Building Energy Simulation Test and Diagnostic Method for Heating, Ventilation, and Air-Conditioning Equipment Models (HVAC BESTEST): Fuel-Fired Furnace Test Cases

A Report of Task 22, Subtask C
Building Energy Analysis Tools

Project C.2 Comparative Evaluation

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INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

PREFACE
INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY

BACKGROUND

The International Energy Agency (IEA) was established in 1974 as an autonomous agency within the framework of the Economic Cooperation and Development (OECD) to carry out a comprehensive program of energy cooperation among its 24 member countries and the Commission of the European Communities.

An important part of the Agency's program involves collaboration in the research, development, and demonstration of new energy technologies to reduce excessive reliance on imported oil, increase long-term energy security, and reduce greenhouse gas emissions. The IEA's R&D activities are headed by the Committee on Energy Research and Technology (CERT) and supported by a small Secretariat staff, headquartered in Paris. In addition, three Working Parties are charged with monitoring the various collaborative energy agreements, identifying new areas for cooperation, and advising the CERT on policy matters.

Collaborative programs in the various energy technology areas are conducted under Implementing Agreements, which are signed by contracting parties (government agencies or entities designated by them). There are currently 40 Implementing Agreements covering fossil fuel technologies, renewable energy technologies, efficient energy end-use technologies, nuclear fusion science and technology, and energy technology information centers.

SOLAR HEATING AND COOLING PROGRAM

The Solar Heating and Cooling Program was one of the first IEA Implementing Agreements to be established. Since 1977, its 21 members have been collaborating to advance active solar, passive solar, and photovoltaic technologies and their application in buildings.

The members are:

Australia	France	Norway
Austria	Germany	Portugal
Belgium	Italy	Spain
Canada	Japan	Sweden
Denmark	Mexico	Switzerland
European Commission	Netherlands	United Kingdom
Finland	New Zealand	United States

A total of 30 Tasks have been initiated, 21 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition, a number of special ad hoc activities – working groups, conferences, and workshops – have been organized.

The Tasks of the IEA Solar Heating and Cooling Programme, both completed and current, are as follows:

Completed Tasks:

Task 1	Investigation of the Performance of Solar Heating and Cooling Systems
Task 2	Coordination of Solar Heating and Cooling R&D
Task 3	Performance Testing of Solar Collectors
Task 4	Development of an Insolation Handbook and Instrument Package
Task 5	Use of Existing Meteorological Information for Solar Energy Application
Task 6	Performance of Solar Systems Using Evacuated Collectors
Task 7	Central Solar Heating Plants with Seasonal Storage
Task 8	Passive and Hybrid Solar Low Energy Buildings
Task 9	Solar Radiation and Pyranometry Studies
Task 10	Solar Materials R&D
Task 11	Passive and Hybrid Solar Commercial Buildings
Task 12	Building Energy Analysis and Design Tools for Solar Applications
Task 13	Advanced Solar Low Energy Buildings
Task 14	Advanced Active Solar Energy Systems
Task 16	Photovoltaics in Buildings
Task 17	Measuring and Modeling Spectral Radiation
Task 18	Advanced Glazing and Associated Materials for Solar and Building Applications
Task 19	Solar Air Systems
Task 20	Solar Energy in Building Renovation
Task 21	Daylight in Buildings
Task 30	Solar Cities

Current Tasks and Working Groups:

Task 22	Building Energy Analysis Tools
Task 23	Optimization of Solar Energy Use in Large Buildings
Task 24	Solar Procurement
Task 25	Solar Assisted Cooling Systems for Air Conditioning of Buildings
Task 26	Solar Combisystems Working Group Materials in Solar Thermal Collectors
Task 27	Performance Assessment of Solar Building Envelope Components
Task 28	Solar Sustainable Housing
Task 29	Solar Crop Drying
Task 31	Daylight Buildings in the 21st Century

TASK 22: BUILDING ENERGY ANALYSIS TOOLS

Goal and objectives of the task

The overall goal of Task 22 is to establish a sound technical basis or analyzing solar, low-energy buildings with available and emerging building energy analysis tools. This goal will be pursued by accomplishing the following objectives:

- Assess the accuracy of available building energy analysis tools in predicting the performance of widely used solar and low-energy concepts;
- Collect and document engineering models of widely used solar and low-energy concepts for use in the next generation building energy analysis tools; and
- Assess and document the impact (value) of improved building analysis tools in analyzing solar, low-energy buildings, and widely disseminate research results tools, industry associations, and government agencies.

Scope of the task

This Task will investigate the availability and accuracy of building energy analysis tools and engineering models to evaluate the performance of solar and low-energy buildings. The scope of the Task is limited to whole-building energy analysis tools, including emerging modular type tools, and to widely used solar and low-energy design concepts. Tool evaluation activities will include analytical, comparative, and empirical methods, with emphasis given to blind empirical validation using measured data from test rooms of full-scale buildings. Documentation of engineering models will use existing standard reporting formats and procedures. The impact of improved building energy analysis will be assessed from a building owner perspective.

The audience for the results of the Task is building energy analysis tool developers and national building energy standards development organizations. However, tool users, such as architects, engineers, energy consultants, product manufacturers, and building owners and managers, are the ultimate beneficiaries of the research, and will be informed through targeted reports and articles.

Means

In order to accomplish the stated goal and objectives, the Participants will carry out research in the framework of four Subtasks:

Subtask A: Tool Evaluation
Subtask B: Model Documentation
Subtask C: Comparative Evaluation
Subtask D: Empirical Evaluation

Participants

The participants in the Task are: Australia, Canada, Finland, France, Germany, Spain, Sweden, Switzerland, United Kingdom, and United States. The United States serves as Operating Agent for this Task, with Michael J. Holtz of Architectural Energy Corporation providing Operating Agent services on behalf of the U.S. Department of Energy.

This report documents work carried out under Subtask C: Comparative Evaluation.

Executive Summary

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

This report documents an analytical verification and comparative diagnostic procedure for testing the ability of whole-building simulation programs to model the performance of fuel-fired furnaces. Results from analytical/semi-analytical solutions and simulation programs that were used in field trials of the test procedure are also presented.

The test cases 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.

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 configuration of the base case building is a single near-adiabatic rectangular zone with energy transfer through a single surface to drive the heating loads. The geometric and material specifications are purposely kept as simple as possible to minimize the opportunity for user input errors. The mechanical equipment represents a simple sealed combustion gas furnace.

The test cases are designed to test the implementation of specific algorithms for the following furnace performance parameters:

- furnace steady state efficiency;
- furnace part load ratio;
- furnace fuel consumption;
- outdoor temperature;
- circulating fan operation;
- draft fan operation;
- thermostat set-backs; and
- undersized capacity.

The tier 1 cases have been carefully specified and are therefore suitable for an analytical/semi-analytical solution. For these cases, the calculated results were compared with the results obtained from the test cases using three different whole-building energy simulation tools: ESP-r/HOT3000, EnergyPlus, and DOE-2.1E.

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

Conclusions

The results obtained by the individual programs for the test cases show good correlation between the software tools and the calculated results for the Tier 1 test cases.

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 EnergyPlus furnace model did not have capability to simulate part load performance or account for parasitic electric power such as that 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.

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FIGURES

1. General Description of Test Cases

This comparative test has been developed so that many different building simulation programs, representing different degrees of modelling complexity, can be tested. This document contains a uniform set of unambiguous test cases for software-to-software comparisons, and program diagnostics. As no two programs require exactly the same input information, we have, therefore, attempted to describe the test cases in a fashion that allows many different building simulation programs (representing different degrees of modelling complexity) to be tested.

Eleven cases have been proposed for testing the performance of fuel-fired furnace models. These tests are divided into two tiers. The first tier employs simplified boundary conditions and tests the basic functionality of furnace models. Boundary conditions that are more realistic are used in the second tier, where specific aspects of furnace models are examined. This document presents the eight tier 1 cases and the three tier 2 cases.

The test cases described in this report complement those presented in the report IEA Building Energy Simulation Test for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST): Air-Conditioning Test Suite by Judkoff and Neymark (2002). The IEA HVAC BESTEST tests examine the performance of space-cooling equipment, whereas the current report considers space-heating equipment.

The test cases presented here isolate the furnace performance by simplifying the zone-side energy transfers. The simulation method will be to isolate a single facet of the furnace model in each test case, starting with the simplest case and progressively adding complexity.

The configuration of the base case building (Case 1a) is a single near-adiabatic rectangular zone with energy transfer through a single surface to drive the heating loads. The geometric and material specifications are purposely kept as simple as possible to minimize the opportunity for input errors on the part of the user. Mechanical equipment specifications represent a simple sealed combustion gas furnace.

The specific test cases are designed to test the implementation of algorithms for the following:

- Furnace steady state efficiency
- Furnace part load ratio
- Furnace fuel consumption
- Outdoor temperature
- Circulating fan operation
- Draft fan operation
- Thermostat set-backs
- Undersized capacity

1.1 Performing the Tests

1.1.1 Input Requirements

Building input data are organized case by case. The base case building (Case 1a) description occupies Section 2. The additional test cases, Cases 1b-1h and Cases 2a-2c, are organized as modifications to the base case and ordered in a manner that will facilitate implementing the tests, and are progressively more complex.

1.1.2 Modelling Rules

1.1.2.1. Consistent Modelling Methods

Where options exist within a simulation program for modelling a specific thermal behaviour, consistent modelling methods shall be used for all cases. For example if a software gives the user a choice of methods for modelling indoor air circulation fans, the same indoor fan modelling method shall be used for all cases.

1.1.2.2. Non-Applicable Inputs

In some instances, the specification will include input values that do not apply to the input structure of your program. For example, your program may not use the listed combined convective/radiative film coefficients, and/or may not apply other listed inputs. When non-applicable input values are found, either use approximation methods suggested in the program's users manual, or simply disregard the non-applicable inputs and continue. Such inputs are in the specification for those programs that may need them.

1.1.2.3. Time Convention

References to time in this specification are to local standard time. Assume that: *hour 1 = the interval from midnight to 1am*. Do not use daylight savings time, or holidays for scheduling. However, the required weather data is in hourly bins.

1.1.2.4. Geometry Convention

If your program includes the thickness of walls in a three-dimensional definition of the building geometry, then wall, roof, and floor thickness should be defined such that the **interior** air volume of the building remains as specified (6m x 8m x 2.7m = 129.6m^3). Make the thickness extend outside, i.e., to the exterior, of the currently defined internal volume.

1.1.2.5. Simulation Initialization

If your software allows, begin the simulation initialization process with zone air conditions equal to outdoor air conditions.

1.1.2.6. Simulation Preconditioning

If your program allows for preconditioning (iterative simulation of an initial time period until temperatures and/or fluxes stabilize at initial values), then use that capability.

1.1.2.7. Simulation Duration

Run the simulation for the three months for which the weather data are provided.

1.1.3 Output Requirements

The user will compare outputs with the analytic/semi-analytical solutions as described in each section, or with the results generated from three simulation software programs, as described in Appendix A.

1.1.4 Specific Input Information

The bulk of the work for implementing these cases is assembling an accurate base building and mechanical system. It is recommended that you double-check all inputs. Weather data, building zone, and mechanical equipment details are described topically in the following subsections.

1.1.5 Weather Data

Weather data is provided with this test suite so that the initial fundamental series of mechanical equipment test may be tightly controlled. These data are presented in WYEC 2 format (ASHRAE). See Appendix D for a detailed description of the WYEC2 format.

Five three-month-long (January 1st – March 31st) weather data files are used in the test suite. The first (**weather file: a**) has a constant outdoor temperature of –30°C, whereas the second and third (**weather files: c and d**) have constant outdoor temperatures of 0°C and +20°C respectively. The fourth set of data (**weather file: e**) features the outdoor temperature varying sinusoidally over each 24-hour period from -20°C to +20°C. The fifth set (**weather file: f**) represents a more realistic weather set from a cold winter location.

Many simulation programs use TMY or WYEC weather data, wherein the hourly time convention is solar time[a]. For these simulations, there are no solar gains therefore; solar time, longitude, latitude, time zone, and ground reflectivity will not impact the simulation results.

1.1.6 Additional Furnace Test Case Descriptions

The following sections describe sequential revisions to the base case required to model the additional furnace test cases. Table 1, below, details the basis of each test case as well as the furnace and fan equipment operating points and the associated weather files. These test cases are further explored in the following sections.

Case	Furnace Capacity (kW)	Steady-State Efficiency	PLR	Outdoor DBT (°C)	Indoor Setpoint Temp (°C)	Weather File	Circulating Fan (W)	Draft Fan (W)
Tier 1 Test Cases								
1a	10	100%	1	-30	20	a	0	0
1b	10	80%	1	-30	20	a	0	0
1c	10	80%	0.4	0	20	c	0	0
1d	10	80%	0.0	20	20	d	0	0
1e	10	80%	0.0-0.8	-20 to 20	20	e	0	0
1f	10	80%	0.0-0.8	-20 to 20	20	e	200-cont.	0
1g	10	80%	0.0-0.8	-20 to 20	20	e	200-cyclic	0
1h	10	80%	0.0-0.8	-20 to 20	20	e	200-cont	50-cyclic
Tier 2 Test Cases								
2a	10	80%	0-1.0	varying	20	f	200-cyclic	50-cyclic
2b	10	80%	0-1.0	varying	15 to 20	f	200-cyclic	50-cyclic
2c	5	80%	0-1.0	varying	15 to 20	f	200-cyclic	50-cyclic

Table 1: Furnace Test Case Descriptions

The following table details the required outputs for each test case.

Case	Hourly Energy Delivered to the Space (GJ)[b]	Rate of Fuel Consumption (m^3/s)	Fan Power (kWh)	Max, Min, Mean Zone Temperature (°C)
Tier 1 Test Cases				
1a	■	■		
1b	■	■		
1c	■	■		
1d	■	■		
1e	■	■		
1f	■	■	■	
1g	■	■	■	
1h	■	■	■	

[a] Solar Time = Standard Time +- 4 minutes/degree x (L_{st} - L_{loc}) + E
Standard Time = local standard time
L_{st} = standard meridian longitude (degrees)
L_{loc} = local site longitude (degrees)
E = 229.2 (0.000075 + 0.001868 cos B – 0.032077 sin B – 0.014615 cos 2B – 0.04089 sin 2B (minutes)
B = 360(n - 81)/365 (degrees), and
n ≡ day of the year, 1 ≤ n ≤ 365.
Additional information on the equation of solar time may be found in the references. (Duffie and Beckman, 1991)
[b] Energy delivered to the space refers to the load at the furnace coil.

Case	Hourly Energy Delivered to the Space (GJ)[b]	Rate of Fuel Consumption (m^3/s)	Fan Power (kWh)	Max, Min, Mean Zone Temperature (°C)
Tier 2 Test Cases				
2a	■	■	■	■
2b	■	■	■	■
2c	■	■	■	■

Table 2: Furnace Test Case Required Results

Reference results for these 11 cases were generated with three simulation programs: ESP-r/HOT3000, DOE-2.1E, and EnergyPlus. These reference results are summarised in Appendix A, while modeller's reports detailing how these programs were used to generate the results are presented in Appendices E through G.

Tier 1 Test Cases

2. Case 1a: Base Case Building and Mechanical System

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 configuration of the base case building is a single near-adiabatic rectangular zone with energy transfer through a single surface to drive the heating loads. Only one significant heat flow path exists:

furnace + fan heat $\xrightarrow{\textit{convection}}$ zone air $\xrightarrow{\textit{convection}}$ heat transfer internal surface $\xrightarrow{\textit{conduction}}$ heat transfer external surface $\xrightarrow{\textit{convection}}$ outside air

Controlling this heat flow path are the setpoint temperature of the zone, the outdoor air temperature, and the heat transfer surface characteristics, which drive the furnace operation.

The approach taken is the isolation of a single facet of furnace model in each test case; starting with the simplest case then progressively adding complexity.

The furnace will run continuously at capacity, and this case is designed to ensure the furnace output is correctly represented in the zone energy balance.

An alternate approach has been provided for those programs that cannot set convection coefficients. This approach is outlined in **Appendix B**, with the heat transfer surface defined as an adiabatic boundary and the heating loads are driven by infiltration.

2.1 Building Zone Description

2.1.1 Building Geometry

The base case building is a 48 m^2 floor area, single story, low mass building with rectangular prism geometry and internal measurements as shown in Figure 1. The zone air volume is 129.6 m^3.

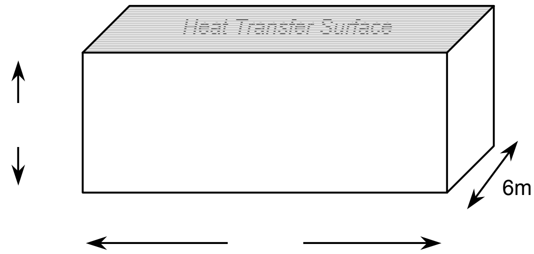

Figure 1: Base case building with heat transfer surface.

2.1.2 Building Envelope Thermal Properties

The base case building is designed as a near-adiabatic test cell. Energy is transferred to the outdoors through the heat transfer surface, with the furnace used to maintain the interior setpoint temperature.

Material properties for the exterior wall, floor, and roof are listed in Table 3. The roof will be modelled as the heat transfer surface. The insulation in the walls and floors has been made very thick and resistant to heat transfer to effectively thermally decouple the zone from ambient conditions, i.e., are made to be adiabatic.

Element	**Area (m^2)**	**k (W/mK)**	**t (m)**	**U[c] (W/ m^2K)**	**R[d] (m^2K/W)**
Wall	75.6	0.01	1.00	0.01	100
Floor	48.0	0.01	1.00	0.01	100
Roof (*Heat Transfer Surface*)	48.0	0.0714	0.01	7.14	0.14

Table 3: Material Specifications for Base Case

Materials of the space have no thermal or moisture capacitance and there is no moisture diffusion through them. If your software requires thermal, moisture capacitance, and/or moisture diffusion, use the minimum allowable values.

If your software does not allow the specified insulation levels, use the thickest allowable and reduce the floor and wall areas to achieve the same UA values as defined in Table 3. The zone air volume must remain at 129.6 m^3.

2.1.3 Weather Data

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

2.1.4 Infiltration

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

Infiltration rate = 0.0 ACH, for entire simulation period.

2.1.5 Internal Heat Gains

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

[c] This is the U-value defined between internal and external surfaces of envelope component, and as such does not include the resistance offered by surface convection and longwave radiation.

[d] This is the R-value defined between internal and external surfaces of envelope component, and as such does not include the resistance offered by surface convection and longwave radiation.

Sensible internal gains = 0 W, continuously.
Latent internal gains = 0 W, continuously.

2.1.6 Surface Convective and Radiative Heat Transfer Coefficients

Solar absorptivity and longwave emissivity and surface convection coefficients will approach zero for all interior and exterior opaque surfaces. The only exception to this is for the heat transfer surface, which will have a constant surface convection coefficient.

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

- internal and external h_c = 20 W/m²K for heat transfer surface;
- internal and external $h_c \rightarrow 0$ for other surfaces;
- longwave emissivity, $\lambda \rightarrow 0$ at all internal and external surfaces; and
- solar absorptivity, $\alpha \rightarrow 0$ at all internal and external surfaces.

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

If your software does not allow a definition of zero for h_c, λ, or α, then set them to as small a number as possible.

In addition, if your program models radiation and convection together, then set the combined heat transfer coefficient for the heat transfer surface (roof) to 20 W/m^{2}K. For all other surfaces, set this value to zero. If your software program requires a non-zero value for the combined heat transfer coefficient, then set it to as small a number as is allowed.

Finally, if your program does not allow for the definition of convection coefficients, please follow the approach of the alternate test cases, outlined in **Appendix B**.

2.2 Mechanical System Description

The mechanical system represents a simple sealed combustion fuel-fired furnace heating system.

2.2.1 General Information

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

2.2.2 Thermostat Control Strategy

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

Heat = on if temperature < 20°C; otherwise **Heat = off**
Cool = off

The controls for this system are ideal in that equipment is assumed to maintain the setpoint exactly, when it is operated and not overloaded. There are no minimum on or off time duration requirements for the unit, and no hysteresis control band, i.e., there is no: ON at setpoint + x°C or OFF at setpoint –y°C. If your software requires input for these then use the minimum allowable values.

2.2.3 Full-load Heating System Performance Data

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

Furnace capacity = 10 kW

Furnace full-load efficiency = 100%

2.2.4 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:

$$\text{PLR} = \frac{\text{Load Placed on Furnace}}{\text{Furnace Capacity}} \tag{1}$$

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 that hour.

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

$$\text{PLF} = \frac{\text{Part Load Efficiency}}{\text{Steady State Efficiency}} = \frac{\eta_{\text{part load}}}{\eta} \tag{2}$$

For simulation programs, 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.

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

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

where Henderson (1998) defines the HIR coefficients for a condensing gas furnace as:

$$\text{HIR(PLR)} = a + b \cdot \text{PLR} + c \cdot \text{PLR}^2 + d \cdot \text{PLR}^3 \tag{4}$$

where a = 0.0080472574
b = 0.87564457
c = 0.29249943
d = -0.17624156

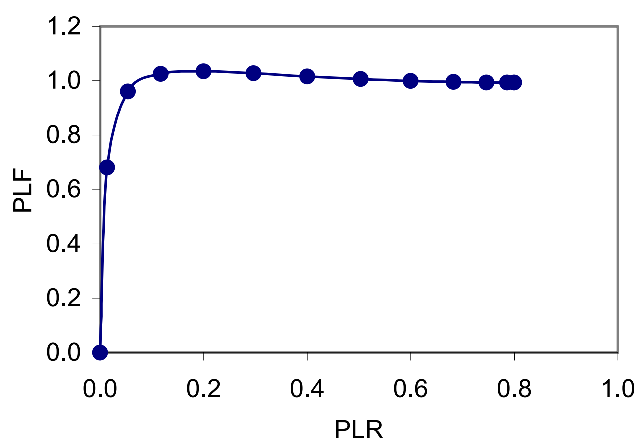

Figure 2: Part Load Ratio Curve.

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 (Case 1a), the furnace runs continuously at full-load capacity therefore, part-load operation is not examined. If your software requires input for the part-load operation, use equations (3-4).

2.2.5 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 to be taken as 38 MJ/m^3. The HHV will be used to calculate the rate of fuel consumption.

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

2.2.6 Fans

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

2.2.6.1. Circulating Fan

Circulating fan power draw = 0 W
Circulating fan runs continuously.

2.2.6.2. Draft Fan

Draft fan power draw = 0 W
Draft fan cycles with burner operation.

2.3 Analytic Solution

This configuration is well posed for an analytical solution. The results can be used for comparison with the software being tested.

A simple schematic of the heat transfer through the heat transfer surface is shown in Figure 3. The following section will describe the simple heat transfer calculation for the analytic solution of the base case. Based on the building description given above, convection and conduction heat transfer will be considered, but radiation will be neglected as the radiative coefficients were defined as zero.

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

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

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

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

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

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

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

$$q_{total} = \left[\left(T_{interior} - T_1\right) + \left(T_1 - T_2\right) + \left(T_2 - T_{exterior}\right)\right] \cdot \left[\frac{1}{h_{interior}} + \frac{t}{k} + \frac{1}{h_{exterior}}\right]^{-1} \qquad (8)$$

which can be reduced to:

$$q_{total} = \left(T_{interior} - T_{exterior}\right) \cdot \left[\frac{1}{h_{interior}} + \frac{t}{k} + \frac{1}{h_{exterior}}\right]^{-1} \qquad (9)$$

Using the values defined in the previous sections and equation (9), the heat flux becomes, q_{total} = 208.28 W/m². The heat transfer surface is 48 m², therefore, the heat transfer through this surface is **Q_{total} = 9998W**. The rate of energy transfer from the furnace to the zone air required to meet this load will be, **$Q_{delivered}$ = 9998W**.

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

$$C = \frac{Q_{fuel}}{HHV} \qquad (10)$$

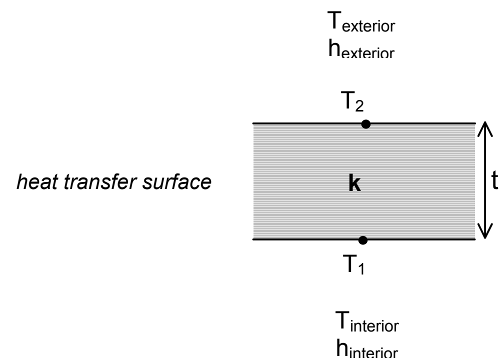

Figure 3: Heat flows through heat transfer surface.

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 – defined as 38 MJ/m^3 in Section 2.2.5.

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

$$\eta = \frac{Q_{delivered}}{Q_{fuel}} \tag{11}$$

As the furnace is 100% efficient, the heat delivered by the furnace is equal to the rate at which the furnace consumed fuel, as calculated with equation (11), i.e., $\mathbf{Q_{delivered} = Q_{fuel} = 9998W}$. Using equation (10), the **rate of fuel consumption** is **0.000263 $\mathbf{m^3/s}$**.

3. Case 1b: Efficiency Test

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

3.1 Building Zone Description

The configuration of this case is the same as the base case building.

3.2 Mechanical System Description

3.2.1 Full-load Heating System Performance Data

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

Furnace capacity = 10 kW
Furnace full-load efficiency = 80%

3.3 Analytic Solution

As with the base case, the energy delivered to the zone by the furnace is $\mathbf{Q_{delivered} = 9998\ W}$. In this case, the furnace is 80% efficient and therefore the furnace will have to consume more fuel than the base case.

Equation (11) gives Q_{fuel} = 12497.5 W, and therefore, the rate of fuel consumption can be calculated with equation (10) as **0.000329 $\mathbf{m^3/s}$**.

4. Case 1c: Simple Part Load Test

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

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

4.1 Building Zone Description

4.1.1 Weather Data

For this test case, use **weather file: c**.

4.2 Mechanical System Description

4.2.1 Full-load Heating System Performance Data

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

Furnace capacity = 10 kW
Furnace full-load efficiency = 80%

4.3 Analytic Solution

Given that the outdoor temperature is now 0°C, and using the equations defined in Section 2.3, the heat load on the furnace can be calculated as $\mathbf{Q_{delivered} = 3999\ W}$, 40% of the design capacity.

Using equations (1), (2), and (10), the part load efficiency can be calculated as $\eta_{\text{part load}} = 0.8125$. Therefore, the rate of fuel consumption is $\mathbf{0.0001295\ m^3/s}$.

5. Case 1d: No Load Test

The objective of this test case is to test a program's ability to accurately respond to zero heat loads on the heating equipment.

5.1 Building Zone Description

5.1.1 Weather Data

For this test case, use **weather file: d**.

5.2 Mechanical System Description

5.2.1 Thermostat Control Strategy

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

Heat = on if temperature < 20°C; otherwise **Heat = off**
Cool = off

As the outdoor temperature is kept at a constant value of 20°C, and the setpoint temperature is 20°C, then the heating system should never turn on.

5.2.2 Part-Load Operation

The furnace runs continuously at 0% full-load capacity.

5.3 Analytic Solution

The zone temperatures should remain at a constant value of 20°C, and there should be no sensible heat load, energy, or fuel consumption by the furnace.

6. Case 1e: Complex Part Load Test

The objective of this test case is to examine a program's ability to accurately respond to variations in load.

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

6.1 Building Zone Description

6.1.1 Weather Data

For this test case, use **weather file: e**.

Figure 4 is a plot of the outdoor temperature varying over the range of +20 °C to –20 °C over a 24-hour period. The equation of the sinusoid is:

$$T = 20 * (\sin(\frac{\pi}{12} \cdot t)) \qquad (12)$$

where T is the resulting outdoor dry bulb temperature and t is the corresponding time of day.

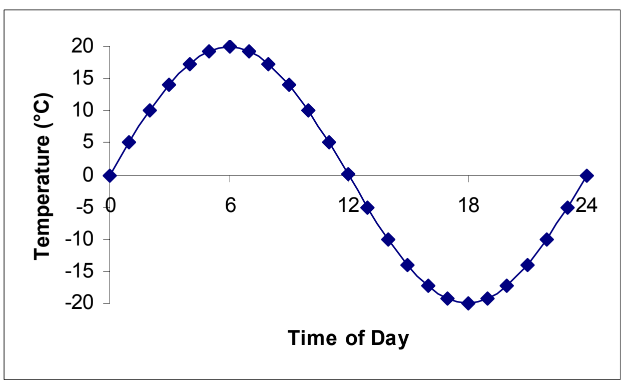

Figure 4: Outdoor temperature varying sinusoidally from +20°C to –20°C over a 24-hour period.

6.2 Mechanical System Description

6.2.1 Full-load Heating System Performance Data

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

Furnace capacity = 10 kW
Furnace full-load efficiency = 80%

6.2.2 *Part-Load Operation*

This case will prove to be a more stringent examination of the part-load curve implementation, as the furnace will run at different part-load operation depending on the outside temperature.

6.3 Semi-Analytical Solution

This section presents a reference result for comparison against building simulation program results. However, unlike the previous cases, an analytic solution is not possible in this case for the three-month simulation period. Rather, the reference result is calculated using a discrete time-step calculation, similar to the approach applied by most building simulation programs. The thermal mass of the house is effectively zero, therefore, a solution can be found on a time step basis. A one-hour time-step is employed here.

The calculation of the heating load on the furnace and the fuel consumption over a 24-hour period is required to examine the impact of the varying outdoor dry bulb temperature. Table 4 defines the calculated sensible heat load to be delivered by the furnace, $Q_{delivered}$, the part load efficiency, $\eta_{part\ load}$, the rate of fuel consumption of the furnace, Q_{fuel}, and the resulting fuel consumption over a 24-hour period. A description of the semi-analytical calculation method is presented in **Appendix C**.

The average-hourly calculated heat delivered by the furnace was **4998.45 W** and the rate of fuel consumption was **0.000132 m^3/s**.

Hour of Day	Temperature (°C)	$Q_{delivered}$ (W)	$\eta_{part\ load}$	Q_{fuel} (W)	Rate of Fuel Consumption (m^3/s)
1	5.18	2964.03	0.821	3608.74	0.000095
2	10.00	1999.53	0.827	2417.76	0.000064
3	14.14	1171.30	0.820	1429.26	0.000038
4	17.32	535.77	0.768	697.18	0.000018
5	19.32	136.26	0.544	250.41	0.000007
6	20.00	0.0	0.0	0.0	0.0
7	19.32	136.26	0.544	250.41	0.000007
8	17.32	535.77	0.768	697.18	0.000018
9	14.14	1171.30	0.820	1429.26	0.000038
10	10.00	1999.53	0.827	2417.76	0.000064
11	5.18	2964.03	0.821	3608.74	0.000095
12	0.00	3999.07	0.813	4921.62	0.000130
13	-5.18	5034.10	0.805	6256.22	0.000165
14	-10.00	5998.60	0.799	7506.51	0.000198
15	-14.14	6826.83	0.796	8576.02	0.000226
16	-17.32	7462.36	0.795	9389.13	0.000247
17	-19.32	7861.87	0.795	9895.21	0.000260
18	-20.00	7998.13	0.795	10066.74	0.000265
19	-19.32	7861.87	0.795	9895.21	0.000260
20	-17.32	7462.36	0.795	9389.13	0.000247
21	-14.14	6826.83	0.796	8576.02	0.000226
22	-10.00	5998.60	0.799	7506.51	0.000198
23	-5.18	5034.10	0.805	6256.22	0.000165
24	0.00	3999.07	0.813	4921.62	0.000130

Table 4: Heat Load, Efficiency, and Fuel Consumption for the Complex Part Load Test.

7. Case 1f: Circulating Fan Test

The objective of this case is to test a program's ability to model circulating fan operation.

Case 1f is the same as Case 1e, except that a circulating fan runs continuously. 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.

7.1 Building Zone Description

The configuration of this case is the same as the building for test case 1e.

7.2 Mechanical System Description

7.2.1 Fans

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

7.2.1.1. Circulating Fan

Circulating fan power draw = 200 W
Circulating fan flow rate = 0.355 m^3/s (752 CFM)
Circulating fan runs continuously.

7.2.1.2. Draft Fan

Draft fan power draw = 0 W
Draft fan cycles with burner operation.

7.3 Semi-Analytical Solution

This section presents a reference result for comparison against building simulation program results. However, unlike many of the previous cases, an analytic solution is not possible in this case. Rather, the reference result is calculated using a discrete time-step calculation, similar to the approach applied by most building simulation programs. A one-hour time-step is employed here.

As the circulation fan runs constantly, 200W of fan heat is continuously added to the heated air stream. This will reduce the energy required from the combustion while maintaining the constant zone temperature. This has the impact of affecting the part load factor and fuel consumption.

The average-hourly values calculated for the heat to be delivered by the furnace was **4759.67 W** and the rate of fuel consumption was **0.0001253 m^3/s**. The total electricity consumption was calculated to be 432 kWh or **1.56GJ** for the three-month period. Table 5 gives the results for a 24-hour period.

Hour of Day	Temperature (°C)	$Q_{delivered}$ (W)	$\eta_{part\ load}$	Q_{fuel} (W)	Rate of Fuel Consumption (m^3/s)	Electricity (kWh)
1	5.18	2764.03	0.82	3358.79	0.0000884	0.2
2	10	1799.53	0.83	2175.84	0.0000573	0.2
3	14.14	971.30	0.81	1196.21	0.0000315	0.2
4	17.32	335.77	0.71	472.15	0.0000124	0.2
5	19.32	0	0	0	0	0.2
6	20	0	0	0	0	0.2
7	19.32	0	0	0	0	0.2
8	17.32	335.77	0.71	472.15	0.0000124	0.2

Hour of Day	Temperature (°C)	$Q_{delivered}$ (W)	$\eta_{part\ load}$	Q_{fuel} (W)	Rate of Fuel Consumption (m^3/s)	Electricity (kWh)
9	14.14	971.30	0.81	1196.21	0.0000315	0.2
10	10.00	1799.53	0.83	2175.84	0.0000573	0.2
11	5.18	2764.03	0.82	3358.79	0.0000884	0.2
12	0	3799.07	0.81	4665.79	0.0001228	0.2
13	-5.18	4834.10	0.81	5997.33	0.0001578	0.2
14	-10	5798.60	0.80	7247.32	0.0001907	0.2
15	-14.14	6626.83	0.80	8318.55	0.0002189	0.2
16	-17.32	7262.36	0.80	9134.20	0.0002404	0.2
17	-19.32	7661.87	0.79	9642.42	0.0002537	0.2
18	-20	7798.13	0.79	9814.78	0.0002583	0.2
19	-19.32	7661.87	0.79	9642.42	0.0002537	0.2
20	-17.32	7262.36	0.80	9134.20	0.0002404	0.2
21	-14.14	6626.83	0.80	8318.55	0.0002189	0.2
22	-10	5798.60	0.80	7247.32	0.0001907	0.2
23	-5.18	4834.10	0.81	5997.33	0.0001578	0.2
24	0	3799.07	0.81	4665.79	0.0001228	0.2

Table 5: Heat Load, Efficiency, Fuel and Electricity Consumption for the Circulating Fan Test.

8. Case 1g: Cycling Circulating Fan Test

The objective of this test case is to test a program's ability to model a cyclic fan operation.

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

8.1 Building Zone Description

The configuration of this case is the same as the building for test case 1e.

8.2 Mechanical System Description

8.2.1 Fans

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

8.2.1.1. Circulating Fan

Circulating fan power draw = 200 W
Circulating fan flow rate = 0.355 m^3/s
Circulating fan cycles with burner operation.

8.2.1.2. Draft Fan

Draft fan power draw = 0 W
Draft fan cycles with burner operation.

8.3 Semi-Analytical Solution

This section presents a reference result for comparison against building simulation program results. However, unlike many of the previous cases, an analytic solution is not possible in this case. Rather, the reference result is calculated using a discrete time-step calculation, similar to the approach applied by most building simulation programs. A one-hour time-step is employed here.

This calculated solution assumes that the PLR is equal to the fraction of time during which the fan operates for a given time-step. In addition, it assumes that there are no effects from fan start-up or shut-down, i.e., when the fan is on it draws 200W. It is recognized that some building simulation programs may apply different assumptions in the modelling of circulation fans. In this case, results would be expected to disagree with these calculated results by a small degree.

As the circulating fan cycles with the burner operation, its hourly energy will vary based on the load on the furnace. It can be calculated as:

$$\text{Energy}_{\text{fan}} = \Delta t \cdot \text{Power}_{\text{fan}} \cdot \text{PLR} \qquad (13)$$

where Δt is the time step, $\text{Power}_{\text{fan}}$ is the rated fan power (200W in this case), and PLR is:

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

where the available Furnace Capacity will include the fan power.

The average-hourly values calculated for the heat to be delivered by the furnace was **4898.48 W** and the rate of fuel consumption was **0.0001289 m^3/s**. These values are higher than the previous case where the circulating fan ran constantly.

The total electricity consumption was 172.76 kWh or **0.62 GJ** for the three-month period, which is lower than in the previous case. Table 6 gives the results for a 24-hour period.

9. Case 1h: Draft Fan Test

The objective of this test case is to test a program's ability to model a draft fan operation.

Case 1h is the same as Case 1e, except that the draft fan electrical consumption is incorporated. 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.

Time of Day	Temperature (°C)	Q_{Total} (W)	$\eta_{part\ load}$	$Q_{Furnace}$ (W)	Fuel Consumption (m^3/hr)	Electricity (kWh)
1	5.18	2964.03	0.82	3536.57	0.0000931	0.059
2	10.00	1999.53	0.83	2369.41	0.0000624	0.040
3	14.14	1171.30	0.82	1400.68	0.0000369	0.023
4	17.32	535.77	0.77	683.24	0.0000180	0.011
5	19.32	136.26	0.54	245.41	0.0000065	0.003
6	20	0	0	0	0	0.000
7	19.32	136.26	0.54	245.41	0.0000065	0.003
8	17.32	535.77	0.77	683.24	0.0000180	0.011
9	14.14	1171.30	0.82	1400.68	0.0000369	0.023
10	10.00	1999.53	0.83	2369.41	0.0000624	0.040
11	5.18	2964.03	0.82	3536.57	0.0000931	0.059
12	0	3999.07	0.81	4823.19	0.0001269	0.080
13	-5.18	5034.10	0.80	6131.09	0.0001613	0.101

Time of Day	Temperature (°C)	Q_{Total} (W)	$\eta_{part\ load}$	$Q_{Furnace}$ (W)	Fuel Consumption (m^3/hr)	Electricity (kWh)
14	-10	5998.60	0.80	7356.38	0.0001936	0.120
15	-14.14	6826.83	0.80	8404.50	0.0002212	0.137
16	-17.32	7462.36	0.79	9201.35	0.0002421	0.149
17	-19.32	7861.87	0.79	9697.30	0.0002552	0.157
18	-20	7998.13	0.79	9865.41	0.0002596	0.160
19	-19.32	7861.87	0.79	9697.30	0.0002552	0.157
20	-17.32	7462.36	0.79	9201.35	0.0002421	0.149
21	-14.14	6826.83	0.80	8404.50	0.0002212	0.137
22	-10	5998.60	0.80	7356.38	0.0001936	0.120
23	-5.18	5034.10	0.80	6131.09	0.0001613	0.101
24	0	3999.07	0.81	4823.19	0.0001269	0.080

Table 6: Heat Load, Efficiency, Fan Power, Fuel and Electricity Consumption for Cycling Fan Case.

9.1 Building Zone Description

The configuration of this case is the same as the building for test case 1e.

9.2 Mechanical System Description

The mechanical system represents a simple sealed combustion natural gas furnace heating system.

9.2.1 Fans

Circulating and draft fans are incorporated into this model. The power draw will be set to 200W for the circulating fan and 50W for the draft fan.

9.2.1.1. Circulating Fan

Circulating fan power draw = 200 W
Circulating fan flow rate = 0.355 m^3/s
Circulating fan runs continuously.

9.2.1.2. Draft Fan

Draft fan power draw = 50 W
Draft fan cycles with burner operation.

9.3 Semi-Analytical Solution

This section presents a reference result for comparison against building simulation program results. However, unlike many of the previous cases, an analytic solution is not possible in this case. Rather, the reference result is calculated using a discrete time-step calculation, similar to the approach applied by most building simulation programs. A one-hour time-step is employed here.

The circulating fan operates continuously at 200W whereas the draft fan cycles with the burner operation. Its hourly energy will vary based on the load on the furnace and can be calculated as[e]:

$$\text{Energy}_{fan} = \Delta t \cdot \text{Power}_{fan} \cdot \text{PLR} \qquad (13)$$

[e] Implicit in this calculation is that the PLR is equal to the fraction of time during which the fan operates for a given time-step. In addition, it is assumed that there are no effects from fan start-up or shut-down, i.e., when the fan is on it draws 50W.

where Δt is the time step, $Power_{fan}$ is the rated fan power (50W in this case), and PLR is:

$$PLR = \frac{\text{Hourly Load}}{\text{Available Capacity}} \quad (1)$$

Time of Day	Temperature (°C)	Q_{Total} (W)	$\eta_{part\ load}$	$Q_{Furnace}$ (W)	Fuel Consumption (m^3/hr)	Electricity (kWh)
1	5.18	2764.03	0.82	3358.79	0.0000884	0.214
2	10.00	1799.53	0.83	2175.84	0.0000573	0.209
3	14.14	971.30	0.81	1196.21	0.0000315	0.205
4	17.32	335.77	0.71	472.15	0.0000124	0.202
5	19.32	0	0	0	0	0.200
6	20	0	0	0	0	0.200
7	19.32	0	0	0	0	0.200
8	17.32	335.77	0.71	472.15	0.0000124	0.202
9	14.14	971.30	0.81	1196.21	0.0000315	0.205
10	10.00	1799.53	0.83	2175.84	0.0000573	0.209
11	5.18	2764.03	0.82	3358.79	0.0000884	0.214
12	0	3799.07	0.81	4665.79	0.0001228	0.219
13	-5.18	4834.10	0.81	5997.33	0.0001578	0.224
14	-10	5798.60	0.80	7247.32	0.0001907	0.229
15	-14.14	6626.83	0.80	8318.55	0.0002189	0.233
16	-17.32	7262.36	0.80	9134.20	0.0002404	0.236
17	-19.32	7661.87	0.79	9642.42	0.0002537	0.238
18	-20	7798.13	0.79	9814.78	0.0002583	0.239
19	-19.32	7661.87	0.79	9642.42	0.0002537	0.238
20	-17.32	7262.36	0.80	9134.20	0.0002404	0.236
21	-14.14	6626.83	0.80	8318.55	0.0002189	0.233
22	-10	5798.60	0.80	7247.32	0.0001907	0.229
23	-5.18	4834.10	0.81	5997.33	0.0001578	0.224
24	0	3799.07	0.81	4665.79	0.0001228	0.219

Table 7: Heat Load, Efficiency, Fan Power, Fuel and Electricity Consumption for Draft Fan Case.

The heat output of the draft fan should not be added to zone energy balance; therefore, there should be no impact on the energy balance of the zone. The average-hourly values calculated for the heat to be delivered by the furnace was **4759.67 W** and the rate of fuel consumption was **0.0001253 m^3/s**.

The electrical consumption of the furnace system should increase with an additional load of the draft fan. The total electricity consumption was calculated as 473.18 kWh or **1.70 GJ** for the three-month period of this test. Table 7 gives the results for a 24-hour period.

Tier 2 Test Cases

The objective of the Tier 2 cases is to test the interactions between furnace, control, and zone models. The approach taken is the same zone configuration as Tier 1 cases except realistic boundary conditions t are incorporated.

10. Case 2a: Realistic Weather Data

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

Case 2a is the same as Case 1h, except that both fans cycle on and off with the burner. This case is designed to test the combined effects of circulating fan, draft fan, and realistic load profile. The output of interest is a comparison of the circulation and draft fan electrical energy consumption and fuel consumption.

10.1 Building Zone Description

10.1.1 Weather Data

For this test case, use **weather file: f**.

10.2 Mechanical System Description

The mechanical system represents a simple sealed combustion fuel-fired furnace heating system – the same as Tier 1 system.

10.2.1 General Information

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

10.2.2 Thermostat Control Strategy

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

Heat = on if temperature < 20°C; otherwise **Heat = off**
Cool = off

The controls for this system are ideal in that equipment is assumed to maintain the setpoint exactly, when it is operated and not overloaded. There are no minimum on or off time duration requirements for the unit, and no hysteresis control band, i.e., there is no: ON at setpoint + x°C or OFF at setpoint –y°C. If your software requires input for these then use the minimum allowable values.

10.2.3 Full-load Heating System Performance Data

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

Furnace capacity = 10 kW
Furnace full-load efficiency = 80%

10.2.4 Part-Load Operation

This case will prove to be a more stringent examination of the part-load curve implementation.

10.2.5 Fans

Circulating and draft fans are incorporated into this model. The power draw will be set to 200W for the circulating fan and 50W for the draft fan.

10.2.5.1. Circulating Fan

Circulating fan power draw = 200 W
Circulating fan flow rate = 0.355 m^3/s
Circulating fan cycles with burner operation.

10.2.5.2. Draft Fan

Draft fan power draw = 50 W
Draft fan cycles with burner operation.

11. Case 2b: Setback Thermostat

The objective of this test case is to test the effects of setback temperatures on furnace fuel consumption.

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. Since the zone and fabric have negligible thermal mass, the zone air's temperature should follow the setpoint schedule.

11.1 Mechanical System Description

11.1.1 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 will be a constant value of 20°C during the day, 6h00 to 23h00, and will then be setback to 15°C during the evening, 23h00 to 6h00. This relationship is illustrated in Figure 5.

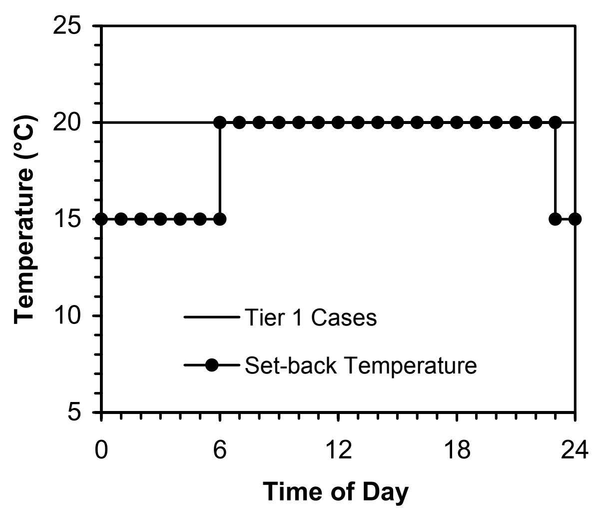

Figure 5: Setback temperatures over a 24-hour period.

For 6h00 ≤ time of day ≤ 23h00, then
Heat = on if temperature < 20°C; otherwise **Heat = off**
Cool = off

For 23h00 < time of day < 6h00, then
Heat = on if temperature < 15°C; otherwise **Heat = off**
Cool = off

12. Case 2c: Undersized Furnace

The objective of this test case is to test the behaviour of furnace algorithm when the system is undersized.

Case 2c is the same as Case 2b, except that the furnace is not sized to meet the peak load. For this reason, the zone temperature will fluctuate throughout the simulation.

12.1 Mechanical System Description

12.1.1 Full-load Heating System Performance Data

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

Furnace capacity = 5 kW
Furnace full-load efficiency = 80%

12.1.2 Part-Load Operation

This case tests the ability of the program to predict zone temperatures when the system operates at it's maximum.

13. Comparison of Results

Appendix A provides a comparison of the results obtained from three different software tools - ESP-r/HOT3000 (ESRU 2000), EnergyPlus (Crawley et al. 2000), and DOE2.1E (Winkelmann et al. 1994).

14. Model Enhancements

Prior to performing the fuel-fired furnace test cases, the EnergyPlus furnace model did not have capability to simulate part load performance and account for parasitic electric power such as that used by the draft fan. These features were added to the furnace model and were available for the first time in EnergyPlus Version 1.0.1.17. This then allowed EnergyPlus to simulate all of the Tier 1 Furnace HVAC BESTEST cases.

15. References

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Appendix A
Comparison of Results

The following table, Table 8, provides a comparison of the results calculated from the methods outlined in the previous sections with the results obtained from the test cases using three different software simulation tools: ESP-r/HOT3000 (ESRU 2000), EnergyPlus (Crawley et al. 2000), and DOE2.1E (Winkelmann et al. 1994).

Case	Analytical/Semi-Analytical		ESP-r/HOT3000		EnergyPlus		DOE2.1E	
	Energy Delivered (GJ)	Rate of Fuel Consum. (m^3/s)	Energy Delivered (GJ)	Rate of Fuel Consum. (m^3/s)	Energy Delivered (GJ)	Rate of Fuel Consum. (m^3/s)	Energy Delivered (GJ)	Rate of Fuel Consum. (m^3/s)
Tier 1 Test Cases								
1a	77.74	0.000263	77.75	0.000263	77.75	0.000263	77.73	0.000265
1b	77.74	0.000329	77.94	0.000328	77.75	0.000329	77.73	0.000331
1c	31.10	0.0001295	31.25	0.000130	31.10	0.0001295	31.12	0.00013
1d	0	0	0	0	0	0	0.15804	0.00000049
1e	31.10	0.000132	31.26	0.000132	31.10	0.000132	31.07	0.000131
1f	29.65	0.0001253	29.88	0.000126	29.59	0.000125	29.55	0.000124
1g	31.10	0.0001289	31.26	0.000129	30.46	0.000129	30.48	0.000128
1h	29.65	0.0001253	29.88	0.000126	29.59	0.000125	29.55	0.000124
Tier 2 Test Cases								
2a	-	-	41.36	0.000171	42.04	0.000176	42.08	0.000177
2b	-	-	39.41	0.000162	39.87	0.000167	39.87	0.000167
2c	-	-	34.32	0.000140	34.59	0.000144	34.49	0.000146

Table 8: Comparison of Energy Delivered by Fuel-Fired Furnace and Rate of Fuel Consumption.

Figure A1 is a chart of the results obtained by the individual programs for the test cases. It can be seen that there is very good correlation between the three software tools and the calculated results for the Tier 1, test cases.

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

The results of the comparison of the circulating and draft fan power consumption (kWh) are shown in Table 9. Again, the results for fan power diverge slightly for the Tier 2 cases.

Case	Analytical/Semi-Analytical	ESP-r/HOT3000	EnergyPlus	DOE2.1E
1f	432	432	433.3	432.1
1g	172.76	170.2	172.2	172.3
1h	473.18	473.4	473.1	473.3
2a	-	281.6	291.4	299.2
2b	-	268.3	276.1	282.2
2c	-	458.3	431.4	480

Table 9: Comparison of Fan Energy Consumption (kWh).

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 10 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.

Case	**Mean Temperature (°C)**			**Maximum Temperature (°C)**			**Minimum Temperature (°C)**		
	ESP-r/ HOT3000	**Energy Plus**	**DOE 2.1E**	**ESP-r/ HOT3000**	**Energy Plus**	**DOE 2.1E**	**ESP-r/ HOT3000**	**Energy Plus**	**DOE 2.1E**
2a	20.01	20	19.96	21.45	20	20.05	20	20	19.83
2b	18.75	18.53	18.5	22.7	20	20.05	15	15	14.88
2c	15.48	15.17	15.46	20.14	20	20.05	1.45	4.48	5.33

Table 10: Comparison of the Mean, Maximum, and Minimum temperatures for the Tier 2 Test Cases.

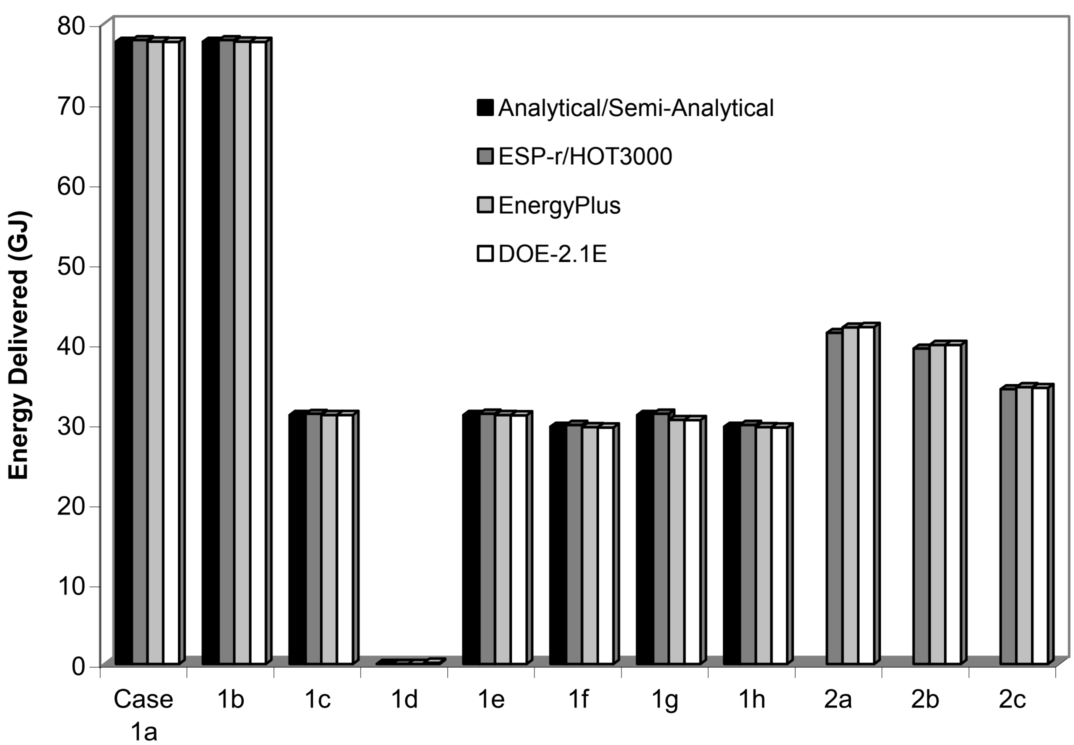

Figure A1: Comparison of the Energy Delivered for Tier 1 and 2 Test Cases, in GJ.

The modeler's reports for these simulations are provided in Appendices D, E, and F.

The simulation input files for the 11 test cases created by the three test tools are provided in the attached CD.

Appendix B
Alternate Test Cases

These alternate test cases are designed for those simulation programs that do not allow the definition of convection heat transfer coefficients. In this approach, the heating loads are driven by infiltration of outdoor air into the zone.

The following sections mirror the sections included in the main sections of the specification, and are defined as variations from the test cases defined therein.

B.1. Case 1a: Base Case Building and Mechanical System

The configuration of the base case building is a single near-adiabatic rectangular zone with energy is transferred to the zone air to maintain the interior setpoint temperature.

The setpoint temperature of zone, outdoor air temperature, and the amount of outdoor air infiltration drives the furnace operation. The furnace will run continuously at capacity, and this case is designed to ensure the furnace output is correctly represented in zone energy balance.

B.1.1 Building Zone Description

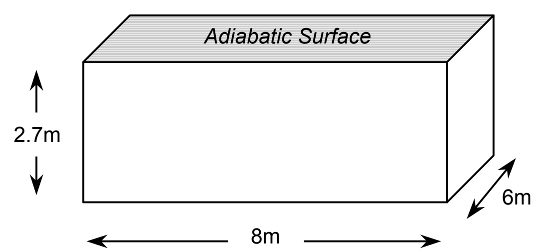

Figure B1: Base case building with the roof as an adiabatic surface.

B.1.1.1 Building Envelope Thermal Properties

The base case building is designed as a near-adiabatic test cell. Energy is transferred from the furnace to the zone air to maintain the interior setpoint temperature. This energy transfer is required to account for the additional load caused by the outdoor air infiltrating into the interior.

Material properties for the exterior wall, floor, and roof are as listed in Table 2 of the specification.

B.1.1.2 Weather Data

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

B.1.1.3 Infiltration

The internal infiltration rate accounted for in the base case model is:

1.1. **Infiltration rate = 0.2 kg/s** for entire simulation period.

It is up to the user to determine the correct combination of ac/h and altitude that brings the desired mass flow rate of air into the building.

B.1.2 Analytic Solution

The rate of energy consumption due to the required sensible heating of the incoming outdoor air, Q_{total}, can be defined as:

$$Q_{total} = \dot{m} \cdot c_p \cdot \Delta T \qquad (15)$$

where:

$\dot{m}$ is the air mass flow rate, kg/s,
c_p is the specific heat of the air, J/kg K, and
ΔT is the temperature difference between the indoor and outdoor air, K.

Using the values defined in the previous sections and equation (9), heat transfer rate required to maintain the interior setpoint temperature is **Q_{total} = 9997 W**. The rate of energy transfer from the furnace to the zone air required to meet this load will be, **$Q_{delivered}$ = 9997 W**.

As the furnace is 100% efficient, the heat delivered by the furnace is equal to the rate at which the furnace consumed fuel, as calculated with equation (11), i.e., **$Q_{delivered}$ = Q_{fuel} = 9997 W**. Using equation (10), the rate of fuel consumption is **0.000263 m^3/s**.

The remaining test cases differ from the originals only in the analytical/calculated solutions. Table 11 defines the numerical results calculated for the infiltration cases.

	Analytical/Semi-Analytical	
Case	**Energy Delivered (GJ)**	**Rate of Fuel Consumption (m^3/s)**
1a	77.77	0.000263
1b	77.77	0.000329
1c	31.11	0.0001296
1d	0	0
1e	31.11	0.000132
1f	29.66	0.0001253
1g	31.11	0.000129
1h	29.66	0.0001253

Table 11: Energy Delivered and Consumed by Fuel-Fired Furnace, in GJ.

Appendix C
Semi-Analytical Solutions

For Cases 1e-1h, analytic solutions are not possible, and as such, the reference results are calculated using a discrete time-step calculation, similar to the approach applied by most building simulation programs. As the thermal mass of the building is effectively zero, a solution can be found on a time step basis. The following details this one-hour time-step approach.

A spreadsheet was created with each row representing one hour of the three-month simulation period. The 'hours' column was filled sequentially with 1 to 24 for each day, beginning again with 1 for the next day. In this way, the exterior dry bulb temperature could be calculated for each hour using equation (12):

$$T = 20 * (\sin(\frac{\pi}{12} \cdot t))$$

where t is the hour of the day.

The load placed on the furnace, Q_{Total}, is then calculated using:

$$Q_{Total} = q_{Total} \cdot \text{Area}$$

where q_{Total} is calculated using equation (9):

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

The part load ratio (PLR) is then calculated using equation (1):

$$PLR = \frac{\text{Load Placed on Furnace}}{\text{Furnace Capacity}}$$

where the Furnace Capacity has been previously defined as 10kW, and the part load factor (PLF) can then be calculated using equations (3) and (4):

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

$$HIR(PLR) = a + b \cdot PLR + c \cdot PLR^2 + d \cdot PLR^3$$

where the coefficients have been previously defined as:

a = 0.0080472574;
b = 0.87564457;
c = 0.29249943; and
d = -0.17624156.

The part load efficiency is a function of the steady-state efficiency and the part load factor (PLF), as was defined in equation (2):

$$PLF = \frac{\text{Part Load Efficiency}}{\text{Steady State Efficiency}} = \frac{\eta_{\text{part load}}}{\eta}$$

which can be rearranged to give:

$$\eta_{\text{part load}} = \eta \cdot PLF$$

$Q_{furnace}$, the rate at which the fuel's chemical energy is converted to thermal mass in the furnace, can be calculated using the definition of the furnace steady state efficiency, as shown in equation (11):

$$\eta = \frac{Q_{Total}}{Q_{furnace}}$$

which can be rearranged to give:

$$Q_{furnace} = Q_{delivered} \cdot \eta$$

The rate of fuel consumption of the furnace is then calculated using equation (10):

$$C = \frac{Q_{fuel}}{HHV}$$

where C is the rate of fuel consumption of the furnace in m^3/s and HHV is the Higher Heating Value of natural gas – defined as 38 MJ/m^3 in Section 2.2.5.

The electrical consumption of the fans that run continuously is simply calculated as a constant consumption. If, for example, a 200W fan runs continuously, then 200W is applied for that timestep. If, on the other hand, the fan cycles with the furnace burner operation, then the fan power is multiplied by the part load ratio (PLR) for that timestep.

A sample spreadsheet is available for interested users.

Appendix D
Summary of WYEC2 Record Format

Weather files in WYEC2 format consist of 8760 identical fixed format records (8784 records for leap years), one for each hour of each day of the year. Each record is 116 characters (plus 2 for CR/LF) in length and is organized according to the table below. This table shows which weather elements are provided in the WYEC2 format for general information only. Further detailed information on present weather, snow cover, and flag codes is available on request.

All WYEC2 values are for Local Standard Time. Irradiance and illuminance fields contain data integrated over the hour, meteorological fields contain observations made at the end of the hour. For example, hour 12 contains irradiance/illuminance from hour 11 to 12 and meteorological observations made at hour 12.

Field Number	Data Positions	Flag Position(s)	Data element
001	001-005	--	WBAN station identification number
002	006-006	--	File source code
003	007-014	--	Year, Month, Day, Hour (2 characters each)
101	015-018	--	Extraterrestrial irradiance, kJ/m²
102	019-022	023-024	Global horizontal irradiance, kJ/m²
103	025-028	029-030	Direct normal irradiance, kJ/m²
104	031-034	035-036	Diffuse horizontal irradiance, kJ/m²
105	037-040	041	Global horizontal illuminance, 100 lux
106	042-045	046	Direct normal illuminance, 100 lux
107	047-050	051	Diffuse horizontal illuminance, 100 lux
108	052-055	056	Zenith luminance, 100 Cd/m²
110	057-058	059	Minutes of sunshine, 0-60 minutes
201	060-063	064	Ceiling height, 10 m
202	065-068	069	Sky condition
203	070-073	074	Visibility, 100 m
204	075-082	083	Present Weather
205	084-088	089	Station pressure, 10 Pa
206	090-093	094	Dry bulb temperature, 0.1°C
207	095-098	099	Dew point temperature, 0.1°C
208	100-102	103	Wind direction, 0-359 degrees
209	104-107	108	Wind speed, 0.1 m/s
210	109-110	111	Total sky cover, 0-10 in tenths
211	112-113	114	Opaque sky cover, 0-10 in tenths
212	115-115	116	Snow cover

Appendix E
ESP-r/HOT3000 Modeller's Report

Application of the Furnace HVAC BESTEST to ESP-r/H3K

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Introduction

This report describes the modelling strategy and assumptions used for the proposed Furnace HVAC BESTEST carried out by CETC at Natural Resources Canada using a modified version of the ESP-r software (ESRU 1996) called ESP-r/H3K. ESP-r/H3K retains ESP-r's modelling approach but includes new models for ground coupling, air infiltration, furnace, air and ground source heat pumps, DHW, and fuel cells. The simulator used was bpsh3k version 1.1 for generating the Tier 1 Test Case results and version 1.7 for generating the Tier 2 Test Case results.

The Furnace HVAC test cases description and the basis of the modeling approach are both described in the report by Purdy and Beausoleil (2002). All the required characteristics of the Tier 1 and Tier 2 Test Cases, specified in the Furnace HVAC BESTEST report, are included in the ESP-r/H3K simulation models created. Details about various aspects of these simulation models, as they are implemented in the ESP-r/H3K environment, are presented in the following sections of this report.

Zone Size and Shape

No assumption had to be made here. The volume of the box was exactly 129.6 m^3

Boundary Conditions

Four walls, roof, and floor were declared as EXTERIOR. It is to be noted that adiabatic boundary conditions on the outside of the walls and floor can be obtained using ADIABATIC boundary conditions in ESP-r/H3K.

Material Properties

Component	Property	Value
Wall	Conductivity (W/m-K)	0.01
	Density (kg/m^3)	0.10
	Specific Heat (J/kg-K)	0.10
	Emissivity	0.01
	Absorptivity	0.01
	Thickness (m)	1.0
Floor	Conductivity (W/m-K)	0.01
	Density (kg/m^3)	0.10
	Specific Heat (J/kg-K)	0.10
	Emissivity	0.01
	Absorptivity	0.01
	Thickness (m)	1.0
Roof	Conductivity (W/m-K)	0.071

	Density (kg/m^3)	0.10
	Specific Heat (J/kg-K)	0.10
	Emissivity	0.01
	Absorptivity	0.01
	Thickness (m)	0.01

If smaller values are used for the properties listed above, ESP-r does not converge to a realistic solution.

Convection Heat Transfer Coefficient

Component	Inside h (W/m^2-K)	Outside h (W/m^2-K)
Wall	0.1	0.1
Floor	0.1	0.1
Roof	20	20

If smaller values are specified for the convection heat transfer coefficient for the wall and the floor, ESP-r does not converge to a realistic solution.

Controls

ESP-r/H3K ideal controller used with heating capacity of 20 kW while the furnace capacity is set to 10 kW. A value greater than 10 kW is used for the ideal controller heating capacity to allow the load of the zone to exceed 10 kW if this is what the solution dictates. It is suggested that the text in the Manual be modified to allow the use of a larger heating capacity (greater than 10 kW) with the controller. This way the load on the furnace will not be limited to a maximum of 10 kW and it is possible to predict the proper number of under heating hours for the zone.

Part-Load Operation

Equations in the report for part-load performance need to be modified. Furnace Part-Load Factor *(PLF)* is given as a function of equipment Part-Load Ratio *(PLR)* and Heat-Input Ratio *(HIR)* by

$$PLF = \frac{PLR}{HIR}$$

where $HIR = a + b \times PLR + c \times PLR^2 + d \times PLR^3$

Simulation Timestep

The simulations were performed with a 1-hour timestep.

Simulation Results

Results for Tier 1 and Tier 2 test cases obtained using ESP-r/H3K are shown in Tables 1, 2, 3, and 4. ESP-r/H3K loads for case1a are slightly higher than the analytical solution probably due to the fact that the emissivity of the outside surfaces is not exactly zero resulting in an extra heat loss due to long wave radiation exchange with the outside. The predicted power consumption of the furnace is 10 kW due to the fact that the loads are slightly larger than 10 kW and the equipment capacity is set to 10 kW.

References

Clarke J. A. 1977. Environmental Systems Performance. Ph.D. Thesis, University of Strathclyde, Glasgow, Scotland.

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Purdy, J. and Beausoleil-Morrison, I. 2002. Building Energy Simulation Test for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST): Fuel-Fired Furnace Test Suite.

Table 1: Tier 1 Test Cases Results

Test Case	Furnace Load (kWh)	Furnace Load (W)	Furnace Input (kWh)	Furnace Input (W)	Fuel Consumption (m^3/s)	Equivalent Efficiency	Fan Energy Consumption (kWh)
1a	21,650	10,023	21,594	9,996	0.000263	100%	---
1b	21,650	10,023	26,994	12,497	0.000328	80.2%	---
1c	8,680	4,018	10,686	4,947	0.000130	81.2%	---
1d	0	0	0	0	0	---	---
1e	8,683	4,019	10,858	5,027	0.000132	80%	---
1f	8,300	3,842	10,338	4,786	0.000126	80.3%	432.
1g	8,683	4,019	10,644	4,927	0.000129	81.5%	170.2
1h	8,300	3,842	10,338	4,786	0.000126	80.3%	473.4

Table 2: Tier 2 Test Cases Results

Test Case	Furnace Load (kWh)	Furnace Load (W)	Furnace Input (kWh)	Furnace Input (W)	Fuel Consumption (m^3/s)	Equivalent Efficiency	Fan Energy Consumption (kWh)
2a	11,490	5,319	14,027	6,494	0.000171	81.9%	281.6
2b	10,946	5,068	13,344	6,178	0.000162	82%	268.3
2c	9,533	4,413	11,497	5,322	0.000140	82.9%	458.3

Table 3: Tier 1 Test Cases average, minimum, and maximum space temperatures

Test Case	Average Temperature (^oC)	Maximum Temperature (^oC)	Minimum Temperature (^oC)
1a	20.0	20.0	20.0
1b	20.0	20.0	20.0
1c	20.0	20.0	20.0
1d	20.0	20.0	20.0
1e	20.01	23.42	20.0
1f	20.07	23.53	20.0
1g	20.01	23.42	20.0
1h	20.07	23.53	20.0

Table 4: Tier 2 Test Cases average, minimum, and maximum space temperatures

Test Case	Average Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
2a	20.01	21.45	20.0
2b	18.75	22.7	15.0
2c[1]	15.48	20.14	1.45[2]

[1]Total under heating hours = 1035
[2]Minimum temperature on 27th of January at 5:30 a.m.

Appendix F
DOE 2.1E Modeller's Report

Application of the Furnace HVAC BESTEST to DOE-2.1E

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March 2003

1.2. Introduction

This report describes the modeling strategy and assumptions used for the proposed Furnace HVAC BESTEST carried out by CETC at Natural Resources Canada using DOE-2.1E version c133. The Furnace HVAC test cases description and the basis of the modeling approach are both described in the report by Purdy and Beausoleil-Morrison (2002). All the required characteristics of the Tier 1 and Tier 2 Test Cases, specified in the Furnace HVAC BESTEST report, are included in the DOE-2.1E simulation models created. Details about various aspects of these simulation models, as they are implemented in DOE-2.1E, are presented in the following sections of this report.

1.3. Building Description in DOE-2

The materials of the walls, floor, and ceiling of the test building were specified using the R-value method in DOE-2. The surface-to-surface thermal resistance of each of these three materials was exactly equal to the value given in Table 1.

The inside film thermal resistance (convection + radiation) for the walls and the floor was set very high so that the heat transfer through these components is practically 0. The inside thermal resistance for the roof was set to 1 / 20 m²-K/W.

The solar absorptance and long wave emissivity of all the surfaces were set to very small values.

The wind speed in the weather file was modified until the outside film resistance (convection + radiation) was as close as possible to 1 / 20 m²-K/W.

1.4. Tier 1 Test Cases

Results for Tier 1 Test Cases are contained in Table 1 and 3. Note that Fan Energy Consumption includes circulation fan energy and draft fan energy when one is specified. All the test cases are modeled with system type PSZ in DOE-2.

Differences between the results in Table 1 and those in the Manual can be attributed to outside film resistance of the roof being slightly lower than 1 / 20 m²-K/W. Also the zone temperature at the system level in DOE-2 is slightly different from 68 °F.

Case1f

Using system PSZ it is possible to model a supply fan in continuous mode. Also DOE-2 accounts for the reduction in the space-heating load due to the heat gain from the fan to the supply air stream.

Case 1g

Using system PSZ it is possible to model a supply fan in the auto or intermittent mode. The supply fan contributes toward satisfying the heating load of the zone, therefore the load on the furnace will be less than when there is no fan (case1e).

Case 1h

Draft fan is specified as a furnace auxiliary power (BDL command FURNACE-AUX-KW in DOE-2).

1.5. Tier 2 Test Cases

Results for Tier 2 Test Cases are contained in Table 2 and 4. Fan Energy is the sum of circulation fan energy and draft fan energy when one is specified.

The HVAC system in this case was modeled using the DOE-2 system PSZ. Part load performance for the furnace given in the document is used.

Additional Output for Test Case2c:
Minimum Zone Temperature: 5.33 oC
Time of Minimum Zone Temperature: January 16th at 2 a.m.
Number of Under Heating Hours: 985

1.6. References

Purdy, J. and Beausoleil-Morrison, I. 2002. Building Energy Simulation Test for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST): Fuel-Fired Furnace Test Suite.

Table 1: Tier 1 Test Cases Results

Test Case	Furnace Load (kWh)	Furnace Load (W)	Furnace Input (kWh)	Furnace Input (W)	Fuel Consumption (m^3/s)	Equivalent Efficiency	Fan Energy Consumption (kWh)
1a	21,592	9,996	21,776	10,081	0.000265	99.1%	---
1b	21,592	9,996	27,220	12,601	0.000331	79.3%	---
1c	8,644	4,002	10,706	4,957	0.000130	80.7%	---
1d	43.9	20.3	40.4	18.7	0.00000049	---	---
1e	8,630	3,995	10,748	4,976	0.000131	80.3%	---
1f	8,209[a]	3,800	10,223	4,733	0.000124	80.3%	432.1
1g	8,466[a]	3,919	10,541	4,880	0.000128	80.3%	172.3
1h	8,209[a]	3,800	10,223	4,733	0.000124	80.3%	473.3[b]

[a] Furnace load accounts for effect of circulation
[b] Draft fan energy included

Table 2: Tier 2 Test Cases Results

Test Case	Furnace Load (kWh)	Furnace Load (W)	Furnace Input (kWh)	Furnace Input (W)	Fuel Consumption (m^3/s)	Equivalent Efficiency	Fan Energy Consumption (kWh)
2a	11,690[a]	5,412	14,555	6,739	0.000177	80.3%	299.2[b]
2b	11,076[a]	5,128	13,781	6,380	0.000167	80.3%	282.2[b]
2c	9,580[a]	4,435	12,046	5,577	0.000146	79.5%	480.0[b]

[a] Furnace load accounts for effect of circulation
[b] Draft fan energy included

Table 3: Tier 1 Test Cases average, minimum, and maximum space temperatures

Test Case	Average Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
1a	19.86	19.88	19.88
1b	19.86	19.88	19.88
1c	19.88	19.88	19.88
1d	20.11	20.11	20.11
1e	20.00	20.11	19.88
1f	20.05	20.50	19.88
1g	20.0	20.11	19.88
1h	20.05	20.50	19.88

Table 4: Tier 2 Test Cases average, minimum, and maximum space temperatures

Test Case	Average Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
2a	19.96	20.05	19.83
2b	18.50	20.05	14.88
2c	15.46	20.05	5.33

Appendix G
EnergyPlus Modeller's Report

EnergyPlus Testing with

Fuel-Fired Furnace HVAC BESTEST

EnergyPlus Version 1.0.2.008

March 2003

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U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Building Technology, State and Community Programs

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1 TEST OBJECTIVES AND OVERVIEW

1.1 Test Type: Analytical and Comparative - HVAC

The International Energy Agency (IEA) HVAC BESTEST – Fuel-Fired Furnace Test Suite procedure and specification contain a set of analytical tests for testing building simulation programs that are capable of modeling fuel-fired furnaces. Also included are comparative results from several other whole building simulation programs. Analytical tests compare a program's results to mathematical solutions for simple cases. This is an excellent method to use for assessing the accuracy of results since there is only one solution for the case analyzed given the boundary conditions. Comparative tests compare a program to itself or to other simulation programs. Both types of testing accomplish results on two different levels, both validation and debugging. Validation is accomplished when the results of the test program compare favorably with the analytical results. Debugging is accomplished when the results for certain cases do not compare favorably with the analytical results and then through systematic checking it is determined that the source of the difference is due to an input error, a modeling inconsistency or flaw in the program logic.

1.2 Test Suite: IEA Fuel-Fired Furnace HVAC BESTEST

The tests described in International Energy Agency (IEA) Building Energy Simulation Test for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST), Fuel-Fired Furnace Test Suite (Purdy & Beausoleil-Morrison 2002) were performed.

The document describes a series of eleven cases that isolate a single facet of the furnace model in each case, starting with the simplest case and progressively adding complexity. The test cases are grouped into two tiers: Tier 1 test cases employ simple boundary conditions and test the basic functionally of the furnace model using constant hourly or sinusoidal outdoor dry-bulb temperatures. Tier 2 uses continuously varying hourly outdoor dry-bulb temperatures from a cold weather location. Specific cases are designed to test a building energy simulation program with respect to the following components:

- Furnace steady state efficiency
- Furnace part load ratio
- Outdoor temperature
- Circulating fan operation
- Draft fan operation.

The following tests were performed as specified in the Fuel-Fired Furnace Test Suite manual:

- Case 1a – Base Case Building and Mechanical System
- 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

1.2.1 Case 1a – Base Case Building and Mechanical System

The basic test building (Figure 1) is a rectangular 48 m² 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. Material properties are described below. For further details, refer to Section 2.1 of the Fuel-Fired Furnace HVAC BESTEST User's Manual.

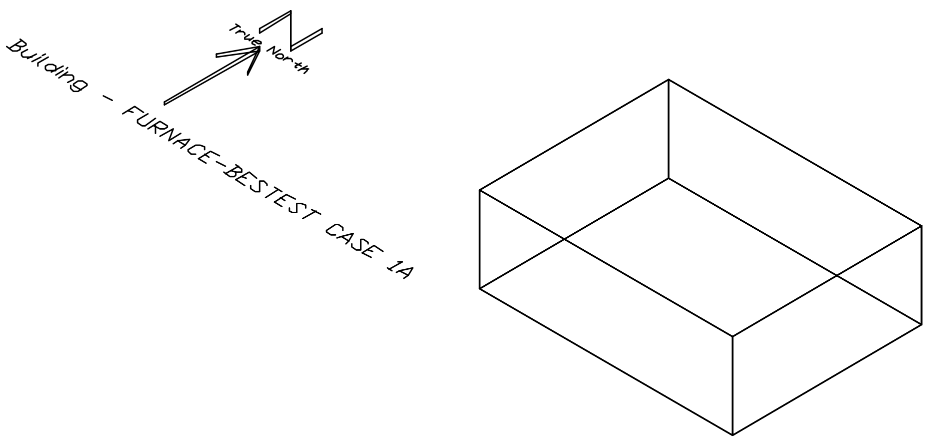


Figure 1. Base Case Building - Isometric View of Southeast Corner

Wall and Floor Construction:

Element	k (W/m-K)	Thickness (m)	U (W/m^2-K)	R (m^2-K/W)
Int. Surface Coeff.			20.0	0.05
Insulation	0.010	1.000	0.010	100.000
Ext. Surface Coeff.			20.0	0.05

Roof Construction:

Element	k (W/m-K)	Thickness (m)	U (W/m^2-K)	R (m^2-K/W)
Int. Surface Coeff.			20.0	0.05
Insulation	0.0714	0.01	7.14	0.14
Ext. Surface Coeff.			20.0	0.05

Opaque Surface Radiative Properties:	**Interior Surface**	**Exterior Surface**
Solar Absorptivity	0.0	0.0
Longwave Emissivity	0.0	0.0

Infiltration: None

Internal Load: None

Mechanical System: 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 is drawn directly from outdoors

There is a non-proportional-type thermostat; cool always off, heating on if zone air temperature <20.0°C. When operating at part load the furnace heat input ratio (HIR) is a function of the part load ratio (PLR):

$HIR = a + b * PLR + c * PLR^2 + d * PLR^3$
$a = 0.0080472574$
$b = 0.87564457$
$c = 0.29249943$
$d = -0.17624156$

For those tests where the supply fan and draft fan are to be simulated, the following is assumed:

Supply fan power = 200 W
Draft fan power = 50 W and cycles with burner

Table 1 summarizes the mechanical system options that were simulated for each test.

1.2.2 Weather Data

Five three-month long (January – March) weather files were provided with the test suite designated as follows:

weather a.txt
weather c.txt
weather d.txt
weather e.txt
weather f. txt

Although hourly values are provided for six different weather variables, the only parameter that varies for each weather file is the ambient dry-bulb temperature; all other data is the same for each weather file. For 'weather a', the outdoor dry-bulb temperature remains constant at -30°C for the three month period. Similarly, 'weather c has a constant 0°C outdoor temperature and ‘weather d’ has a constant 20°C outdoor temperature. ‘Weather e’ features the outdoor temperature varying sinusoidally each 24-hour period from -20°C to +20°C. Diffuse and direct normal solar intensity and wind speed are all set to 0.0 for all hours thus eliminating the impact of these effects on the results and outdoor air relative humidity is held constant at 50% for all weather files. ‘Weather f’ represents a more realistic weather set from a cold winter location and was provided in a WYEC2 format.

For the first four weather sets, EnergyPlus compatible weather files had to be created. Because weather file ‘f’ was provided originally in WYEC2 format, it was decoded directly using the EnergyPlus weather converting utility. The latest version of the Furnace HVAC BESTEST specification indicates that the first four weather files are now also available in WYEC2 format. These later weather files have not yet been received and were not used during the Round 1 or Round 2 testing reported herein. Some of the differences in EnergyPlus results compared to the BESTEST analytical results might be attributed to minor weather file inconsistencies.

1.2.3 Simulation and Reporting Period

Simulations for all cases were run for a three-month period. For cases which used weather files a, c or d, the results do not vary from hour to hour. For cases using ‘weather e’, the results vary within a 24-hour period and then repeat for each day of the simulation. For Cases 2a through 2c, the results vary hourly over the entire 3-month simulation period. The Fuel-Fired Furnace Test Suite manual provided analytical results for Cases 1a through 1h to compare the simulation program’s results to.

Table 1. Furnace HVAC BESTEST Case Descriptions

Case	Furnace Capacity (W)	Furnace Full Load Efficiency (%)	Part Load Simulation	Outdoor Temperature (C)	Circulating Fan Power (W)	Draft Fan Power (W)	Comments
1a	10000	100	No	-30	0	0	Base Case Building
1b	10000	80	No	-30	0	0	Efficiency Test
1c	10000	80	Yes	0	0	0	Simple Part Load Test
1d	10000	80	No	20	0	0	No Load Test
1e	10000	80	Yes	Sinusoidal	0	0	Complex Part Load Test
1f	10000	80	Yes	Sinusoidal	200 continuous	0	Circulating Fan Test
1g	10000	80	Yes	Sinusoidal	200 cycles with burner	0	Cycling Circulating Fan Test
1h	10000	80	Yes	Sinusoidal	200 continuous	50 cycles with burner	Draft Fan Test

2a	10000	80	Yes	Varying	200 cycles with furnace	50 cycles with burner	Realistic Weather
2b	10000	80	Yes	Varying	200 cycles with furnace	50 cycles with burner	Setback Thermostat
2c	5000	80	Yes	Varying	200 cycles with furnace	50 cycles with burner	Undersized Furnace

2 MODELER REPORT

2.1 Modeling Methodology

For modeling of the simple fuel-fired furnace, the EnergyPlus Blow-Thru Furnace: Heat Only model was utilized. As indicated in Figure 1, the components of the furnace model include a supply fan and gas-fired heating coil that supplies heated air to the conditioned spaces. A single action thermostat in the control zone controls the amount of heat delivered to the space by cycling the burner. The supply fan operation can also be specified as either continuous or cycling. If a draft fan is present, its electric power is specified using the parasitic electric load input parameter on the COIL:Gas:Heating object. The model also allows for a furnace part load performance curve to be specified where the heat input ratio (HIR) is expressed as a cubic function of the part load.

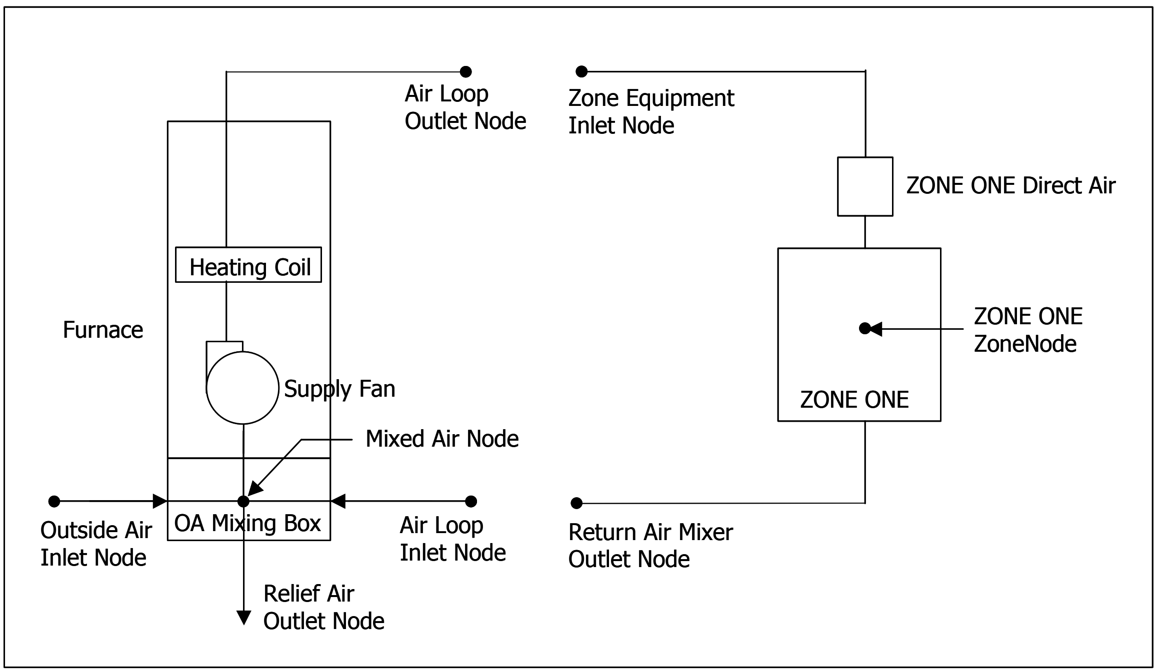


Figure 1. EnergyPlus Furnace Model

2.2 Modeling Assumptions

During the Furnace HVAC BESTEST analysis using EnergyPlus the following assumptions, consistent with the testing specification, were followed:

- The furnace is a convective heating system that injects heat directly into the zone air
- The zone air is fully mixed
- The furnace has no pilot light

- The furnace draws combustion air directly from outdoors
- The furnace has a sealed combustion chamber where the flue does not extract air from the zone
- The air distribution ducts have no thermal or air losses
- Ideal thermostat control with no throttling range.

2.3 Modeling Difficulties

2.3.1 Weather Data

The weather files a, c, d, e and f provided as part of the Furnace HVAC BESTEST package are not directly usable by EnergyPlus. The first four weather files had data presented in a tab delimited test format and contained only the following data for each hourly weather record:

Outdoor dry-bulb temperature, °C
Relative humidity, %
Wind speed, m/s
Wind direction, clockwise degrees from north
Direct normal solar intensity, W/m^2
Diffuse solar on the horizontal, W/m^2.

Except for the dry-bulb temperature and relative humidity, all other parameters had values of 0.0 for every hour. Weather file f was a WYEC2 weather file for Ottawa, Canada. EnergyPlus comes with a weather decoding utility that works with weather files that are in TMY2 or WYEC2 format. The first four Furnace HVAC BESTEST weather files were not in either of these formats and therefore the EnergyPlus weather files had to be custom made.

2.3.2 Building Envelope Construction

The specification for the building envelope indicates that the exterior walls and floor are made up of one opaque layer of insulation (R=100) to approach an almost adiabatic condition while the roof was constructed of opaque layer with an R=0.14. The heating requirement in the zone each hour was due to the heat transfer through the roof surface. The analytical solution assumed that the inside and outside film coefficient of the roof surface was constant at 20 W/m-K. EnergyPlus does not allow the user to set these coefficients. They are calculated each hour as a function of several variables including temperature and air speed. 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 as follows:

E-Plus Interior Film	4.04W/m2-K
E-Plus Outside Film	8.23 W/m2-K

The BESTEST values are 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, 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. Instead, 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 sinusoidally over a 24-hour period, the roof area was set to 87.96 m2 in order to meet the heat loss for the first hour of the day. For all other hours in the day, there was a slight difference between the Furnace BESTEST and EnergyPlus heat loss through the roof, differing by < 0.3%. Cases 2a, 2b and 2c used the same building model as Case 1h.

The latest Furnace HVAC BESTEST specification contained alternate test cases for simulation programs like EnergyPlus that do not allow the definition of convection heat transfer coefficients. The alternate procedure requires the user to set the properties of all surfaces in the space to near-adiabatic test cell conditions. The load on the space each hour is then imposed by a constant infiltration of outdoor air at 0.2 kg/s (mass flow rate). This still created problems for EnergyPlus since the user is required to specify an infiltration rate in terms of m3/s (volume flow rate), which is then converted to a mass flow rate each hour using the actual outdoor air density for each hour. A constant infiltration mass flow rate of 0.2 kg/s could therefore not be imposed on EnergyPlus.

2.3.3 Building Envelope Construction

Prior to EnergyPlus Version 1.0.1.17, the EnergyPlus furnace model did not have capability to simulate part load performance and account for parasitic electric power such as that used by the draft fan. These features were added to the furnace model and were available for the first time in EnergyPlus Version 1.0.1.17. This then allowed EnergyPlus to simulate all of the Tier 1 Furnace HVAC BESTEST cases.

2.3.4 Circulating Fan Flow Rate

The only information that the test suite specification gives for the indoor circulating fan is that it uses 200 W of power. This is not a direct input for the EnergyPlus fan object. The EnergyPlus fan object requires the user to define the following parameters from which the fan input power is calculated:

Air volume flow rate, m3/s [Q]
Delta pressure, Pa [$\triangle$P]
Total fan efficiency, dimensionless [Eff]

The fan input power W in watts is then:

$$W = Q * \triangle P / Eff$$

It was assumed that Q = 2 m3/s and $\triangle$P = 1 Pa. For 200 W input power the total fan efficiency is therefore 0.01.

2.4 Results – Round 1

Results from the first modeling with EnergyPlus Version 1.0.1.19 are presented in Table 2. Note that all results are expressed in Watts (W) to conform to the units of the analytical results reported in the Furnace

BESTEST Manual. The part load operation of the supply fan in Case 1g indicates that there may be a bug in the EnergyPlus code. All other results are within 0.2%.

Table 2 – Furnace HVAC BESTEST Results for EnergyPlus Version 1.0.1.19

Case 1a - Base Case Building, 100% Efficient Furnace			
	BESTEST	EnergyPlus	Difference (%)
Hourly Heat delivered to Space (W)	9,998	9,999	0.008%
Hourly Fuel Input (W)	9,998	10,000	0.020%
Case 1b - 80% Efficient Furnace			
	BESTEST	EnergyPlus	Difference (%)
Hourly Heat delivered to Space (W)	9,998	9,999	0.008%
Hourly Fuel Input (W)	12,498	12,500	0.020%
Case 1c - Simple Part Load Test			
	BESTEST	EnergyPlus	Difference (%)
Hourly Heat delivered to Space (W)	3,999	4,000	0.013%
Hourly Fuel Input (W)	4,922	4,922	0.007%
Case 1d - No Load Test			
	BESTEST	EnergyPlus	Difference (%)
Hourly Heat delivered to Space (W)	-	-	0.000%
Hourly Fuel Input (W)	-	-	0.000%
Case 1e - Complex Part Load Test			
	BESTEST	EnergyPlus	Difference (%)
Daily Heat delivered to Space (W)	95,978	95,988	0.011%
Daily Fuel Input (W)	119,963	120,077	0.095%
Total Fan Power (W)	-	-	0.000%
Case 1f - Circulating Fan Test			
	BESTEST	EnergyPlus	Difference (%)
Daily Heat delivered to Space (W)	91,505	91,327	-0.195%
Daily Fuel Input (W)	114,232	114,106	-0.111%
Total Fan Power (W)	4,800	4,800	0.000%
Case 1g - Cycling Circulating Fan Test			
	BESTEST	EnergyPlus	Difference (%)
Daily Heat delivered to Space (W)	95,978	94,007	-2.053%
Daily Fuel Input (W)	117,564	117,570	0.006%
Total Fan Power (W)	1,920	2,193	14.236%
Case 1h - Draft Fan Test			
	BESTEST	EnergyPlus	Difference (%)
Daily Heat delivered to Space (W)	91,505	91,327	-0.195%
Daily Fuel Input (W)	114,232	114,106	-0.111%
Total Fan Power (W)	5,257	5,257	-0.007%

2.5 Results – Round 2

During Round 2 of the testing, EnergyPlus Version 1.0.2.008 was used to perform the simulations. Also during Round 2 the three new Tier 2 test were added and the results for the Tier 1 cases were expressed instead in units of GJ and m3/s to be consistent with the calculated/analytical results reported in the August 2002 version of the Furnace HVAC BESTEST manual. BESTEST analytical results were not available for the Tier 2 tests.

Results from the second round of simulations with EnergyPlus Version 1.0.2.008 are presented in Table 3.

2.6 Software Errors Discovered and/or Comparison between Different Versions of the Same Software – Round 2

The suite of Furnace HVAC BESTEST cases were simulated again using EnergyPlus Version 1.0.2.008 (the first public release of Version 2.0, July 2002). The EnergyPlus input files were identical to those used in Round 1 for Cases 1a through 1h. New EnergyPlus input files, however, had to be developed for the new cases 2a through 2c.

EnergyPlus Version 1.0.2.008 had one significant code change compared to Version 1.0.1.019 which did result in some changes compared to Round 1:

- A change was made to the manner in which the supply fan was simulated during part load operation

The following changes in EnergyPlus results were observed:

- The total fan power disagreement between EnergyPlus and BESTEST for Case 1g improved and were within <2% of each other
- Results for all other Tier 1 cases were within 1.4% of the BESTEST analytical results

2.7 Results – Round 3

In March 2003, an additional requirement was added to the test suite specification, i.e., the circulating fan volume flow rate was set to 0.355 m3/s. To accommodate this change and still have the fan input power remains at 200 W, the fan total efficiency input was changed from the previous value of 0.01 used in Rounds 1 and 2 to a new value of 0.441975. As expected, the results for Round 3 were identical to the Round 2 results presented in Table 3 and in Appendix H.

Table 3 – Furnace HVAC BESTEST Results for EnergyPlus Version 1.0.2.008

Case 1a - Base Case Building, 100% Efficient Furnace			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	77.74	77.75	0.013%
Average Rate of Fuel Consumption (m3/s)	0.000263	0.000263	0.048%
Case 1b - 80% Efficient Furnace			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	77.74	77.75	0.013%
Average Rate of Fuel Consumption (m3/s)	0.000329	0.000329	-0.028%
Case 1c - Simple Part Load Test			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	31.10	31.10	0.000%
Average Rate of Fuel Consumption (m3/s)	0.0001295	0.0001292	-0.263%
Case 1d - No Load Test			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	-	-	0.000%
Average Rate of Fuel Consumption (m3/s)	-	-	0.000%
Case 1e - Complex Part Load Test			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	31.10	31.10	0.000%
Average Rate of Fuel Consumption (m3/s)	0.000132	0.000130	-1.407%
Total Fan Power (GJ)	-	-	0.000%
Case 1f - Circulating Fan Test			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	29.65	29.58	-0.242%
Average Rate of Fuel Consumption (m3/s)	0.0001253	0.0001237	-1.260%
Total Fan Power (GJ)	1.560	1.555	-0.308%
Case 1g - Cycling Circulating Fan Test			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	31.10	30.49	-1.955%
Average Rate of Fuel Consumption (m3/s)	0.0001289	0.0001275	-1.048%
Total Fan Power (GJ)	0.620	0.610	-1.660%
Case 1h - Draft Fan Test			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)	29.65	29.58	-0.242%
Average Rate of Fuel Consumption (m3/s)	0.0001253	0.0001237	-1.260%
Total Fan Power (GJ)	1.703	1.701	-0.118%

Table 3 – Furnace HVAC BESTEST Results for EnergyPlus Version 1.0.2.008 (Continued)

Case 2a - Realistic Weather Data			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)		42.04	
Average Rate of Fuel Consumption (m3/s)		0.0001757	
Total Circulating Fan Power (GJ)		0.841	
Total Draft Fan Power (GJ)		0.208	
Average Space Temperature (C)		20.0017	
Minimum Space Temperature (C)		20.0005	
Time of Minimum Temperature, Month/Day		01/27	
Time of Minimum Temperature, Hour		08:00	
Maximum Space Temperature (C)		20.0019	
Time of Maximum Temperature, Month/Day		03/26	
Time of Maximum Temperature, Hour		10:00	
Case 2b - Setback Thermostat			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)		39.87	
Average Rate of Fuel Consumption (m3/s)		0.0001666	
Total Circulating Fan Power (GJ)		0.797	
Total Draft Fan Power (GJ)		0.197	
Average Space Temperature (C)		18.5285	
Minimum Space Temperature (C)		15.0004	
Time of Minimum Temperature, Month/Day		01/27	
Time of Minimum Temperature, Hour		01:00	
Maximum Space Temperature (C)		20.0019	
Time of Maximum Temperature, Month/Day		03/09	
Time of Maximum Temperature, Hour		22:00	
Case 2c - Undersized Furnace			
	BESTEST	EnergyPlus	Difference (%)
Energy Delivered to Space (GJ)		34.59	
Average Rate of Fuel Consumption (m3/s)		0.0001440	
Total Circulating Fan Power (GJ)		1.383	
Total Draft Fan Power (GJ)		0.170	
Average Space Temperature (C)		15.1742	
Minimum Space Temperature (C)		4.4757	
Time of Minimum Temperature, Month/Day		01/27	
Time of Minimum Temperature, Hour		09:00	
Maximum Space Temperature (C)		20.0037	
Time of Maximum Temperature, Month/Day		03/29	
Time of Maximum Temperature, Hour		23:00	

Note: BESTEST analytical results were not available for Cases 2a through 2c, therefore percentage differences could not be calculated

3 RESULTS AND DISCUSSION

The results of the EnergyPlus Fuel-Fired Furnace HVAC comparison with the analytical results for cases where results varied hourly, i.e., Cases 1e through 1h and Cases 2a through 2c, are summarized on a set of charts which are presented in Appendix H. A visual inspection of these charts indicates that EnergyPlus compares extremely well to the analytical results.

4 CONCLUSIONS

EnergyPlus Version 1.0.2.008 was used to model a range of HVAC equipment specifications for a fuel-fired furnace as specified in *International Energy Agency Building Energy Simulation Test for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST), Fuel-Fired Furnace Test Suite.* The ability of EnergyPlus to predict the heat delivered to the zone, the fuel consumed by the furnace and electric energy usage of the circulating fan and draft fan were tested using a test suite of 11 test cases. The results predicted by EnergyPlus for the eight different cases making up Tier 1 were compared to results of analytical solutions, which were provided as part of the test suite manual. EnergyPlus results agreed to within +/- 2% of the analytical results.

The Fuel-Fired Furnace HVAC BESTEST suite is a valuable testing tool that provides excellent benchmarks for testing HVAC system and equipment algorithms versus the results of analytical solutions. As discussed above, the Fuel-Fired Furnace HVAC BESTEST allowed the developers of EnergyPlus to identify the following errors in algorithms and improve simulation accuracy.

- Part load operation of circulating fan which is part of the EnergyPlus FURNACE:BLOWTHRU:HEATONLY object

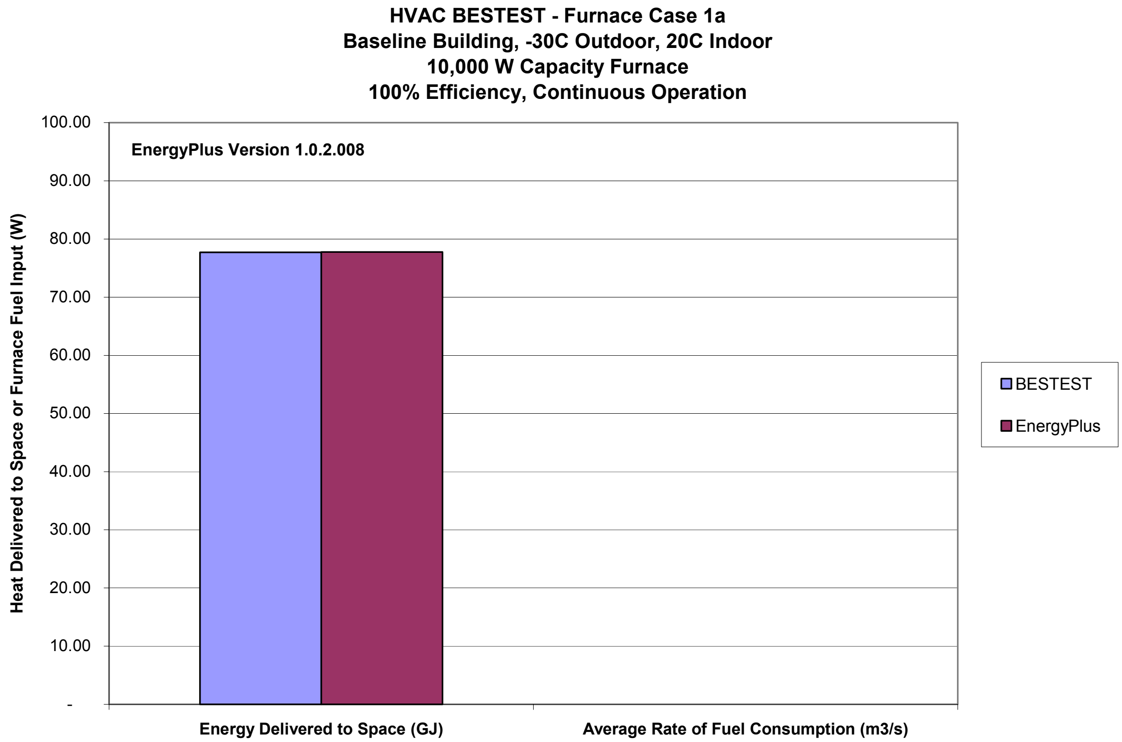
5 REFERENCES

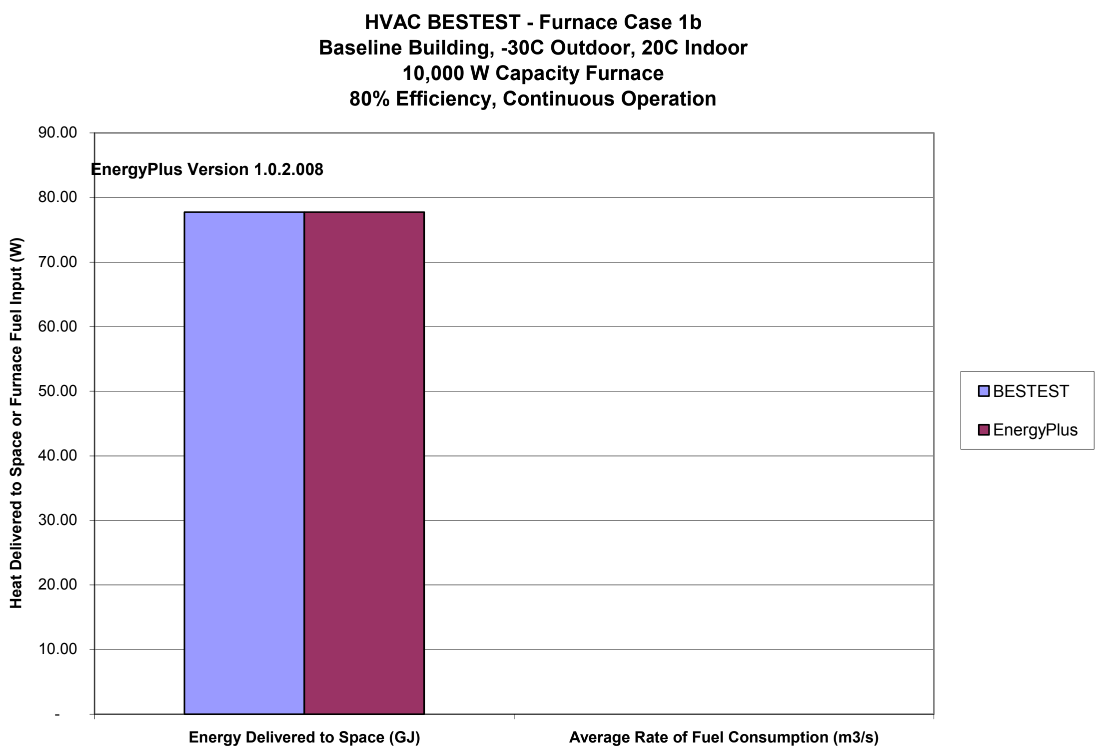
Purdy, J. and Beausoleil-Morrison, I. 2002. *International Energy Agency Building Energy Simulation Test for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST), Fuel-Fired Furnace Test Suite*, CANMET Energy Technology Centre, 2002.

http://www.eren.doe.gov/buildings/energy_tools/energyplus/

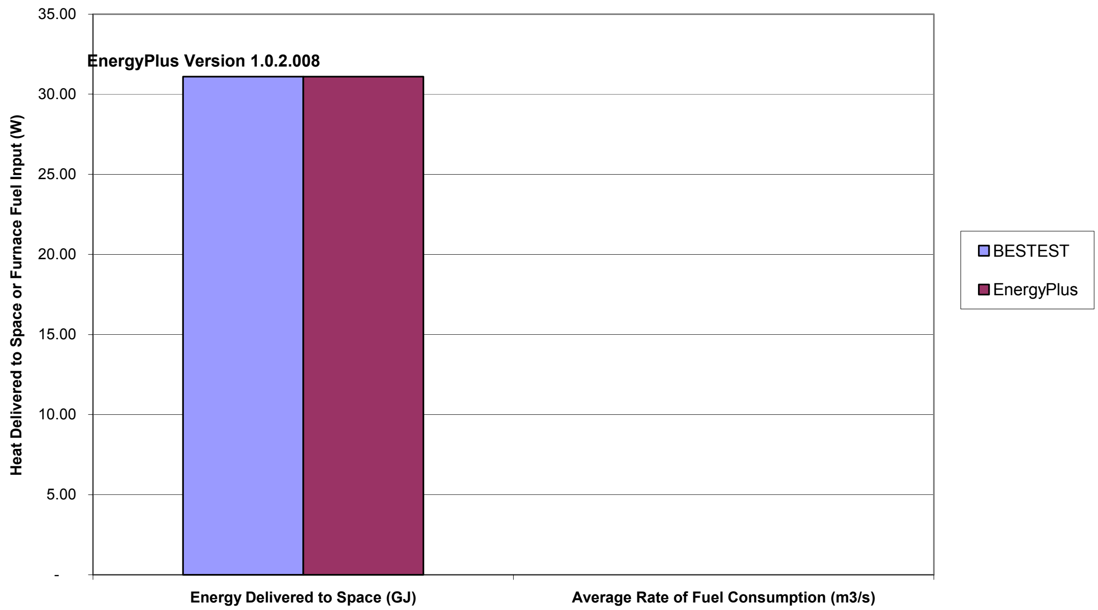
Appendix H

Charts Comparing EnergyPlus Results with Analytical Solutions

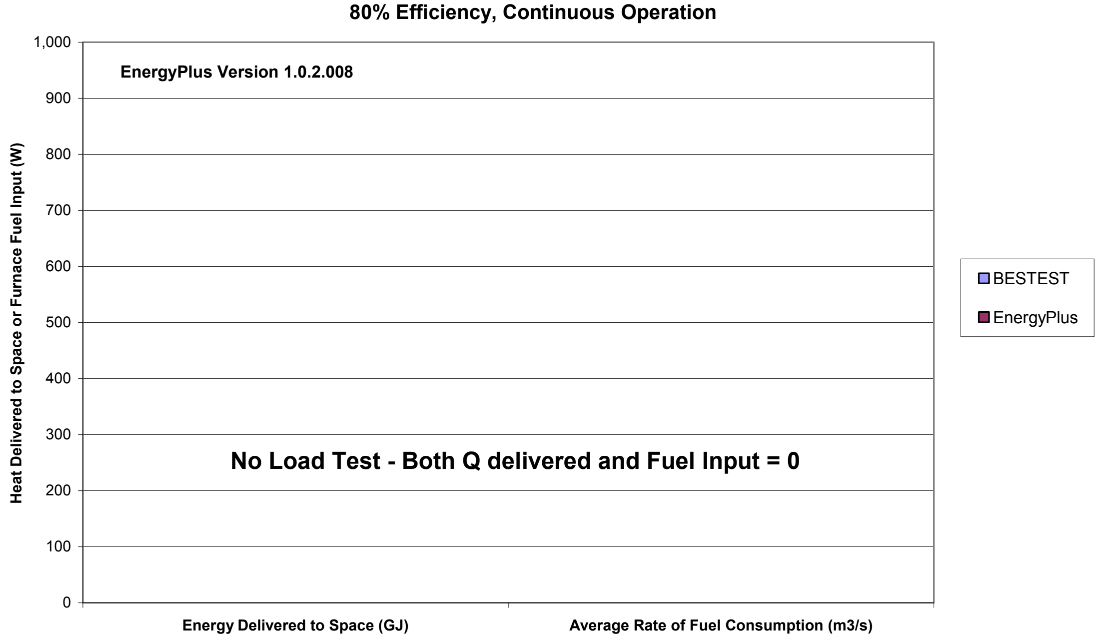

HVAC BESTEST - Furnace Case 1a
Baseline Building, -30C Outdoor, 20C Indoor
10,000 W Capacity Furnace
100% Efficiency, Continuous Operation
EnergyPlus Version 1.0.2.008
Heat Delivered to Space or Furnace Fuel Input (W)
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
-
Energy Delivered to Space (GJ)
Average Rate of Fuel Consumption (m3/s)
BESTEST
EnergyPlus


HVAC BESTEST - Furnace Case 1b
Baseline Building, -30C Outdoor, 20C Indoor
10,000 W Capacity Furnace
80% Efficiency, Continuous Operation
EnergyPlus Version 1.0.2.008
Heat Delivered to Space or Furnace Fuel Input (W)
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
-
Energy Delivered to Space (GJ)
Average Rate of Fuel Consumption (m3/s)
BESTEST
EnergyPlus

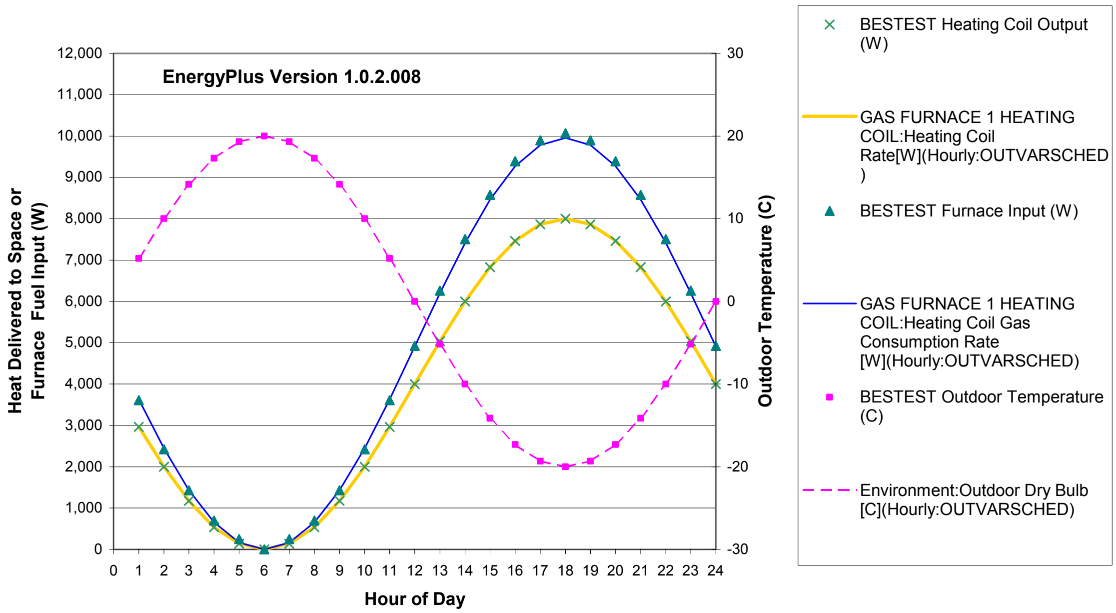
HVAC BESTEST - Furnace Case 1c
Baseline Building, 0C Outdoor, 20C Indoor
10,000 W Capacity Furnace
Part-Load Performance Curve
80% Efficiency, Continuous Operation



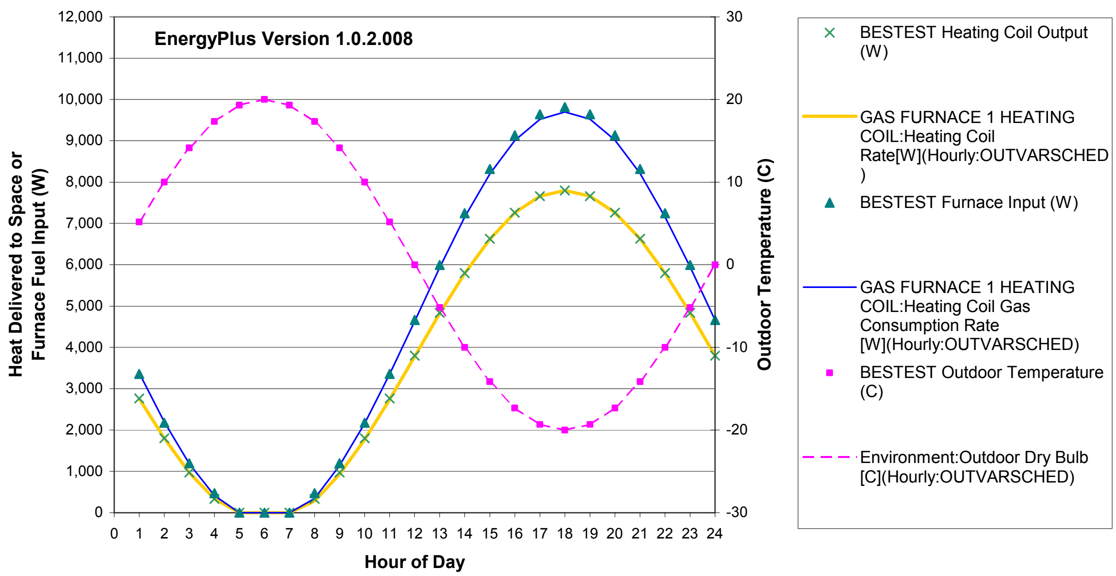
HVAC BESTEST - Furnace Case 1d
Baseline Building, 20C Outdoor, 20C Indoor
10,000 W Capacity Furnace
Part-Load Performance Curve
80% Efficiency, Continuous Operation



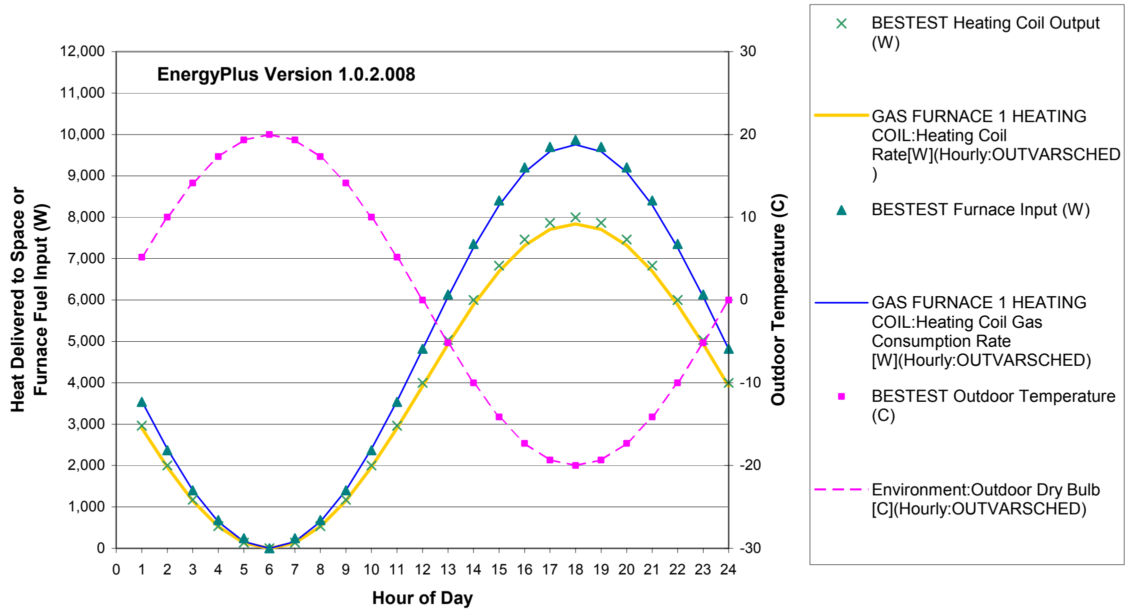
HVAC BESTEST - Furnace Test 1e, January 1
Baseline Building, 20C Indoor
Sinusoidal Change in External Temperature
80% Efficient 10,000W Furnace with Part Load Curve, 0W Supply Fan



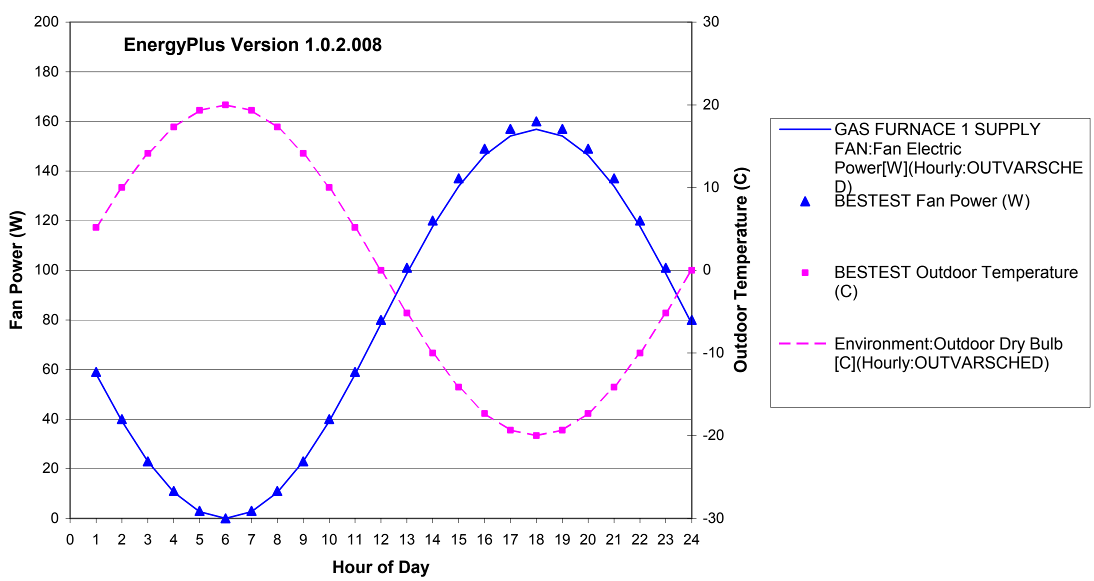
HVAC BESTEST - Furnace Test 1f, January 1
Baseline Building, 20C Indoor
Sinusoidal Change in External Temperature
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, Continuous Fan & Cycling Burner Operation



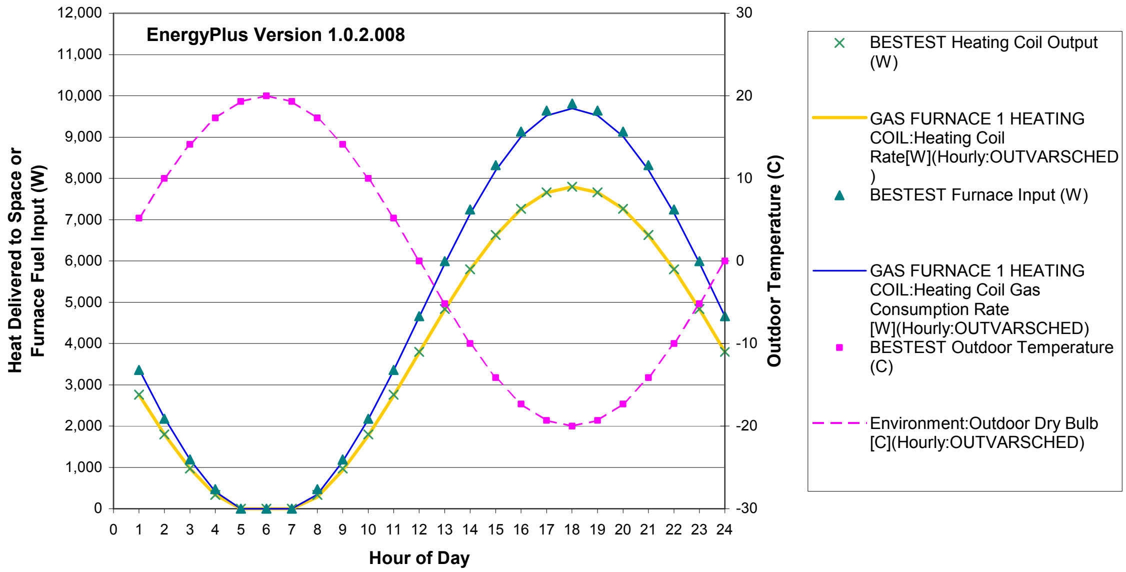
HVAC BESTEST - Furnace Test 1g, January 1
Baseline Building, 20C Indoor
Sinusoidal Change in External Temperature
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, Cycling Fan & Burner Operation



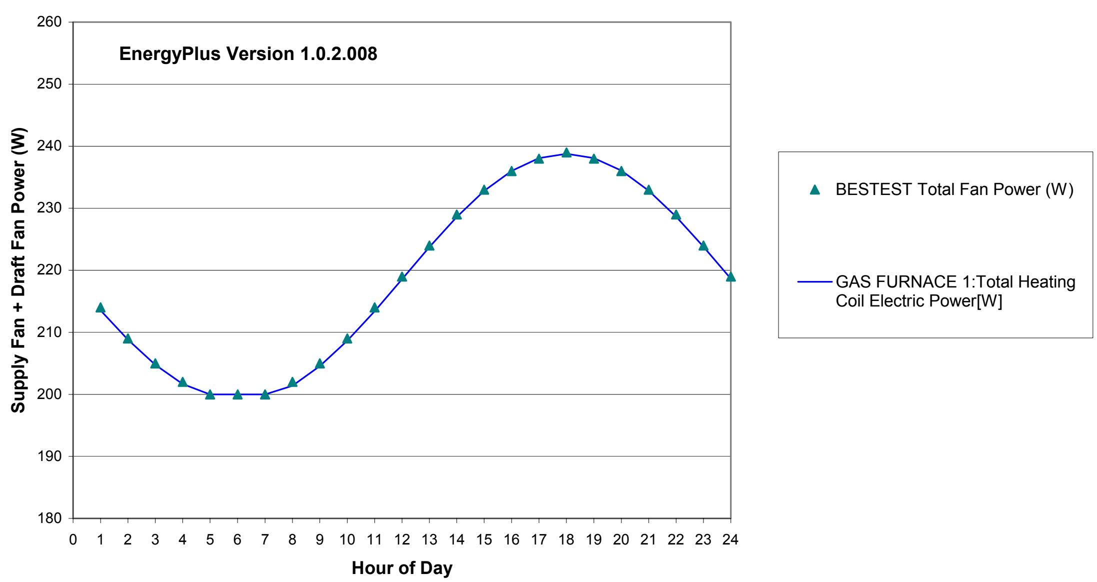
HVAC BESTEST - Furnace Test 1g, January 1
Baseline Building, 20C Indoor
Sinusoidal Change in External Temperature
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, Cycling Fan & Burner Operation



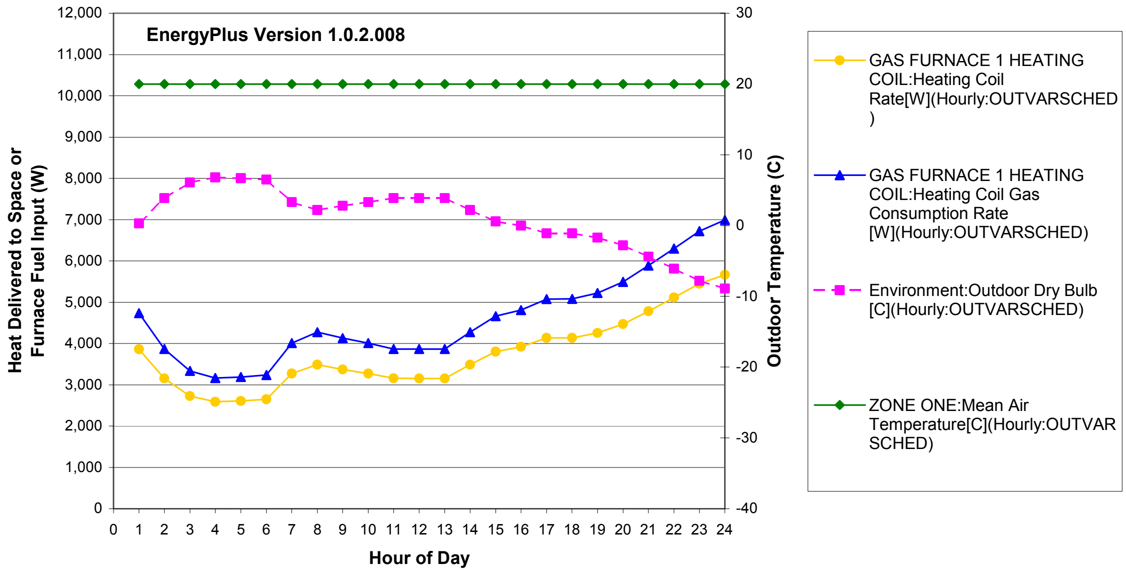
HVAC BESTEST - Furnace Test 1h, January 1
Baseline Building, 20C Indoor
Sinusoidal Change in External Temperature
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, Continuous Fan & Cycling Burner Operation
50W Draft Fan



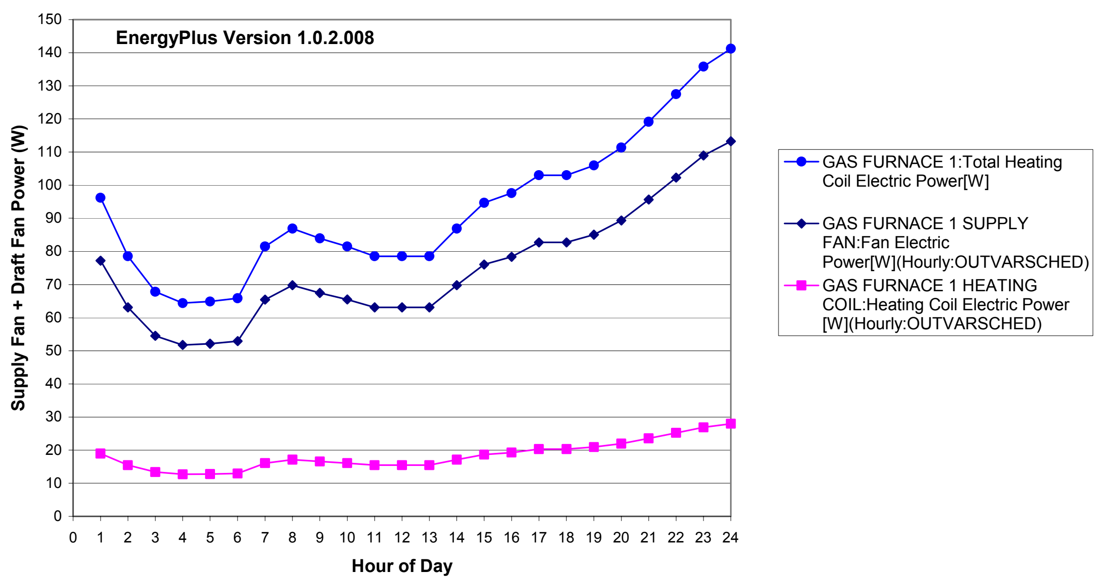
HVAC BESTEST - Furnace Test 1h, January 1
Sinusoidal Change in External Temperature
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, Continuous Fan & Cycling Burner Operation
50W Draft Fan



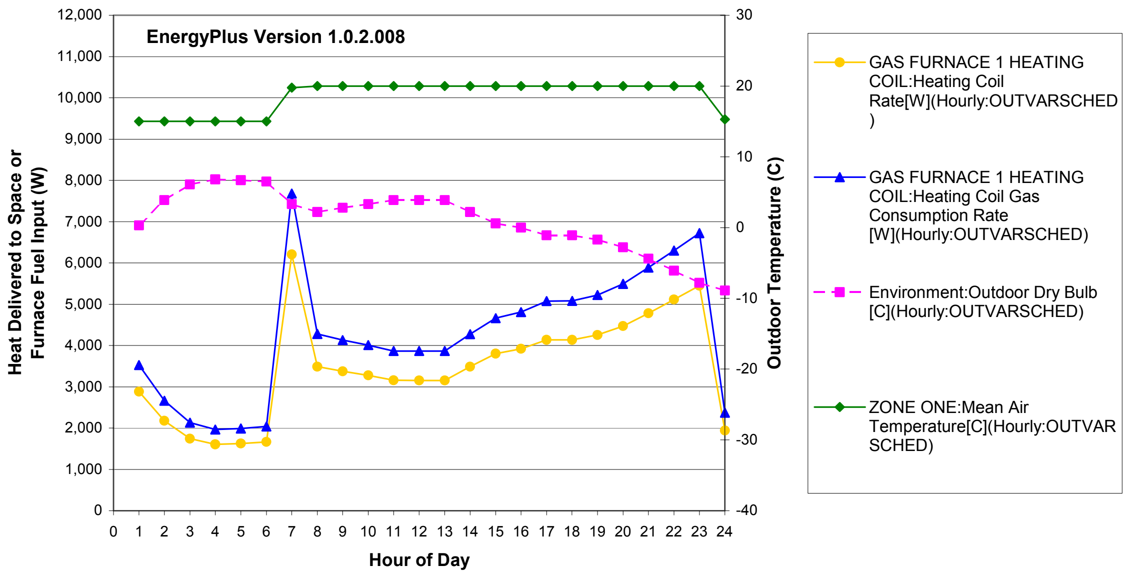
HVAC BESTEST - Furnace Test 2a, January 1
Baseline Building, 20C Indoor
Ottawa Weather File
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, 50W Draft Fan
Fans Cycling with Burner Operation



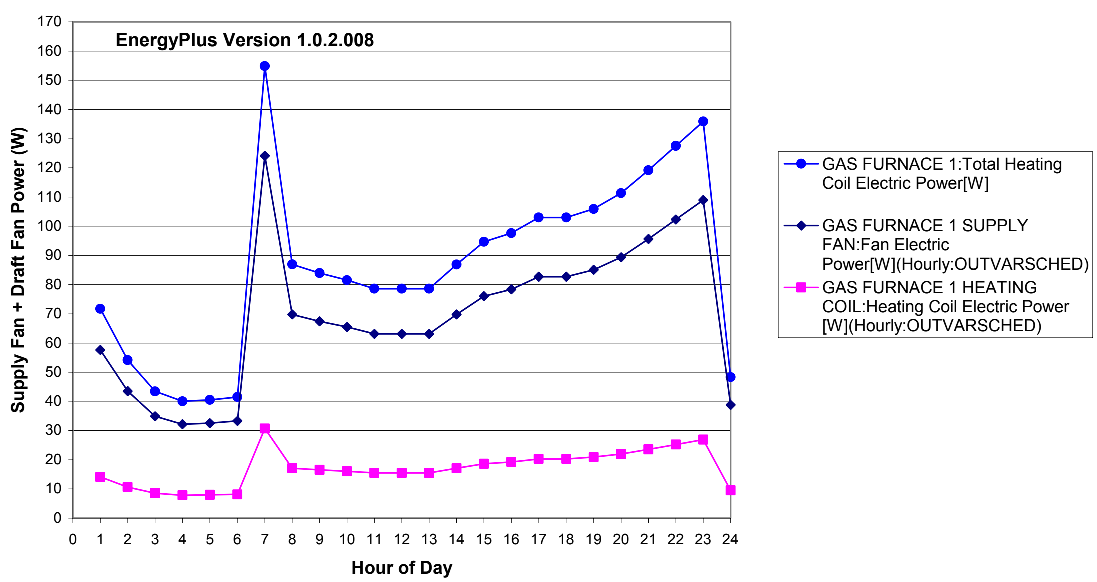
HVAC BESTEST - Furnace Test 2a, January 1
Baseline Building, 20C Indoor
Ottawa Weather File
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, 50W Draft Fan
Fans Cycling with Burner Operation



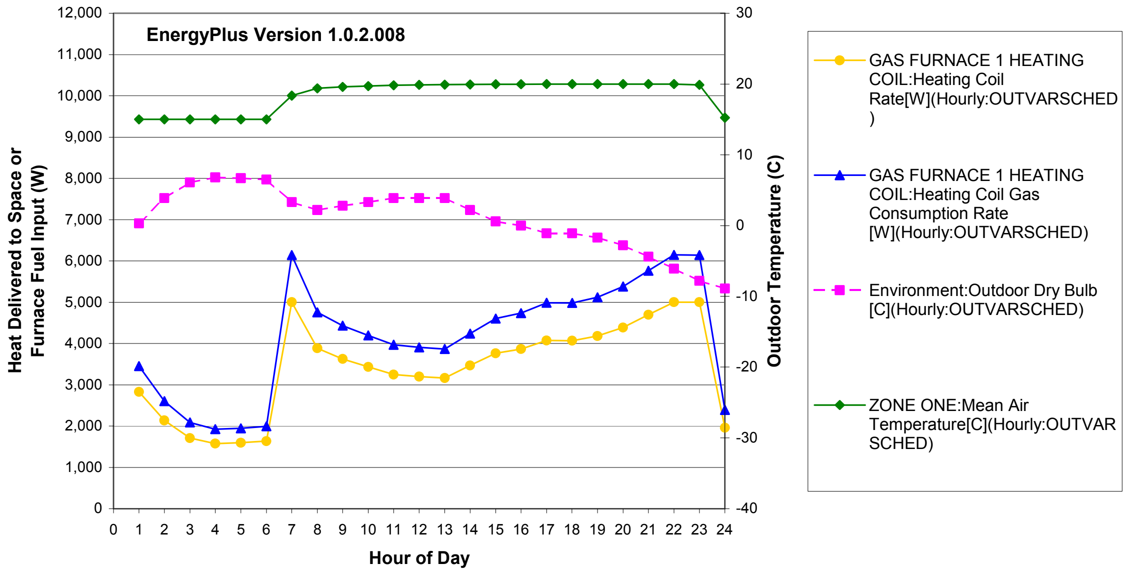
HVAC BESTEST - Furnace Test 2b, January 1
Baseline Building, 20C Indoor with Night Setback to 15C
Ottawa Weather File
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, 50W Draft Fan
Fans Cycling with Burner Operation



HVAC BESTEST - Furnace Test 2b, January 1
Baseline Building, 20C Indoor with Night Setback to 15C
Ottawa Weather File
80% Efficient 10,000W Furnace with Part Load Curve
200W Supply Fan, 50W Draft Fan
Fans Cycling with Burner Operation



HVAC BESTEST - Furnace Test 2c, January 1
Baseline Building, 20C Indoor with Night Setback to 15C
Ottawa Weather File
80% Efficient Undersized 5,000W Furnace with Part Load Curve
200W Supply Fan, 50W Draft Fan
Fans Cycling with Burner Operation



HVAC BESTEST - Furnace Test 2c, January 1
Baseline Building, 20C Indoor with Night Setback to 15C
Ottawa Weather File
80% Efficient Undersized 5,000W Furnace with Part Load Curve
200W Supply Fan, 50W Draft Fan
Fans Cycling with Burner Operation