A VALIDATION SUITE FOR FUEL-FIRED FURNACE MODELS

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ABSTRACT

Validation is the key when attempting to instill confidence in a building simulation tool. The user expects that the underlying algorithms are correct, and will have more confidence in the simulation results generated using a program that has undergone validation testing.

The IEA BESTEST (Judkoff and Neymark 1995) was developed by the International Energy Agency Solar Heating and Cooling (IEA/SHC) Task 12 and the Energy Conservation in Buildings and Community Systems Annex 21 as a test procedure for building simulation program developers. The test involves comparing simulation results, for a series of test cases, to results from state-of-the-art building energy simulation programs. In this case, the results from the simulation programs consist of heating and cooling energy demands for a test house; no simulation of the mechanical system is considered.

The HVAC BESTEST (Neymark and Judkoff 2002), developed under IEA/SHC Task 22, is an extension of the IEA BESTEST for testing mechanical system simulation models. HVAC BESTEST has its own set of results from several state-of-the-art software tools, and in some cases, analytical solutions. The focus of the first draft of HVAC BESTEST was the modelling of unitary space cooling equipment, but various HVAC equipment tests have since been developed, including forced-air fuel-fired furnace equipment and radiant heating and cooling equipment.

This paper documents a series of test cases for validating the modelling of fuel-fired furnaces in whole-building simulation programs. Analytical and semi-analytical solutions are included in addition to results from several building simulation tools.

INTRODUCTION

A suite of test cases have been developed, under the auspices of Task 22 of the International Energy Agency's Solar Heating and Cooling Programme, to evaluate the ability of whole-building energy analysis simulation programs to accurately model the performance of residential fuel-fired furnaces.

ASHRAE (2000) defines a fuel-fired furnace as a piece of heating equipment where combustion takes place within a combustion chamber. Circulating air passes over the outside surfaces of a heat exchanger such that it does not contact the fuel or the products of combustion, which are passed to the outside atmosphere through a vent.

The test cases described in this report isolate the furnace performance by simplifying the zone-side energy transfers. The simulation method isolates a single facet of the furnace model in each test case, starting with the simplest case and progressively adding complexity.

Software Validation

The primary validation constructs as defined by Judkoff and Neymark (1995) are: analytical verification—comparing the program or subroutine output to a well known analytical solution; empirical validation—comparing program or subroutine outputs to monitored data; and comparative testing— comparing a program to itself or other programs.

The limitations of each approach can be summarized as follows. *Analytical verification* necessitates very simple boundary conditions, and is best suited to simple cases for which analytical solutions are known. *Empirical measurements* can be made in real buildings, controlled test cells, or in a laboratory, but the design and operation of experiments leading to high-quality data sets is complex and expensive. *Comparative testing* includes both sensitivity testing and intermodal comparisons. This approach enables inexpensive comparisons at many levels of complexity. In practice, however, difficulties in equivalencing program inputs can lead to significant uncertainty in inter-model comparisons.

A general principal applies to all three approaches: the simpler and more controlled the test case, the easier it is to identify and diagnose sources of error.

Fuel-Fired Furnace Test Cases

These test cases complement those presented in the HVAC BESTEST report (Neymark and Judkoff 2002), which examine the performance of space-cooling equipment.

Case	Furnace Cap. (kW)	Effic-iency (%)	PLR	Outdoor DBT (°C)	Indoor Setpoint (°C)	Circ. Fan (W)	Draft Fan (W)
1a	10	100	1	-30	20	0	0
1b	10	80	1	-30	20	0	0
1c	10	80	0.4	0	20	0	0
1d	10	80	0.0	20	20	0	0
1e	10	80	0.0-0.8	sinusoidal	20	0	0
1f	10	80	0.0-0.8	sinusoidal	20	200-con	0
1g	10	80	0.0-0.8	sinusoidal	20	200-cyc	0
1h	10	80	0.0-0.8	sinusoidal	20	200-con	50-cyc
2a	10	80	0-1.0	realistic	20	200-cyc	50-cyc
2b	10	80	0-1.0	realistic	15-20	200-cyc	50-cyc
2b	5	80	0-1.0	realistic	15-20	200-cyc	50-cyc

Table 1: Furnace Test Case Description[1]

Eleven cases (*Cases 1a-1h* and *2a-2c*) have been proposed for testing the performance of residential fuel-fired furnace models. These tests are divided into two tiers. The first tier (*Cases 1a-1h*) employs simplified boundary conditions and tests the basic functionality of furnace models. Boundary conditions that are more realistic are used in the second tier (*Cases 2a-2c*), where specific aspects of furnace models are examined.

The specific test cases are designed to test the implementation of algorithms for: furnace steady-state efficiency; furnace part-load ratio; furnace fuel consumption; circulating fan operation; draft fan operation; thermostat setbacks; and undersized capacity.

The results obtained for the test cases have been compared to analytical and semi-analytical results as well as three different whole-building energy simulation tools: *ESP-r/HOT3000* (Haltrecht et al. 1999)[2], *EnergyPlus* (Crawley et al. 2002), and *DOE-2.1E* (Winkelmann et al. 1994). These results are intended to be used as a starting point for evaluating other building energy simulation tools.

Test Cases

The test cases have been developed so that many different building simulation programs, representing different degrees of modelling complexity, can be tested.

The building input data are organized case by case, with *Case 1a* being the base case. The additional test cases, *Cases 1b-1h* and *Cases 2a-2c*, are organized as modifications to the base case and ordered to facilitate their implementation.

Table 1 provides a summary of the test cases, including the outdoor dry bulb temperature (DBT), the indoor setpoint temperature as well as the furnace and fan equipment operating points. These test cases are further explored in the following sections.

It is important to note that these test case are targeted at non-explicit furnace models, the typical approach used in whole-building simulation. Rather than modelling the cycling of the burner and the furnace fans, the unit's performance is represented in a manner that represents the equipment's thermal output and fuel consumption as integrated over a time scale that is greater than the burner cycling rate.

This paper provides an overview of the test cases developed, outlines the simulation of these test cases with the reference software tools, and compares their results to the analytical and semi-analytical results. Users interested in running the test cases are encouraged to consult the full report (Purdy and Beausoleil-Morrison 2003).

CASE 1a: BASE CASE

The objective of this test case is to test a program's ability to model heating equipment performance under controlled load and weather conditions.

The base case building is designed as a near-adiabatic test cell. Energy is transferred to the outdoors through the heat transfer surface, while the furnace used is to maintain the interior setpoint temperature, i.e., there is energy transfer through a single surface to drive the heating loads.

Building Geometry Description

The base case building is a 48 m^2 floor area, single story, low mass building with rectangular geometry and internal measurements, shown in Figure 1.

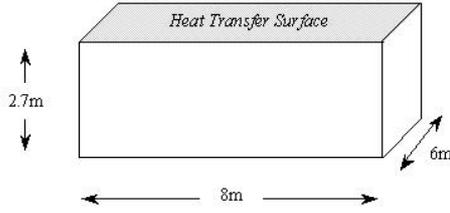*Building Envelope Thermal Properties*

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[1] PLR is the furnace part-load ratio—Equation (1).

[2] Numerous modelling capabilities have been added to ESP-r's (ESRU 2000) extensible structure, including models to predict the performance of residential HVAC equipment. This simulation environment is referred to as *ESP-r/HOT3000* throughout the paper.

Figure 1: Building with heat transfer surface.

Material properties for the exterior wall, floor, and roof are listed in Table 2. The roof is modelled as the heat transfer surface. The insulation in the walls and floors has been made very thick and resistant to heat transfer to ensure they are adiabatic.

Element	Area (m^2)	k (W/mK)	t (m)	U (W/m^2K)
Wall	75.6	0.01	1.00	0.01
Floor	48.0	0.01	1.00	0.01
Roof	48.0	0.0714	0.01	7.14

Table 2: Material Specifications for Base Case

Simulationists are advised that if their software does not permit the specified insulation levels, they are to use the thickest allowable and reduce the floor and wall areas to achieve the same UA values as defined in Table 2. The zone air volume remains 129.6 m^3.

Weather Data

The weather data used for this simulation represents artificial weather conditions with no solar gains, zero wind speed, constant outdoor dry bulb temperature (-30°C), and 50% relative humidity.

Infiltration

There is no internal infiltration accounted for in the base case model.

Internal Heat Gains

Internal heat gains (sensible or latent) are not accounted for in the base case model.

Surface Convective and Radiative Heat Transfer Coefficients

Solar absorptivity and longwave emissivity and surface convection coefficients approach zero for all interior and exterior opaque surfaces, with the only exception being the heat transfer surface, which has a constant surface convection coefficient.

The surface convection coefficients (h_c), longwave emissivity (λ), and solar absorptivity (α) are defined for all internal and external surfaces:

- internal and external $h_c = 20$ W/m^2K for heat transfer surface;
- internal and external $h_c = 0$ for other surfaces;

- longwave emissivity, $\lambda = 0$ at all internal and external surfaces; and
- solar absorptivity, $\alpha = 0$ at all internal and external surfaces.

The floor has the same exterior film coefficient as the other walls, as if the entire zone were suspended above the ground.

Again, the simulationists are advised to set h_c, λ, and α to as small a number as possible, if their software does not allow a zero definition.

Mechanical System Description

The mechanical system represents a simple sealed combustion fuel-fired furnace, where:

- the furnace injects heat directly to the zone air (i.e. a convective heating system);
- the zone air is fully mixed;
- the furnace draws combustion air from outdoors;
- the furnace flue does not extract air from the zone;
- there is no pilot light; and
- there are no air or thermal losses from the distribution ducts.

Thermostat Control Strategy

The zone setpoint temperature for the base case is set to a constant 20°C. If the zone thermostat senses the air temperature is less than 20°C, the furnace turns on; otherwise, the furnace is off.

Full-load Heating System Performance Data

The equipment full-load capacity and performance data for the natural gas furnace are as follows:

Furnace capacity = 10 kW

Furnace full-load efficiency = 100%

Part-load Operation

Residential furnaces cycle on and off to meet their load at off-design conditions. The part-load ratio (*PLR*) is used to predict the energy use of a furnace under part-load conditions, and is defined as:

$$PLR = \frac{Load\ Placed\ on\ Furnace}{Furnace\ Capacity} \qquad (1)$$

where the *Load Placed on Furnace* is integrated over the hour and the *Furnace Capacity* is the capacity of the furnace to supply heat for the hour.

The part-load factor (*PLF*) represents the degradation in furnace efficiency due to part-load operation:

$$PLF = \frac{Part\ Load\ Efficiency}{SS\ Efficiency} = \frac{\eta_{part-load}}{\eta} \qquad (2)$$

where the steady-state efficiency (η) is defined as the efficiency of the furnace under standard operating conditions. It is calculated (ASHRAE 2000) by measuring the furnace output and dividing by the

furnace fuel input.

The part-load performance can be defined in terms of a part-load curve, a plot of *PLF* vs. *PLR*. The part-load curve chosen for this suite of test cases is illustrated in Figure 2 and represents a condensing gas furnace (Henderson 1998).[3]
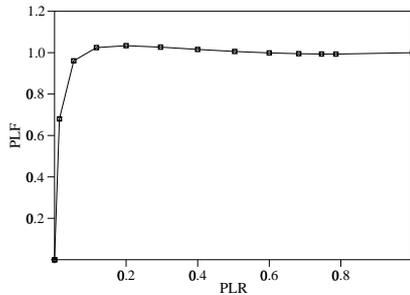

Figure 2: Part-load ratio curve.

The *PLR* is defined from Equation (1) and the *PLF* is defined as:

$$PLF = \frac{PLR}{HIR(PLR)} \qquad (3)$$

where Henderson defines the *HIR* coefficients for a condensing gas furnace as:

$$HIR(PLR) = a + b * PLR + c * PLR^2 + d * PLR^3 \quad (4)$$

a = 0.0080472574

b = 0.87564457

c = 0.29249943

d = -0.17624156

HIR(*PLR*) is the correlation factor applied to the *HIR* (Heat-Input-Ratio) at full-load to correct for the effect of part-load performance.

For the base case, the furnace runs continuously at full-load capacity, therefore, part-load operation is not examined.

Fuel Higher Heating Value (HHV)

The amount of heat generated by the combustion of a unit of fuel—including the latent heat of vaporization—is known as the higher heating value (*HHV*). For these tests, the *HHV* of natural gas is taken as 38 MJ/m^3, and is used to calculate the rate of fuel consumption.[4]

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[3] The choice of this particular part-load curve does not reflect upon the validity of the curve, rather, it is provided to ensure that the part-load curve is properly implemented.

[4] The fuel flow rate and *HHV* are reported at standard temperature and pressure (STP) conditions, and therefore, the altitude and density of air at the building site does not affect the results.

Fans

There is no fan power and no heat generated by the fans for the base case. The circulating and draft fans are simulated, but their power draw is set to zero.

Circulating fan = 0 W, runs continuously.

Draft fan = 0 W, cycles with burner operation.

CASE 1b: EFFICIENCY

This case is designed to ensure the furnace efficiency is accurately represented in the fuel consumption calculation. The only modification required for *Case 1b* is that the furnace runs continuously at 80% efficiency at full-load capacity.

Building Geometry Description

The configuration is the same as the base case building.

Mechanical System Description

Full-load Heating System Performance Data

The equipment full-load capacity and performance data are as follows:

Furnace capacity = 10 kW

Furnace full-load efficiency = 80%

CASE 1c: SIMPLE PART-LOAD

This case is designed to ensure that the furnace part-load curves are properly implemented. *Case 1c* is exactly the same as *Case 1b*, except that the furnace does not run at full-load capacity due to the fact that the indoor-outside temperature difference has been reduced.

Building Geometry Description

Weather Data

The weather data used for this simulation represents artificial weather data with a constant outdoor dry bulb temperature of 0°C.

For case *Case 1b*, the temperature difference between the indoor setpoint and the outdoor dry-bulb temperatures was 50°C. For this case, this difference is reduced to 20°C, and the furnace therefore runs continuously at 40% full-load capacity and part-load operation is examined.

CASE 1d: NO LOAD

This case is designed to test the program's ability to accurately respond to zero heat loads on the heating equipment. The geometry and mechanical systems for this case are the same as defined for *Case 1b*.

Building Geometry Description

Weather Data

The weather file for this case defines a constant outdoor temperature of 20°C. As the zone setpoint

temperature is also 20°C, the heating system should never turn on.

CASE 1e: COMPLEX PART-LOAD

This case is designed to ensure that the model accurately responds to variations in load and operates over the full range of the part-load curve. This represents a more challenging test of whether the part-load ratio is properly implemented. In *Case 1e*, a weather file with a sinusoidally varying outdoor temperature is used.

Building Geometry Description

Weather Data

The weather data used for this test case represents artificial weather with an outdoor dry bulb temperature varying over the range of -20°C to +20°C over a 24-hour period, as shown in Figure 3.
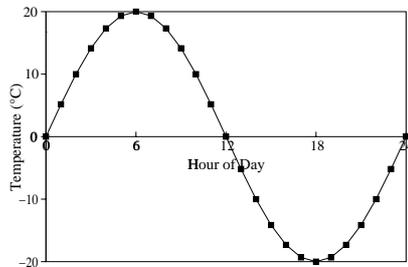

Figure 3: Outdoor dry bulb temperature.

CASE 1f: CIRCULATING FAN

This case is designed to ensure that the fan electrical consumption is properly calculated and that the heat output of the circulating fan is correctly reflected in the zone energy balance. *Case 1f* is the same as *Case 1e*, except that a circulating fan runs continuously.

Mechanical System Description

Fans

A circulating fan is incorporated into this model. Its power draw is set to 200 W and it operates continuously. There is no draft fan power and no heat generated by the draft fans for this test case. The draft fan is simulated, but its power draw is set to zero.

Circulating fan = 200 W, runs continuously.

Circulating fan flow rate = 0.355 m^3/s

Draft fan = 0 W, cycles with burner operation.

CASE 1g: CYCLING CIRCULATING FAN

This case is designed to ensure that the impact of fan cycling is properly considered in the calculation of the circulation fan electrical consumption. *Case 1g* is the same as *Case 1e*, except that the circulating fan cycles with burner operation.

Mechanical System Description

Fans

Circulating fan = 200 W, cycles with burner.

Draft fan = 0 W, cycles with burner operation.

CASE 1h: DRAFT FAN

This case is designed to ensure that the impact of the draft fan is properly considered in calculation of electrical consumption, but not accounted for in the fuel consumption. The heat output of the draft fan should not be added to zone energy balance. *Case 1h* is the same as *Case 1e*, except that the draft fan electrical consumption is incorporated.

Mechanical System Description

Fans

Circulating fan = 200 W, runs continuously.

Draft fan = 0 W, cycles with burner operation.

CASE 2a: REALISTIC WEATHER DATA

This case is designed to test the combined effects of circulating fan, draft fan, and realistic load profile. *Case 2a* is the same as *Case 1h*, except that both fans cycle on and off with the burner.

Building Geometry Description

Weather Data

The weather data used for this simulation represents realistic weather data.

Mechanical System Description

Fans

Circulating fan = 200 W, cycles with burner.

Draft fan = 0 W, cycles with burner operation.

CASE 2b: SETBACK THERMOSTAT

This case is designed to ensure that the effects of setback temperatures are accurately represented in the fuel consumption calculation. Since the zone and building envelope have negligible thermal mass, the zone's air temperature should follow the setpoint schedule. *Case 2b* is the same as *Case 2a*, except that the zone setpoint temperature is reduced from 20°C to 15°C from 23h00 to 6h00. **Mechanical System Description**

Thermostat Control Strategy

The zone setpoint temperature for the earlier test cases was a constant value of 20°C. For this case, the zone setpoint is a constant value of 20°C during the day, and is setback to 15°C during the evening, as shown in Figure 4.

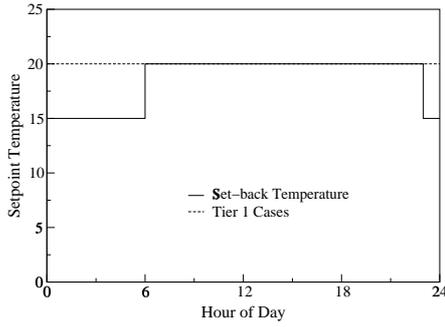## *CASE 2c*: UNDERSIZED FURNACE

Figure 4: Setback temperatures over 24-hrs.

This case is designed to test the behaviour of furnace algorithm when the system is under-sized, and the zone temperature fluctuates throughout the simulation. *Case 2c* is the same as *Case 2b*, except that the furnace is not sized to meet the peak load.

Mechanical System Description

The equipment full-load capacity and performance data for the natural gas furnace are as follows:

Furnace capacity = 5 kW

Furnace full-load efficiency = 80%

ANALYTICAL AND SEMI-ANALYTICAL SOLUTIONS

This configuration allows for an analytical and semi-analytical solutions, and the results can be used for comparison with the software being tested.

The following section describes the simple heat transfer calculation for the analytic solution of the base case. The interested reader is directed to the full report for a complete review of the analytical and semi-analytical solutions.

Based on the building description given above, convection and conduction heat transfer is considered, but radiation is neglected as the radiative coefficients are defined as zero.

The convective flux from the interior of the zone to the interior surface can be defined as:

$$q_{interior} = h_{interior} \ (T_{interior} - T_1) \qquad (5)$$

where T_1 is the interior surface temperature of the heat transfer surface.

The conductive flux through the heat transfer surface can be defined as:

$$q_{convective} = \frac{k}{t} \ (T_1 - T_2) \qquad (6)$$

where T_2 is the exterior surface temperature of the heat transfer surface.

The convective flux from the exterior surface to the exterior ambient can be defined as:

$$q_{exterior} = h_{exterior} \ (T_2 - T_{exterior}) \qquad (7)$$

Combining Equations (5 - 7) gives the total heat flux through the surface:

$$q_{total} = (T_{interior} - T_{exterior})[\ \frac{1}{h_{interior}} + \frac{t}{k} + \frac{1}{h_{interior}} \ ]^{-1} (8)$$

Using the material properties defined in the previous sections and Equation (8), the heat transfer through this surface — the rate of energy transfer from the furnace to the zone air required to meet this load — can be calculated.

The rate of fuel consumption of the furnace can be calculated as:

$$C = \frac{Q_{fuel}}{HHV} \qquad (9)$$

where C is the rate of fuel consumption of the furnace in m^3/s, Q_{fuel} is the rate at which the fuel's chemical energy is converted to thermal energy, and HHV is the Higher Heating Value of natural gas— previously defined as $38 MJ/m^3$.

Q_{fuel} can be calculated using the definition of the furnace steady-state efficiency, η:

$$\eta = \frac{Q_{delivered}}{Q_{fuel}} \qquad (10)$$

For the base case, the furnace has a steady-state efficiency of 100%, and therefore, the heat delivered by the furnace is equal to the rate at which the furnace consumes fuel. For the rest of the test cases, on the other hand, the furnace is 80% efficient, and the furnace, therefore, has to consume more fuel to produce the same heating output.

REFERENCE SOFTWARE TOOLS

ESP-r/HOT3000

The simulation of the test cases was performed by a simulationist at CETC-Ottawa (Natural Resources Canada) using a modified version of the ESP-r software (ESRU 2000) called *ESP-r/HOT3000* (Haltrecht et al. 1999). *ESP-r/HOT3000* version 1.1 was used for generating the Tier 1 results and version 1.7 was used for generating the Tier 2 results.

Two aspects of the *ESP-r/HOT3000* model were different from the specification. The emissivity of the outside surfaces was not set to the required value of zero, which resulted in an extra heat loss due to long wave radiation exchange with the outside. In addition, an ideal controller was used with a capacity of 20 kW to allow the zone load to exceed 10 kW, if dictated by the solution. The furnace capacity was set to 10 kW.

DOE2.1E

The simulation of the test cases was performed by a simulationist at CETC-Ottawa using *DOE-2.1E* version c133 (Winkelmann et al. 1994).

All the required characteristics of the test cases are included in the *DOE-2.1E* simulation models.

The materials of the walls, floor, and ceiling of the model were specified using the R-value method in DOE-2, and the surface-to-surface thermal resistances were set to the values given in Table 2.

The inside film thermal resistance (convection + radiation) for the walls and the floor were set very high so that the heat transfer through these components is practically zero.

The wind speed in the weather file was set so that the outside film resistance (convection + radiation) was as close to the specified value as possible. In addition, the solar absorptance and long wave emissivity of all surfaces were set to very small values.

All of the test cases were modelled with the system type PSZ. For the applicable cases, the draft fan was specified as a furnace auxiliary power (using the BDL command FURNACE-AUX-KW).

EnergyPlus

The simulation of the test cases was performed by a simulationist at GARD Analytics using *EnergyPlus* Version 1.0.2.008 (Crawley et al. 2000).

The Blow-Thru Furnace: Heat Only model was simulated, and a supply fan and gas-fired heating coil supplied heated air to the conditioned spaces. A single action thermostat controlled the amount of heat delivered to the space by cycling the burner. The supply fan operation was specified as either continuous or cycling.

If a draft fan was present, its electric power was specified using the parasitic electric load input parameter on the COIL:Gas:Heating object. The model allowed for a furnace part-load performance curve to be specified, and the heat input ratio (*HIR*) was expressed as a cubic function of the part-load.

REFERENCE RESULTS COMPARISON

The following is a comparison of the results obtained from three different software tools—*ESP-r/HOT3000*, *EnergyPlus*, and *DOE2.1E*—and the analytical and semi-analytical solutions. Figure 5 charts the results obtained by the individual programs for the test cases.

The Tier 1 analytical and semi-analytical results were compared with the results obtained from the test cases using three different whole-building energy simulation tools: *ESP-r/HOT3000*, *Energy-Plus*, and *DOE-2.1E*.

It can be seen that there is very good correlation between the three software tools and the analytical

and semi-analytical results for the Tier 1 test cases.

For the Tier 2 cases, there are no analytical or semi-analytical results for comparison and as expected, there is slightly more diversity in the results generated by the three simulation tools.

In addition, the mean, maximum, and minimum zone temperatures were of interest for the Tier 2 test cases, especially *Case 2c* where the furnace is undersized. Table 3 shows a comparison of these values for the three test simulation tools.

It can be seen that with the exception of *ESP-r/HOT3000* minimum temperature for *Case 2c*, the results compare very well with each other.

The differences in the test results are due to the different algorithms used to simulate the furnace and fans, the different controllers used in each simulation, as well as the differences in the application of the test specification.

EnergyPlus, for example, does not allow for the specification of internal and exterior surface film coefficients. In this case, the simulationists adjusted the size of the heat transfer surface to meet the required heat loss.

The differences between the *DOE2.1E* and *ESP-r/HOT3000* models and the test specification were detailed in the Reference Software Tools section.

CONCLUSIONS

A series of IEA BESTEST validation test cases were developed to aide software developers in ensuring the accuracy of their residential fuel-fired furnace algorithms.

Eleven cases have been proposed, whereby the first tier tests the basic functionality of furnace models and the second tier examines specific aspects of the furnace models.

Three reference software tools were simulated using the test cases, and their results were compared: the Tier 1 analytical and semi-analytical results were compared with the whole-building energy simulation tools, whereas, for the Tier 2 cases, the three simulation tools were compared to each other.

These test cases have been successful in discovering errors in the fuel-fired furnace algorithms developed in the tested programs. For example, prior to performing the fuel-fired furnace test cases, the *Energy-Plus* furnace model did not have capability to simulate part-load performance and account for parasitic electric power used by the draft fan.

The results generated with the reference programs are intended to be used as a starting point for evaluating other building energy simulation tools.
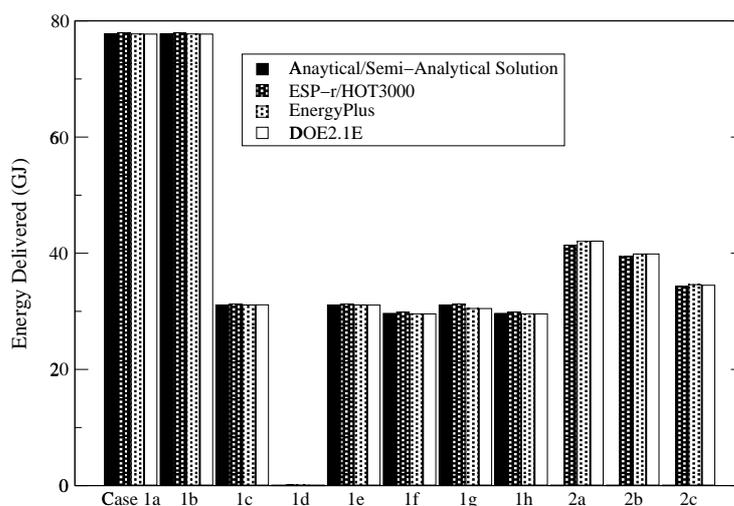
Figure 5: Comparison of Energy Delivered, in GJ.[5]

Case	Mean Temperature (°C)			Max Temperature(°C)			Min Temperature(°C)		
	E/H3K	Energy+	DOE	E/H3K	Energy+	DOE	E/H3K	Energy+	DOE
2a	20.01	20	19.96	21.45	20	20.05	20	20	19.88
2b	18.75	18.53	18.50	22.7	20	20.05	15	15	14.94
2c	15.48	15.17	15.46	20.14	20.14	20.05	1.45	4.48	5.33

Table 3: Comparison of Mean, Max and Min Temperatures.[6]

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[5] Case 1d corresponds to the no-load case and as such, the Energy Delivered for this case should be zero.

[6] E/H3K refers to *ESP-r/HOT3000*, Energy+ refers to *EnergyPlus*, and DOE refers to *DOE2.1E*.