K/W. The heating requirement in the zone was due to the heat transfer through the roof surface. The analytical solution assumed that the inside and outside surface film coefficients for the roof surface were constant at 20 W/m^2-K. Prior to EnergyPlus version 1.1.0.018 released in April 2003, the user could not independently specify these coefficients. In accordance with ASHRAE accepted methodology, EnergyPlus recognizes the difference between horizontal and vertical heat transfer through surfaces and assigns different convection coefficient values for walls, ceilings and floors depending on the type of convection coefficient chosen. For the case of NO WIND and NO SUN and with INSIDE CONVECTION ALGORITHM and OUTSIDE CONVECTION ALGORITHM set equal to SIMPLE, EnergyPlus sets the surface film coefficients for the roof as follows:

E-Plus Interior Film	4.04	W/m^2-K
E-Plus Outside Film	8.23	W/m^2-K

The values used in the Fuel-Fired Furnace analytical solution were so much greater than the EnergyPlus values, that even by adjusting the roof R-value in EnergyPlus to a very small number, i.e., R=0.0001 m^2-K/W, the resulting EnergyPlus roof heat loss of 9,079 W was still much lower than the 9,998 W indicated in the analytical solution for Case 1a. Therefore, the roof area in EnergyPlus had to be increased from 48 m^2 to 101.16 m^2 in order to achieve the desired 9,998 W heat loss for Cases 1a, 1b, 1c and 1d. For Cases 1e through 1h where the outdoor temperature varied sinusoidually over a 24-hour period, the roof area was set to 87.96 m^2 in order to match the heat loss for the first hour of the day to that from the analytical solution. For all other hours in the day, there was a slight difference between the Fuel-Fired Furnace analytical heat loss and the EnergyPlus heat loss through the roof, differing by < 0.3%. Cases 2a, 2b and 2c used the same building model as Case 1h.

With EnergyPlus version 1.1.0.018, a new option was given to the user for specifying the inside and outside surface convection coefficients primarily for use with test suites such as the HVAC BESTEST Fuel-Fired Furnace. The new CONVECTIONCOEFFICIENTS object was used to set the inside and outside convection coefficient of the roof surface to a constant 20 W/m^2-K. This resulted in a roof heat flux of 10,000 W, which is within 0.02% of the 9,998 W from the analytical solution.

Parasitic Load for Draft Fan

Prior to EnergyPlus version 1.0.1.017 (June 2002) the EnergyPlus furnace model did not have the capability to account for parasitic electric power such as that used by the 50 W draft fan. This feature was added to the furnace model with version 1.0.1.017 which then allowed EnergyPlus to simulate the draft fan operation in Cases 1h, 2a, 2b and 2c.

Part Load Performance for Heating Coil

Initial versions of EnergyPlus did not have the capability to simulate part load operation of a gas heating coil. With the HVAC BESTEST Fuel-Fired Furnace test suite requiring this capability for many of the test cases, a part load heating input ratio (HIR) curve was added to the gas heating coil model with EnergyPlus version 1.0.1.017.

Fan Run Time Fraction Versus Heating Coil PLR

Prior to EnergyPlus version 1.0.1.031 the supply fan power was not tracking the heating part load as expected for a couple of hours of the day. The fan run time jumped from approximately 0.4 to 1.0 and back to 0.4 while the heating load curve was smooth across these hours. The error was traced to the fan run time fraction versus furnace heating coil part load ratio (PLR) simulation logic. The problem was corrected by forcing the simulation to go through the air loop simulation a minimum of two times so that certain components were properly initialized.

Cycling Fan

In EnergyPlus 1.1.0.012 simulation code was added to iterate for cases with a cycling fan and cycling coil when the heater has a part load performance curve. This was needed to correctly account for the amount of fan heat, with the balance of the heating load being picked up by the heating coil.

Case 2c Undersized Furnace Input Error

For Case 2c the furnace is undersized to 5000 W. The heating capacity of the furnace in EnergyPlus must be specified by the user in two places: the furnace object and heating coil object. In the early rounds of testing with EnergyPlus, the furnace object heating capacity was set to 5000 W while the heating coil object capacity was set to 10000 W. As can be seen in Figure 5, this caused the fan power consumption to be smaller than it should have been. With EnergyPlus Version 1.2.2.030 this input error was corrected.

Results of Testing

Figures 4 and 5 present a comparison of how the EnergyPlus results have changed with each new public release and also how results compare with the analytical results. Analytical results were available for only Cases 1a – 1h. For Cases 2a – 2c the only comparison of results that were possible were with two other programs that participated in the IEA sponsored testing. Figures 6 and 7 display these comparisons with the two other programs and the analytical results for all cases with EnergyPlus results shown for the latest public release version 1.2.3.031.

CONCLUSION

Formal independent testing during the development of EnergyPlus has helped produce and ensure a more robust and credible tool. Application of published test suites such as the IEA HVAC BESTEST E300-E545 series of tests and the IEA HVAC BESTEST Fuel-Fired test series for whole building energy simulation programs has been very useful in detecting bugs and confirming that basic modeling algorithms are working properly. As discussed above, the use of both test suites with EnergyPlus allowed the developers to identify errors in algorithms and improve simulation accuracy.

ACKNOWLEDGMENT

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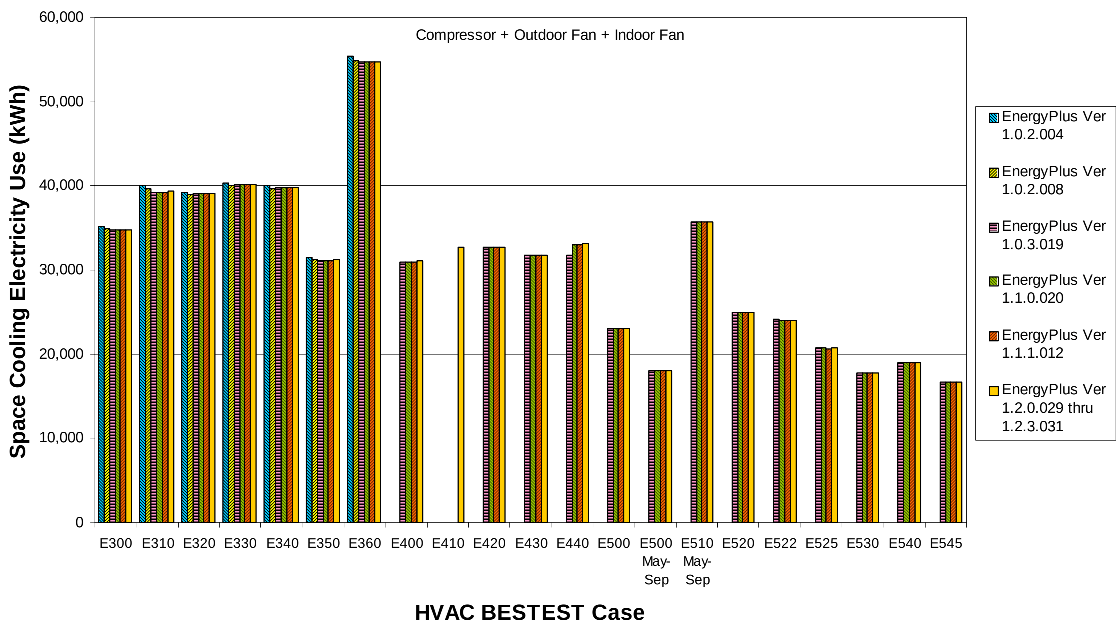

Figure 1 HVAC BESTEST Cases E300 – E545 Space Cooling Electric Consumption Results for Various Versions of EnergyPlus. *Changes in early versions due to modification of coil outlet condition algorithm and use of h_g for converting zone latent load into HVAC load. (Case E410 not possible with early versions of EnergyPlus.)*

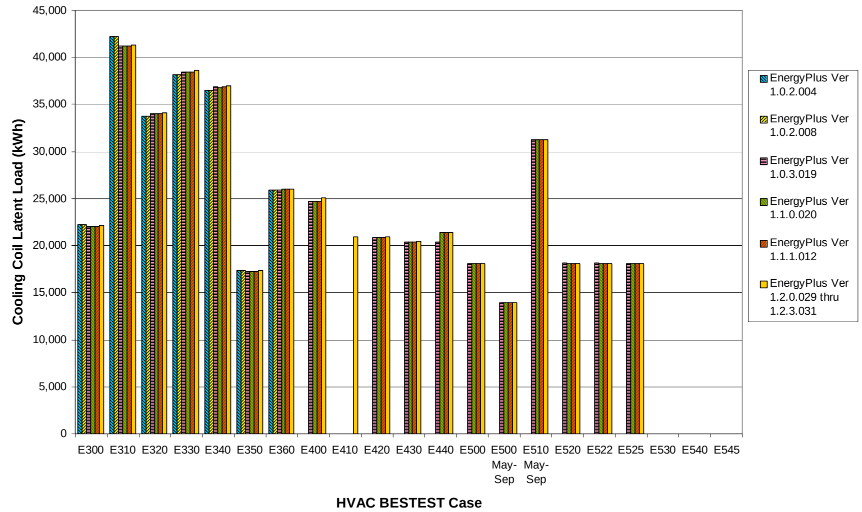

Figure 2 HVAC BESTEST Cases E300 – E545 Cooling Coil Latent Load Results for Various Versions of EnergyPlus. *Changes in early versions due to modification of coil outlet condition algorithm and use of h_g for converting zone latent load into HVAC load Cases E530, E540 and E545 Tested Dry Coil Scenarios.*

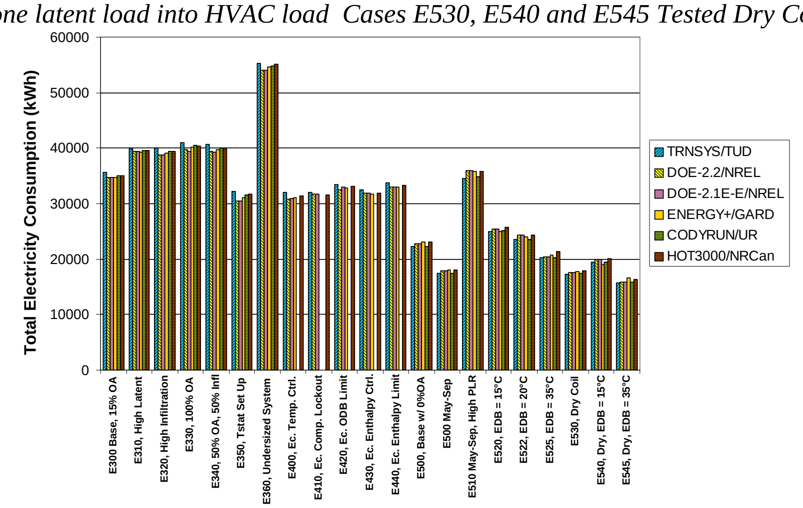

Figure 3 HVAC BESTEST Cases E300 – E545 Space Cooling Electric Consumption Results for Various Programs (Neymark & Judkoff 2004). *EnergyPlus 1.2.3.031 results are within the range of results for the other programs tested except for dry coil cases E540 and E545 which are just outside of range (+/- 1.8% difference).*

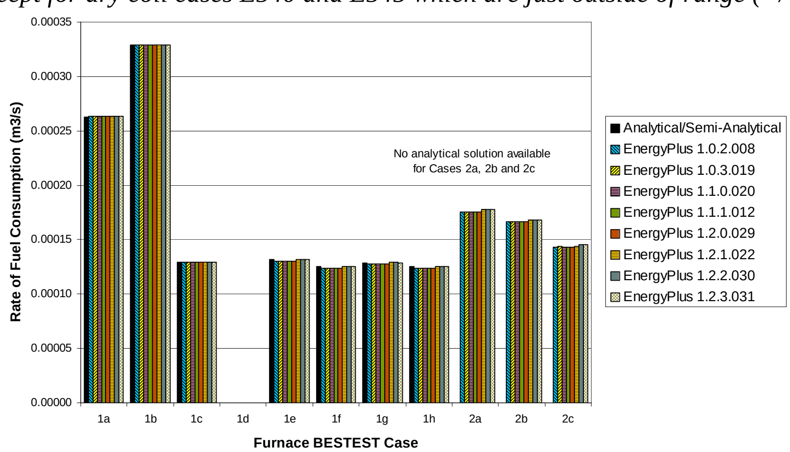

Figure 4 HVAC BESTEST Fuel-Fired Furnace Energy Consumption Results for Various Versions of EnergyPlus Compared to Analytical Results. *The latest EnergyPlus results are within +/- 0.2% of analytical results. Case 1d is a no-load test. No analytical results were available for Cases 2a – 2c.*

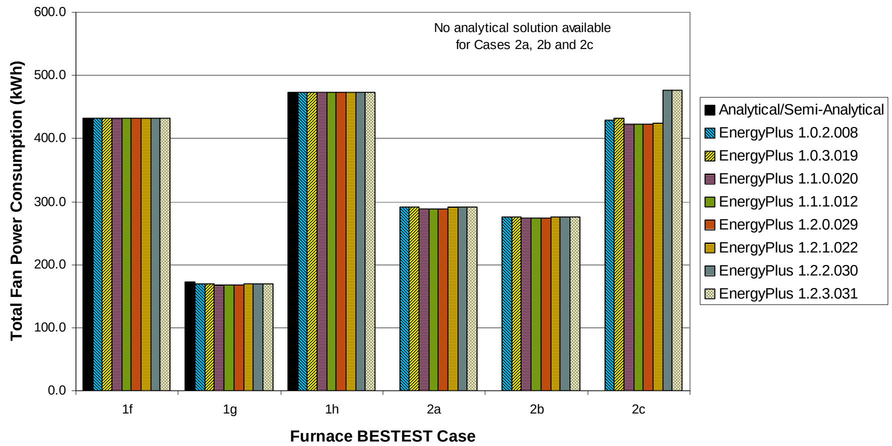

Figure 5 HVAC BESTEST Fuel-Fired Furnace Total Fan Power Consumption Results for Various Versions of EnergyPlus Compared to Analytical Results. *The latest EnergyPlus results are within –1.6% of analytical results. No analytical results were available for Cases 2a – 2c. For the undersized furnace Case 2c, the capacity of the heating coil used with early versions of EnergyPlus was set incorrectly.*

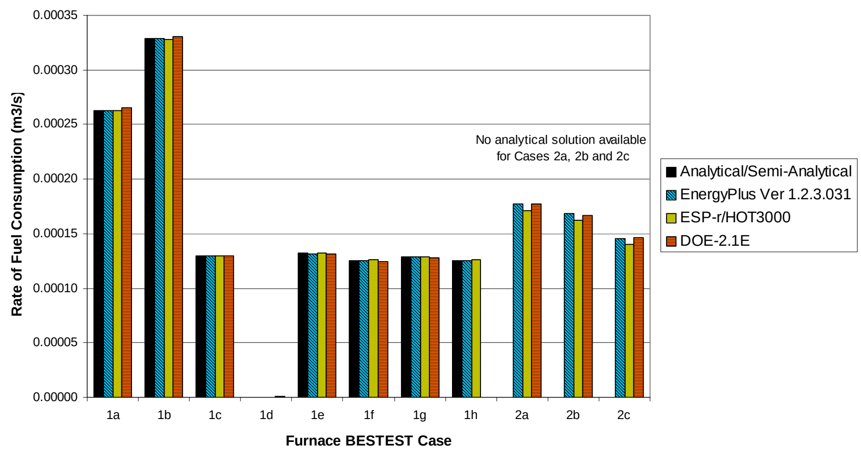

Figure 6 HVAC BESTEST Fuel-Fired Furnace Energy Consumption Results Compared to Analytical Solution and Other Programs (Purdy & Beausoleil-Morrison 2003).

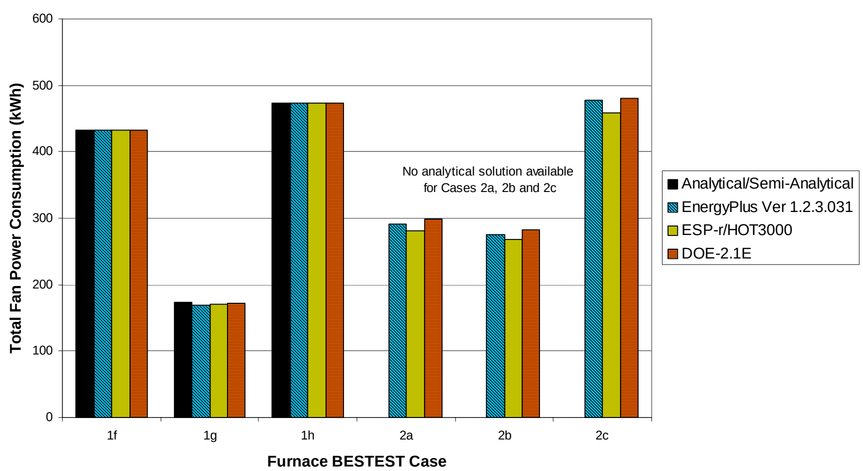

Figure 7 HVAC BESTEST Fuel-Fired Furnace Total Fan Power Consumption Compared to Analytical Solution and Other Programs (Purdy & Beausoleil-Morrison 2003).