EnergyPlus Testing with HVAC BESTEST
Part 1 - Tests E100 to E200

EnergyPlus Version 1.2.0.029

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1 TEST OBJECTIVES AND OVERVIEW

1.1 Test Type: Analytical and Comparative - HVAC

The International Energy Agency (IEA) HVAC BESTEST contains a set of analytical tests as well as a set of comparative results from seven other whole building simulation programs that participated in the IEA project. 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 HVAC BESTEST

The tests described in International Energy Agency (IEA) Solar Heating and Cooling Programme Task 22 Building Energy Simulation Test and Diagnostic Method for HVAC Equipment Models (HVAC BESTEST), Volume 1: Cases E100 – E200, (Neymark & Judkoff 2001) were performed using the EnergyPlus program. Final comparison results for all programs that participated in the IEA project are reported in an NREL report by the same name as above but with a January 2002 publish date (Neymark & Judkoff 2002).

As stated in its Introduction, the IEA HVAC BESTEST report "documents an analytical verification and comparative diagnostic procedure for testing the ability of whole building simulation programs to model the performance of unitary space cooling equipment that is typically modeled using manufacturer design data presented in the form of empirically derived performance maps. The report also includes results from simulation programs that were used for field trials of the test procedure."

The following tests were performed with EnergyPlus as specified in the HVAC BESTEST User's Manual:

- Case E100 – Base Case Building and Mechanical System
- Additional Dry Coil Test Cases (Cases E110, E120, E130, E140, as described in Sections 1.3.2 & 1.3.3 of Manual)
- Humid Zone Test Cases (Cases E150, E160, E165, E170, E180, E185, E190, E195, E200, as described in Section 1.3.4 of Manual)

1.2.1 Case E100 – Base Case Building and Mechanical System

The basic test building (Figure 1) is a rectangular 48 m^2 single zone (8 m wide x 6 m long x 2.7 m high) with no interior partitions and no windows. The building is intended as a near-adiabatic cell with cooling load driven by user specified internal gains. Material properties are described below. For further details refer to Section 1.3.2.1 of the HVAC BESTEST User's Manual.

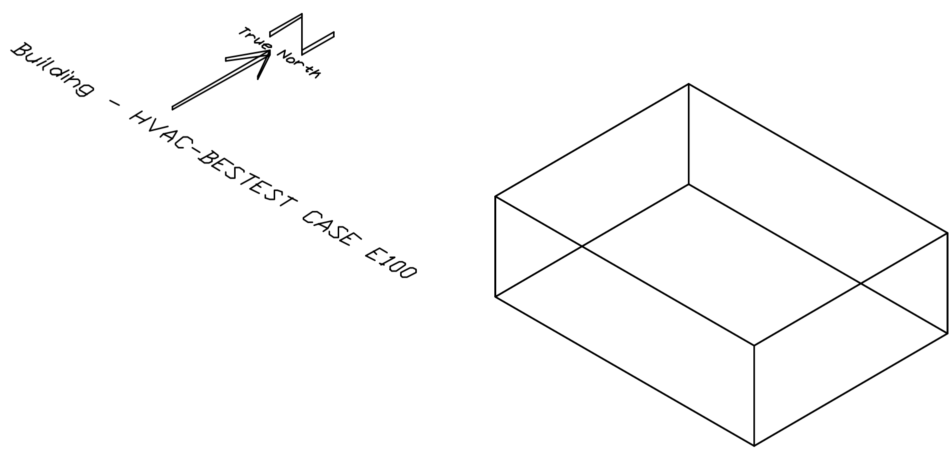

Figure 1 Base Building (Case E100) - Isometric View of Southeast Corner

Wall, Roof and Floor Construction:

Element	k (W/m-K)	Thickness (m)	U (W/m^2-K)	R (m^2-K/W)
Int. Surface Coeff.			8.290	0.121
Insulation	0.010	1.000	0.010	100.000
Ext. Surface Coeff.			29.300	0.034
Overall, air-to-air			0.010	100.155

Opaque Surface Radiative Properties:

	Interior Surface	**Exterior Surface**
Solar Absorptance	0.6	0.1
Infrared Emittance	0.9	0.9

Infiltration: None

Internal Load: 5400 W sensible, continuous, 100% convective; no latent load

Mechanical System: Simple unitary vapor compression cooling system with air cooled condenser and indoor evaporator coil, 100% convective air system, no outside air or exhaust air, single speed, draw-through air distribution fan, indoor and outdoor fans cycle on/off with compressor, no cylinder unloading, no hot gas bypass, crankcase heater and other auxiliary energy = 0. Performance characteristics at ARI rating conditions of 35.0°C outdoor dry-bulb, 26.7°C cooling coil entering dry-bulb and 19.4°C cooling coil entering wet-bulb are:

Net Total Capacity	7852	W
Airflow	0.425	m3/s
Apparatus Dew Point	13.8	°C
Compressor Power	1858	W
Indoor Fan Power	230	W
Outdoor Fan Power	108	W
COP	3.62	
Seasonal COP	3.78	

There is a non-proportional-type thermostat, heat always off, cooling on if zone air temperature >22.2°C and heat extraction rate is assumed to equal the maximum capacity of the equipment for the hour's environmental conditions. For further specifications and equipment's full-load and part load performance map, see Section 1.3.2.2 and Tables 1-6 in HVAC BESTEST User's Manual.

1.2.2 Dry Zone and Wet Zone Series (Cases E110 – E200)

The 13 other cases represent a set of fundamental mechanical equipment tests. These cases test a program's ability to model unitary space cooling equipment performance under controlled load and weather conditions. Given the underlying physical assumptions in the case definitions, there is a mathematically provable and deterministic solution for each case. The results of analytical solutions are included in the IEA/NREL report. Only the following parameters are varied to develop the remaining test cases:

- Internal sensible gains
- Internal latent gains
- Thermostat setpoint (indoor dry-bulb temperature)
- Outdoor dry-bulb temperature.

Table 1 summarizes how these parameters are varied for all of the test cases modeled.

1.2.3 Weather Data

Four three-month long (January – March) TMY format weather files were provided with the test suite designated as follows with the numeric code representing the outdoor dry-bulb temperature (without the decimal) used in the weather file:

HVBT294.TMY
HVBT350.TMY

HVBT406.TMY
HVBT461.TMY

The only parameter that is different for each weather file is the ambient dry-bulb temperature; all other data is the same for each weather file.

1.2.4 Simulation and Reporting Period

Simulations for all cases were run for a three month period. The first month of the simulation period (January) served as an initialization period. The output results reported were for the second month of the simulation (February).

Table 1 HVAC BESTEST Case Descriptions

Case #	Zone			Weather	Comments
	Internal Gains		Setpoint		
	Sensible (W)	Latent (W)	EDB (C)	ODB (C)	
Dry Zone Series					
E100	5400	0	22.2	46.1	Base Case, dry coil. High PLR.
E110	5400	0	22.2	29.4	High PLR. Tests low ODB versus E100
E120	5400	0	26.7	29.4	High PLR. Tests high EDB versus E110. Tests ODB & EDB interaction vs. E100
E130	270	0	22.2	46.1	Low PLR test versus E100
E140	270	0	22.2	29.4	Tests ODB at low PLR vs. E130 Tests PLR at low ODB vs. E110
Humid Zone Series					
E150	5400	1100	22.2	29.4	High PLR. High SHR. Tests latent load versus E110.
E160	5400	1100	26.7	29.4	High PLR. High SHR. Tests EDB versus E150.
E165	5400	1100	23.3	40.6	High PLR. High SHR. Tests ODB & EDB interaction with latent load vs. E160.
E170	2100	1100	22.2	29.4	Mid PLR. Mid SHR. Tests low sensible load versus E150.
E180	2100	4400	22.2	29.4	High PLR. Low SHR. Tests SHR versus E150. Tests high latent load vs. E170.
E185	2100	4400	22.2	46.1	High PLR. Low SHR. Tests ODB versus E180.
E190	270	550	22.2	29.4	Low PLR. Low SHR. Tests low PLR at constant SHR vs. E180. Tests latent load at low PLR versus E140
E195	270	550	22.2	46.1	Low PLR. Low SHR. Tests ODB at low PLR & SHR vs. E190. Tests low PLR at constant SHR vs. E185. Tests latent load at low PLR vs. E130.
Full load test at ARI conditions					
E200	6120	1817	26.7	35.0	Tests for ARI indoor wet-bulb temperature at full sensible and latent loads.
Abbreviations:	PLR = part load ratio; EDB = cooling coil entering dry-bulb temperature; ARI = Air Conditioning and Refrigeration Institute				ODB = outdoor dry-bulb temperature; SHR = sensible heat ratio

2 MODELER REPORT

The material included in this section is a slightly revised copy of the Modeler Report which was prepared by GARD Analytics at NREL's request for inclusion in their final report to the International Energy Agency (IEA) Tool Evaluation and Improvement Experts Group. It documents the modeling approach taken to simulate the HVAC BESTEST cases using EnergyPlus. Several iterations occurred during which the input models were fine tuned, bugs were found in EnergyPlus and software changes were made. This Modeler Report was written to chronicle these experiences and demonstrate how the HVAC BESTEST test suite can be used in the development of whole building energy analysis software.

2.1 Modeling Methodology

For modeling of the simple unitary vapor compression cooling system, the EnergyPlus Window Air Conditioner model was utilized. No other DX coil cooling system was available at the time that this work began, but others have been added since then. The Window Air Conditioner model consists of three modules for which specifications can be entered: DX cooling coil, indoor fan and outside air mixer. The outside air quantity was set to 0.0. The DX coil model is based upon the DOE-2.1E DX coil simulation algorithms with modifications to the coil bypass factor calculations.

The building envelope loads and internal loads are calculated each hour to determine the zone load that the mechanical HVAC system must satisfy. The DX coil model then uses performance information at rated conditions along with curve fits for variations in total capacity, energy input ratio and part load fraction to determine performance at part load conditions. Sensible/latent capacity splits are determined by the rated sensible heat ratio (SHR) and the apparatus dewpoint/bypass factor approach.

Five performance curves are required:

1) The total cooling capacity modifier curve (function of temperature) is a bi-quadratic curve with two independent variables: wet bulb temperature of the air entering the cooling coil, and dry bulb temperature of the air entering the air-cooled condenser. The output of this curve is multiplied by the rated total cooling capacity to give the total cooling capacity at specific temperature operating conditions (i.e., at temperatures different from the rating point temperatures).
2) The total cooling capacity modifier curve (function of flow fraction) is a quadratic curve with the independent variable being the ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The output of this curve is multiplied by the rated total cooling capacity and the total cooling capacity modifier curve (function of temperature) to give the total cooling capacity at the specific temperature and air flow conditions at which the coil is operating.

3) The energy input ratio (EIR) modifier curve (function of temperature) is a bi-quadratic curve with two independent variables: wet bulb temperature of the air entering the cooling coil, and dry bulb temperature of the air entering the air-cooled condenser. The output of this curve is multiplied by the rated EIR (inverse of the rated COP) to give the EIR at specific temperature operating conditions (i.e., at temperatures different from the rating point temperatures).

4) The energy input ratio (EIR) modifier curve (function of flow fraction) is a quadratic curve with the independent variable being the ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The output of this curve is multiplied by the rated EIR (inverse of the rated COP) and the EIR modifier curve (function of temperature) to give the EIR at the specific temperature and airflow conditions at which the coil is operating.

5) The part load fraction correlation (function of part load ratio) is a quadratic curve with the independent variable being part load ratio (sensible cooling load / steady-state sensible cooling capacity). The output of this curve is used in combination with the rated EIR and EIR modifier curves to give the "effective" EIR for a given simulation time step. The part load fraction correlation accounts for efficiency losses due to compressor cycling. In the earlier versions of EnergyPlus, this correction could only be applied to the condensing unit power, but a revision was made to also allow a part load correction for the indoor fan (see Round 4 discussion).

The DX coil model as implemented in EnergyPlus does not allow for simulation of the cooling coil bypass factor characteristics as called out in the specification.

2.2 Modeling Assumptions

2.2.1 Thermostat Control

Ideal thermostat control was assumed with no throttling range.

2.2.2 DX Coil Curve Fits

Since EnergyPlus utilizes a DX coil model very similar to that used in DOE-2, the performance curves initially used in EnergyPlus were identical to those used in DOE-2. Joel Neymark, who provided the DOE-2 modeling support for HVAC BESTEST, kindly provided us with a copy of the DOE-2 input files that he used for performing the DOE-2 analysis. Provided with the matrix of performance data in English units for each of the curves, we converted the temperature input variables to metric units and reran DOE-2 to get the curve fit coefficients. (This shortcut on the curves was done in order to save some time. New curve coefficients were developer later, see Round 4.) The resulting coefficients used for the initial runs are presented below.

1) **Total cooling capacity modifier curve** (function of temperature)
Form: Bi-quadratic curve
curve = a + b*wb + c*wb**2 + d*edb + e*edb**2 + f*wb*edb

Independent variables: wet bulb temperature of the air entering the cooling coil, and dry bulb temperature of the air entering the air-cooled condenser.

a = 0.40731210
b = 0.04517144
c = 0.00008412
d = 0.00140582
e = -0.00003830
f = -0.00046771

2) **Total cooling capacity modifier curve** (function of flow fraction)
Form: Quadratic curve
curve = a + b*ff + c*ff**2
Independent variables: ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow).

Since the indoor fan always operates at constant volume flow, the modifier will be 1.0, therefore:

a = 1.0
b = 0.0
c = 0.0

3) **Energy input ratio (EIR) modifier curve** (function of temperature)
Form: Bi-quadratic curve
curve = a + b*wb + c*wb**2 + d*edb + e*edb**2 + f*wb*edb
Independent variables: wet bulb temperature of the air entering the cooling coil, and dry bulb temperature of the air entering the air-cooled condenser.

a = 0.72724128
b = -0.02055985
c = 0.00075095
d = 0.01355680
e = 0.00040789
f = -0.00086178

4) **Energy input ratio (EIR) modifier curve** (function of flow fraction)
Form: Quadratic curve
curve = a + b*ff + c*ff**2
Independent variables: ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow).

Since the indoor fan always operates at constant volume flow, the modifier will be 1.0, therefore:

a = 1.0
b = 0.0
c = 0.0

5) **Part load fraction correlation** (function of part load ratio)
Form: Quadratic curve
curve = a + b*ff + c*ff**2
Independent variable: part load ratio (sensible cooling load/steady state sensible cooling capacity)

Part load performance was specified in Figure 1-3 of Volume 1 of the HVAC BESTEST specification, therefore:

a = 0.771
b = -0.229
c = 0.0

2.3 Modeling Options

Throughout the HVAC BESTEST exercise with EnergyPlus, the Window Air Conditioner model was used to simulate the HVAC system. Subsequent to the initial rounds of testing, two new DX system models have been added to EnergyPlus, Furnace:BlowThru:HeatCool and DXSystem:AirLoop. No attempt was made to utilize Furnace:BlowThru:HeatCool since it does not accommodate a draw-thru fan option. DXSystem:AirLoop is a significantly different equipment configuration which has not been tested with this suite.

2.4 Modeling Difficulties

2.4.1 Weather Data

The TMY weather files provided as part of the HVAC BESTEST package are not directly usable by EnergyPlus. In order to create an EnergyPlus compatible weather file, the TMY file was first converted to BLAST format using the BLAST weather processor (WIFE). An EnergyPlus translator was then used to convert the weather data from the BLAST format to EnergyPlus format.

Table 1-2 of HVAC BESTEST Volume 1 indicates that the ambient dry-bulb and relative humidity should be as follows for the various data sets:

Data Set	HVAC BESTEST Dry-Bulb Temp.	HVAC BESTEST Relative Humidity
HVBT294.TMY	29.4 C	39%
HVBT350.TMY	35.0 C	28%
HVBT406.TMY	40.6 C	21%
HVBT461.TMY	46.1 C	16%

The converted EnergyPlus weather data set contains slightly different values for ambient relative humidity as indicated below:

Data Set	EnergyPlus Dry-Bulb Temp.	EnergyPlus Relative Humidity
HVBT294.TMY	29.4 C	38.98%
HVBT350.TMY	35.0 C	28.41%
HVBT406.TMY	40.6 C	20.98%
HVBT461.TMY	46.1 C	15.76%

2.4.2 Building Envelope Construction

The specification for the building envelope indicates that the exterior walls, roof and floor are made up of one opaque layer of insulation (R=100) with differing radiative properties for the interior surface and exterior surface (ref. Table 1-4 of Volume 1). To allow the surface radiative properties to be set at different values, the exterior wall, roof and floor had to be simulated as two insulation layers, each with an R=50. The EnergyPlus description for this construction was as follows:

```
MATERIAL:Regular-R,
        INSULATION-EXT,           ! Material Name
        VerySmooth,               ! Roughness
        50.00,                    ! Thermal Resistance {m2-K/W}
        0.9000,                   ! Thermal Absorptance
        0.1000,                   ! Solar Absorptance
        0.1000;                   ! Visible Absorptance

MATERIAL:Regular-R,
        INSULATION-INT,           ! Material Name
        VerySmooth,               ! Roughness
        50.00,                    ! Thermal Resistance {m2-K/W}
        0.9000,                   ! Thermal Absorptance
        0.6000,                   ! Solar Absorptance
        0.6000;                   ! Visible Absorptance

CONSTRUCTION,
        LTWALL,                   ! Construction Name
                ! Material layer names follow:
        INSULATION-EXT,
        INSULATION-INT;
```

2.4.3 Indoor Fan

The specification calls for the unitary air conditioner to have a draw-thru indoor fan. The Window Air Conditioner model in early beta versions of EnergyPlus could only model a blow-thru fan configuration. In Version 1.0.0 Build 005 and later a draw-thru configuration is also available. This limitation may have affected the latent load on the cooling coil and the compressor energy consumption in the early results (Round 1 and Round 2), but other issues were also contributing errors at that point. A draw-thru fan was modeled in Round 3 and thereafter.

2.4.4 Compressor and Condenser Fan Breakout

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

2.5 Software Errors Discovered and/or Comparison Between Different Versions of the Same Software – Round 1

During the first round of simulations several potential software errors were identified in EnergyPlus Beta Version 5-07:

- Fan electrical power and fan heat were consistently low compared to the analytical results for all tests.

- The reported cooling coil loads were consistently too high and apparently had not been adjusted for the fraction of the time step that the equipment operated, however, the DX coil electricity consumption and actual load delivered to the space were being adjusted appropriately for cycling time.

- For the dry coil cases, the reported sensible coil load was slightly higher than the reported total coil load. Latent load was not available as an output variable, but was calculated by subtracting the sensible from the total. This error caused small negative latent loads to be calculated for the dry coil cases.

- Zone relative humidity was higher for many tests compared to the analytical results, especially for the tests with wet coils. This difference was probably due to simulating a blow-thru configuration rather than the required draw-thru configuration.

Software change requests were posted. Once a new version became available, the tests were rerun.

2.6 Results – Round 1

Results from the first modeling with EnergyPlus Beta 5-07 are presented in Table 2. The evaporator total coil load was too large because cycling during the time step was not accounted for. The negative latent coil loads for cases E100 through E140 result from the reported coil sensible load being greater than the total load.

Table 2 – HVAC BESTEST Results for EnergyPlus Beta 5 Build 07

Cases	February Totals										February Mean			February Maximum			February Minimum		
	Cooling Energy Consumption				Evaporator Coil Load			Zone Load											
	Total (kWh)	Compressor (kWh)	Supply Fan (kWh)	Condenser Fan (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)
E100	1517.1		136.5		4210.0	4265.4	-55.4	3653.7	3653.7	0.0	2.41	22.2	0.0075	2.41	22.2	0.0076	2.37	22.2	0.0074
E110	1029.8		114.0		4979.6	5036.4	-56.8	3635.2	3635.2	0.0	3.53	22.2	0.0064	3.54	22.2	0.0064	3.48	22.2	0.0063
E120	988.3		107.1		5380.0	5455.8	-75.8	3630.2	3630.2	0.0	3.67	26.7	0.0080	3.68	26.7	0.0081	3.62	26.7	0.0079
E130	105.0		7.7		4210.8	4267.0	-56.2	206.3	206.3	0.0	1.96	22.2	0.0075	1.97	22.2	0.0076	1.93	22.2	0.0074
E140	63.1		5.9		4979.6	5036.9	-57.2	187.8	187.8	0.0	2.98	22.2	0.0064	2.98	22.2	0.0064	2.93	22.2	0.0063
E150	1185.1		133.9		5129.7	4328.5	801.2	4374.4	3635.2	739.2	3.69	22.2	0.0083	3.71	22.2	0.0084	3.68	22.2	0.0082
E160	1124.0		122.2		5700.6	4821.1	879.6	4369.4	3630.2	739.2	3.89	26.7	0.0101	3.91	26.7	0.0101	3.87	26.7	0.0100
E165	1495.7		144.8		4790.6	4053.8	736.8	4385.5	3646.3	739.2	2.93	23.3	0.0093	2.95	23.3	0.0093	2.92	23.3	0.0092
E170	622.0		62.0		5492.9	3688.1	1804.9	2156.8	1417.6	739.2	3.47	22.2	0.0106	3.50	22.2	0.0106	3.45	22.2	0.0105
E180	1088.1		112.1		6250.7	2138.4	4112.3	4374.4	1417.6	2956.8	4.02	22.2	0.0165	4.09	22.2	0.0165	3.96	22.2	0.0164
E185	1570.8		136.4		5182.5	1807.7	3374.8	4392.9	1436.1	2956.8	2.80	22.2	0.0164	2.85	22.2	0.0164	2.75	22.2	0.0162
E190	161.5		14.3		6250.7	2217.2	4033.5	557.4	187.8	369.6	3.45	22.2	0.0162	3.52	22.2	0.0163	3.37	22.2	0.0160
E195	247.6		17.9		5175.4	1963.8	3211.7	575.9	206.3	369.6	2.33	22.2	0.0158	2.37	22.2	0.0159	2.27	22.2	0.0156
E200	1472.6		153.7		5562.7	4380.1	1182.5	5341.1	4120.2	1221.0	3.63	26.7	0.0113	3.65	26.7	0.0114	3.61	26.7	0.0112

2.7 Software Errors Discovered and/or Comparison Between Different Versions of the Same Software – Round 2

EnergyPlus Beta 5-14 included changes to fix the following problems which were identified in HVAC BESTEST Round 1:

- Reporting of cooling coil loads were corrected to account for run time during cycling operation.

- The methods of calculating SHR and coil bypass factor were modified to eliminate the problem where the dry coil cases reported sensible coil loads which were slightly higher than the reported total coil loads. This error was causing small negative latent loads to be calculated for the dry coil cases.

During the second round of simulations with EnergyPlus Beta 5-14 the cooling coil error identified during the first round of simulations was corrected to account for cycling during each time step, and this brought the evaporator coil loads closer to the range of results for the other programs; but the loads were still higher than they should be. Another potential error was therefore identified which may have been masked by the coil problem identified in Round 1:

- Although there was excellent agreement for zone total cooling load, the evaporator cooling coil load was larger than the zone cooling load plus fan heat.

- Also, the mean indoor dry bulb for Case E200 moved from 26.7C to 27.1C.

- The other problems identified in Round 1 still remained (low fan power, poor agreement in zone humidity ratio).

2.8 Results – Round 2

Results from the second round of simulations with EnergyPlus Beta 5-14 are presented in Table 3.

Table 3 – HVAC BESTEST Results for EnergyPlus Beta 5 Build 14

	February Totals										February Mean			February Maximum			February Minimum		
	Cooling Energy Consumption				Evaporator Coil Load			Zone Load											
Cases	Total (kWh)	Compressor (kWh)	Supply Fan (kWh)	Condenser Fan (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)
E100	1535.8		138.7		3842.1	3842.1	0.0	3653.7	3653.7	0.0	2.38	22.2	0.0074	2.38	22.2	0.0074	2.38	22.2	0.0074
E110	1039.6		115.2		3792.2	3792.2	0.0	3635.2	3635.2	0.0	3.50	22.2	0.0062	3.50	22.2	0.0062	3.49	22.2	0.0062
E120	1003.0		109.2		3792.0	3792.0	0.0	3630.2	3630.2	0.0	3.62	26.7	0.0078	3.63	26.7	0.0078	3.61	26.7	0.0078
E130	106.6		7.8		216.9	216.9	0.0	206.3	206.3	0.0	1.93	22.2	0.0074	1.94	22.2	0.0074	1.93	22.2	0.0074
E140	63.8		6.0		195.9	195.9	0.0	187.8	187.8	0.0	2.94	22.2	0.0062	2.95	22.2	0.0062	2.94	22.2	0.0062
E150	1197.9		135.6		4589.9	3820.1	769.8	4374.4	3635.2	739.2	3.65	22.2	0.0084	3.67	22.2	0.0084	3.64	22.2	0.0083
E160	1139.1		124.1		4587.2	3814.9	772.3	4369.4	3630.2	739.2	3.84	26.7	0.0102	3.86	26.7	0.0102	3.82	26.7	0.0101
E165	1513.5		146.9		4620.2	3849.7	770.4	4385.5	3646.3	739.2	2.90	23.3	0.0094	2.92	23.3	0.0094	2.88	23.3	0.0093
E170	630.3		62.9		2272.2	1502.4	769.7	2156.8	1417.6	739.2	3.42	22.2	0.0107	3.45	22.2	0.0107	3.40	22.2	0.0106
E180	1104.9		114.2		4640.3	1561.5	3078.9	4374.4	1417.6	2956.8	3.96	22.2	0.0166	4.02	22.2	0.0166	3.90	22.2	0.0165
E185	1594.9		139.0		4686.1	1607.2	3078.9	4392.9	1436.1	2956.8	2.75	22.2	0.0165	2.81	22.2	0.0165	2.71	22.2	0.0163
E190	164.4		14.5		591.1	206.2	384.9	557.4	187.8	369.6	3.39	22.2	0.0163	3.45	22.2	0.0164	3.31	22.2	0.0162
E195	251.9		18.2		613.9	229.0	384.9	575.9	206.3	369.6	2.29	22.2	0.0159	2.33	22.2	0.0160	2.23	22.2	0.0157
E200	1486.6		155.2		5627.7	4351.7	1276.0	5340.7	4119.7	1221.0	3.59	27.1	0.0116	3.60	27.2	0.0117	3.59	27.0	0.0115

2.9 Software Errors Discovered and/or Comparison Between Different Versions of the Same Software – Round 3

The suite of HVAC BESTEST cases were simulated again using EnergyPlus Version 1.0.0.011 (the first public release of Version 1.0, April 2001) which included the following changes from Beta 5-14:

- Modified method for calculating coil outlet conditions.
- Changed to use of Double Precision throughout all of EnergyPlus. (This change was prompted by various issues not related to HVAC BESTEST.)
- Added two output variables for tracking run time
  - Window AC Fan RunTime Fraction
  - Window AC Compressor RunTime Fraction
- Added an output variable for coil latent load.
- Added Draw-Thru Fan option to Window AC.
- The name of the DX coil object was changed from COIL:DX:DOE2 to COIL:DX:BF-Empirical to better represent its algorithmic basis.

In addition, the following input file changes were made :

- Changed from blow-thru fan to draw-thru configuration.
- Updated the DX coil object name to COIL:DX:BF-Empirical.

The following changes in results were observed:

- Indoor fan power consumption and fan heat decreased significantly from Round 2, moving farther below the analytical results.
- Space cooling electricity consumption changed slightly from Round 2 and moved closer to the analytical results.
- Mean indoor humidity ratio decreased compared to Round 2, moving farther away from the analytical results for most of the dry coil cases and moving closer to the analytical results for the wet coil cases.
- Mean indoor dry bulb for Case E200 moved further out of range to 27.5C (the setpoint for this case is 26.7C).

In general, except for fan power and fan heat, the overall EnergyPlus Version 1.0.0.011 results compared much better to the HVAC BESTEST analytical results.

2.10 Results – Round 3

Results from the third round of simulations with EnergyPlus Version 1.0.0.011 are presented in Table 4.

Table 4 – HVAC BESTEST Results for EnergyPlus Version 1.0.0 Build 011

	February Totals										February Mean			February Maximum			February Minimum		
	Cooling Energy Consumption				Evaporator Coil Load			Zone Load											
Cases	Total (kWh)	Compressor (kWh)	Supply Fan (kWh)	Condenser Fan (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)
E100	1527.6		132.6		3834.9	3834.9	0.0	3654.1	3654.1	0.0	2.39	22.2	0.0071	2.39	22.2	0.0071	2.39	22.2	0.0071
E110	1032.2		109.2		3785.3	3785.3	0.0	3635.6	3635.6	0.0	3.52	22.2	0.0060	3.53	22.2	0.0060	3.52	22.2	0.0060
E120	1001.3		104.4		3786.5	3786.5	0.0	3630.5	3630.5	0.0	3.63	26.7	0.0077	3.63	26.7	0.0077	3.62	26.7	0.0077
E130	106.3		7.5		217.0	217.0	0.0	206.7	206.7	0.0	1.94	22.2	0.0071	1.95	22.2	0.0071	1.94	22.2	0.0071
E140	63.5		5.7		195.9	195.9	0.0	188.2	188.2	0.0	2.96	22.2	0.0060	2.96	22.2	0.0060	2.96	22.2	0.0060
E150	1197.5		130.9		4584.5	3815.0	769.5	4374.7	3635.5	739.2	3.65	22.2	0.0082	3.68	22.2	0.0082	3.64	22.2	0.0081
E160	1137.3		119.1		4581.3	3809.3	772.1	4369.7	3630.5	739.2	3.84	26.7	0.0100	3.87	26.7	0.0100	3.83	26.7	0.0099
E165	1514.9		142.2		4614.7	3844.5	770.2	4385.9	3646.7	739.2	2.90	23.3	0.0092	2.92	23.3	0.0092	2.88	23.3	0.0091
E170	631.2		61.0		2270.2	1500.7	769.5	2157.1	1417.9	739.2	3.42	22.2	0.0105	3.45	22.2	0.0105	3.40	22.2	0.0104
E180	1100.9		110.8		4636.5	1558.6	3077.9	4374.7	1418.0	2956.8	3.97	22.2	0.0163	4.04	22.2	0.0163	3.92	22.2	0.0162
E185	1590.5		135.5		4682.1	1604.2	3077.9	4393.3	1436.5	2956.8	2.76	22.2	0.0161	2.81	22.2	0.0162	2.72	22.2	0.0160
E190	164.0		14.1		591.0	206.2	384.8	557.8	188.2	369.6	3.40	22.2	0.0160	3.46	22.2	0.0161	3.33	22.2	0.0158
E195	253.3		17.9		613.9	229.2	384.8	576.3	206.7	369.6	2.28	22.2	0.0156	2.32	22.2	0.0156	2.23	22.2	0.0154
E200	1479.4		148.4		5621.0	4345.1	1276.0	5340.7	4119.7	1221.0	3.61	27.5	0.0116	3.62	27.6	0.0117	3.61	27.4	0.0115

2.11 Software Errors Discovered and/or Comparison Between Different Versions of the Same Software – Round 4

The suite of HVAC BESTEST cases were simulated again using EnergyPlus Version 1.0.0.023 (a maintenance release, June 2001) which included both input file and source code changes from Version 1.0.0.011.

Input file changes for Round 4:

- The equipment performance curves were refit from scratch using the Excel function LINEST. Data for the curves were taken from Table 1-6c of the HVAC BESTEST specification. Curve fits were developed using SI units since this is what EnergyPlus requires. Previously, the DOE-2 curve coefficients from Neymark's work had been used, but the EIR curve fit done for DOE-2 applied only to the compressor input power. The EIR curve required for the EnergyPlus DX Coil model is based on compressor input power plus outdoor condenser fan power. The resulting curves used for the latest round of EnergyPlus simulations were as follows:

  CoolCapFT = a + b*wb + c*wb**2 + d*edb + e*edb**2 + f*wb*edb
  where
  wb = wet-bulb temperature of air entering the cooling coil
  edb = dry-bulb temperature of the air entering the air-cooled condenser
  a = 0.43863482
  b = 0.04259180
  c = 0.00015024
  d = 0.00100248
  e = -0.00003314
  f = -0.00046664
  Data points were taken from first three columns of Table 1-6c of specification. CoolCap data was normalized to ARI rated capacity of 8,181 W, i.e. CoolCapFT = 1.0 at 19.4 C wb and 35.0 C edb.

  EIRFT = a + b*wb + c*wb**2 + d*edb + e*edb**2 + f*wb*edb
  where:
  wb = wet-bulb temperature of air entering the cooling coil
  edb = dry-bulb temperature of the air entering the air-cooled condenser
  a = 0.77127580
  b = -0.02218018
  c = 0.00074086
  d = 0.01306849
  e = 0.00039124
  f = -0.00082052
  edb and wb data points were taken from the first two columns of Table 1-6c of specification. Energy input data points for corresponding pairs of edb and wb were taken from column labeled "Compressor Power" in Table 1-6c with an additional 108 W added to them for outdoor fan power. EIR is energy input ratio

[(compressor + outdoor fan power)/cooling capacity] normalized to ARI rated conditions, i.e. EIRFT = 1.0 at 19.4 C wb and 35.0 C edb.

- Relaxed the min/max limits of the performance curve independent variables, wb and edb, to allow extrapolation of CoolCapFT and EIRFT outside the bounds of the equipment performance data given in the specification in accordance with comments in Section 1.3.2.2.3.2 of Volume 1.

- The BESTEST CDF curve was determined based on net total capacities of the unit while the EnergyPlus DX Coil model requires that the part load curve be expressed on the basis of gross sensible capacities. A new CDF curve was developed which was intended to be on a gross capacity basis, but a later review of this curve showed an error in the derivation. Further review showed that there is really little difference between net part load and gross part load, so the revised curve was then removed and the original CDF curve was used.

- The CDF curve (part load curve) was applied to the indoor fan operation where previously there was no input available for this. This change also required using the FAN:SIMPLE:ONOFF object instead of FAN:SIMPLE:CONSTVOLUME which has been used previously.

- Added one week of infiltration to the beginning of the Case E120 run period to prevent overdrying of the zone during the simulation warmup period. (See the results discussion below for more details.)

Relevant source code changes from Version 1.0.0.011 to Version 1.0.0.023:

- Standard air conditions for converting volume flow to mass flow in the indoor fan calculations were changed. HVAC BESTEST specifies that the volume flow rate is for dry air at 20C. EnergyPlus was using a dry-bulb of 25C at the initial outdoor barometric pressure with a humidity ratio of 0.014 kg/kg, although the EnergyPlus documentation indicated 21C and 101325 Pa was being used. EnergyPlus now calculates the initial air mass flow based on dry air at 20C at the standard barometric pressure for the specified altitude, and the documentation reflects this change.

- The specific heat for air throughout the air-side HVAC simulation was changed from a dry c_p basis to a moist c_p basis. Previously, a mixture of dry and moist c_p had been used for various HVAC calculations.

- The heat of vaporization (h_{fg}) for converting a zone latent load into a load in the HVAC system was changed.

- A new input field was added to FAN:SIMPLE:ONOFF to allow a CDF curve (part load curve) to be applied to the indoor fan operation where previously part load adjustments could only be applied to the compressor and outdoor fan.

- Changed the moisture initialization to use the initial outdoor humidity ratio to initialize all HVAC air nodes.

The following changes in results were observed:

- The sensible and latent coil loads improved and now track very close to the analytical results.

- The mean indoor temperature for Case E200 improved and now, along with rest of the cases, matches exactly with the analytical results.

- The mean indoor humidity ratio tracks the analytical values better, especially for the wet coil cases. For Case E120 however, the EnergyPlus humidity ratio (0.0038) was much less than the analytical value (0.0079). Introducing infiltration for the first week of January only and then turning infiltration off, eliminates this problem and gives a mean indoor humidity ratio for the month of February of 0.0081. Even though all nodes are initialized to the outdoor humidity ratio at the beginning of the simulation, conditions during the simulation warmup days overdry the zone for this case. Without the infiltration during the first week, there is no source of moisture to overcome the overdrying and establish the desired equilibrium.

- Indoor fan power consumption and fan heat match analytical results in most cases or are slightly less than analytical results.

- COP results changed but are still mixed. One problem may have to do with the basis of the CDF curve in BESTEST versus what EnergyPlus requires. The BESTEST CDF curve was determined based on net total capacities of the unit while the EnergyPlus DX Coil model requires that the part load curve be expressed on the basis of gross sensible capacities.

2.12 Results – Round 4

Results from the fourth round of simulations with EnergyPlus Version 1.0.0.023 are presented in Table 5.

Table 5 – HVAC BESTEST Results for EnergyPlus Version 1.0.0 Build 023

Cases	February Totals										February Mean			February Maximum			February Minimum		
	Cooling Energy Consumption				Evaporator Coil Load			Zone Load											
	Total (kWh)	Compressor (kWh)	Supply Fan (kWh)	Condenser Fan (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	Total (kWh)	Sensible (kWh)	Latent (kWh)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)	COP	IDB (°C)	Humidity Ratio (kg/kg)
E100	1520.0		143.6		3797.6	3797.6	0.0	3654.1	3654.1	0.0	2.40	22.2	0.0075	2.41	22.2	0.0075	2.40	22.2	0.0075
E110	1069.1		127.5		3763.1	3763.1	0.0	3635.5	3635.5	0.0	3.40	22.2	0.0066	3.40	22.2	0.0066	3.40	22.2	0.0066
E120	1006.4		116.4		3746.9	3746.9	0.0	3630.5	3630.5	0.0	3.61	26.7	0.0080	3.61	26.7	0.0080	3.60	26.7	0.0080
E130	108.6		10.3		217.0	217.0	0.0	206.7	206.7	0.0	1.90	22.2	0.0075	1.91	22.2	0.0075	1.90	22.2	0.0075
E140	67.9		8.1		196.3	196.3	0.0	188.2	188.2	0.0	2.77	22.2	0.0066	2.78	22.2	0.0066	2.77	22.2	0.0066
E150	1197.1		140.2		4508.7	3776.0	732.7	4374.7	3635.6	739.2	3.65	22.2	0.0084	3.68	22.2	0.0084	3.64	22.2	0.0083
E160	1131.7		128.3		4491.0	3759.0	732.0	4369.7	3630.5	739.2	3.86	26.7	0.0103	3.88	26.7	0.0103	3.84	26.7	0.0102
E165	1491.1		148.5		4528.7	3795.5	733.2	4385.9	3646.7	739.2	2.94	23.3	0.0094	2.96	23.3	0.0094	2.93	23.3	0.0093
E170	635.4		73.0		2224.9	1491.2	733.6	2157.1	1417.9	739.2	3.40	22.2	0.0106	3.42	22.2	0.0106	3.37	22.2	0.0105
E180	1082.0		118.4		4481.2	1537.3	2943.9	4374.7	1418.0	2956.8	4.04	22.2	0.0162	4.11	22.2	0.0162	3.99	22.2	0.0161
E185	1540.4		139.1		4522.6	1576.6	2946.0	4393.3	1436.5	2956.8	2.85	22.2	0.0161	2.90	22.2	0.0161	2.80	22.2	0.0159
E190	164.3		18.0		574.3	206.4	367.9	557.8	188.2	369.6	3.39	22.2	0.0159	3.45	22.2	0.0159	3.32	22.2	0.0157
E195	250.2		22.7		597.7	229.6	368.1	576.3	206.7	369.6	2.30	22.2	0.0154	2.35	22.2	0.0155	2.25	22.2	0.0153
E200	1464.6		153.4		5484.5	4274.3	1210.2	5341.5	4120.5	1221.0	3.65	26.7	0.0115	3.67	26.7	0.0115	3.63	26.7	0.0113

2.13 Comparison of Changes that Occurred with Early Versions of EnergyPlus

This section documents the comparative changes that took place in results (see Figures 2 through 9) as modifications were made to the EnergyPlus code or changes were made in the modeling approach (see Table 6). The analytical results shown in Figures 2 –9 represent the baseline against which all EnergyPlus results were compared. Results for other intermediate versions of EnergyPlus not discussed above have been included. EnergyPlus Version 1.0.0.023 (June 2001) was the most current public release of the software at the time this section of the report was written.

Table 6 – Summary of Pertinent EnergyPlus Changes that were Implemented

Version	Input File Changes	Code Changes
Beta 5-12 thru Beta 5-14		DX coil calculations modified to account for cycling Modified method of calculating SHR and coil bypass factor
Beta 5-15 thru Beta 5-18	Changed DX coil object names	Changed name of DX coil object from COIL:DX:DOE2 to COIL:DX:BF-Empirical to better represent its algorithmic basis (no impact on results)
Ver 1.0.0.001 thru Ver 1.0.0.011	Changed from blow-thru to draw-thru fan configuration	Changed to double precision Modified method of calculating coil outlet conditions Added draw-thru fan option to WindowAC model
Ver 1.0.0.012 thru Ver 1.0.0.014	New equipment performance curves Adjusted fan mass flow and efficiency to achieve desired mass flow and fan power	
Ver 1.0.0.015 thru Ver 1.0.0.017	Went back to specified values for fan mass flow and efficiency	Partial implementation of moist c_p Fan power calculated using a standard initial density for volume to mass flow conversion
Ver 1.0.0.018 thru Ver 1.0.0.019	Changed basis of CDF curve from net to gross Opened up min/max limits for performance curves	Complete implementation of moist c_p h_{fg} calculation modified for latent loads
Ver 1.0.0.020 thru Ver 1.0.0.023	Went back to original CDF curve (modified curve used with Ver 1-19 was incorrect) Changed from FAN:SIMPLE:CONSTVOLUME to FAN:SIMPLE:ONOFF Used CDF curve for fan power to account for cycling	Implemented optional PLR curve for fan cycling Changed moisture initializations to use outdoor humidity ratio

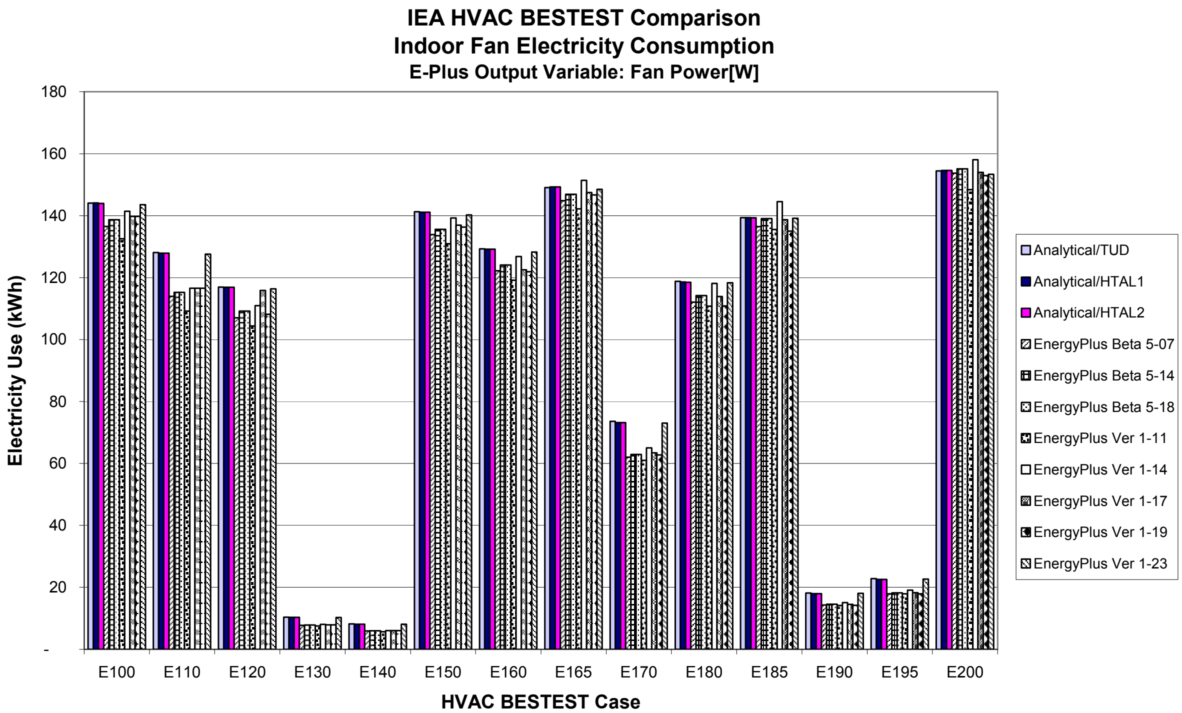

Figure 2 Indoor Fan Power Results for Early Versions of EnergyPlus

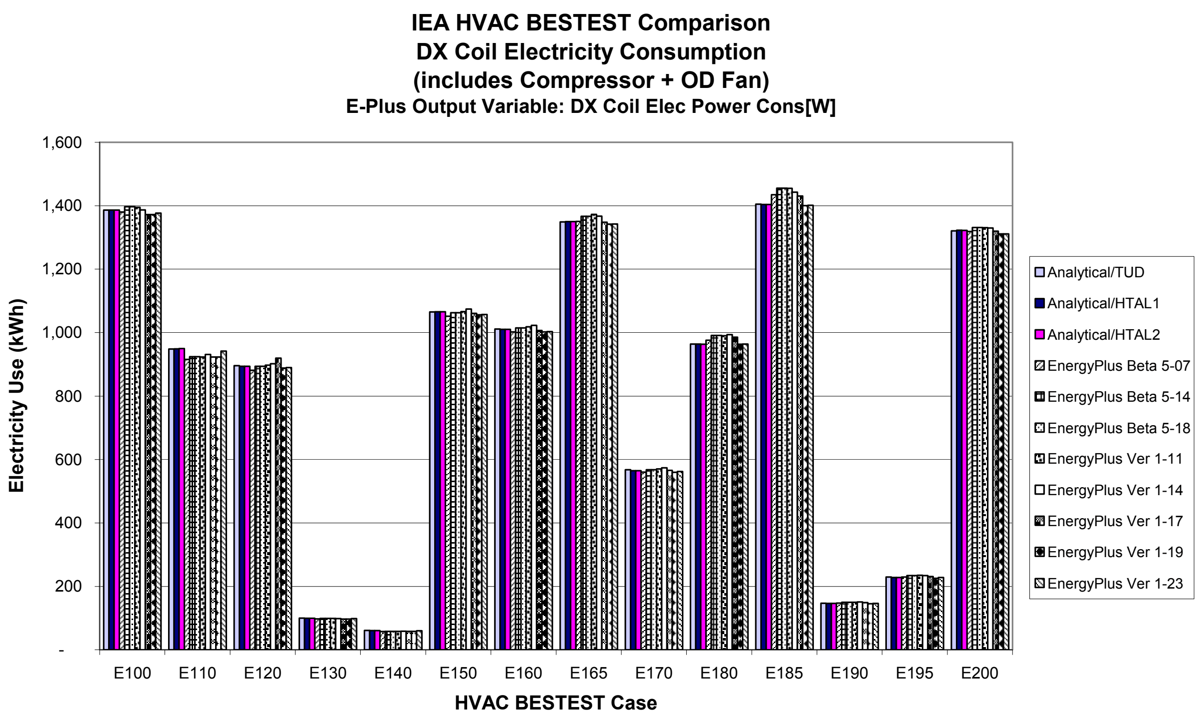

Figure 3 Compressor Plus Outdoor Fan Electricity Consumption Results for Early Versions of EnergyPlus

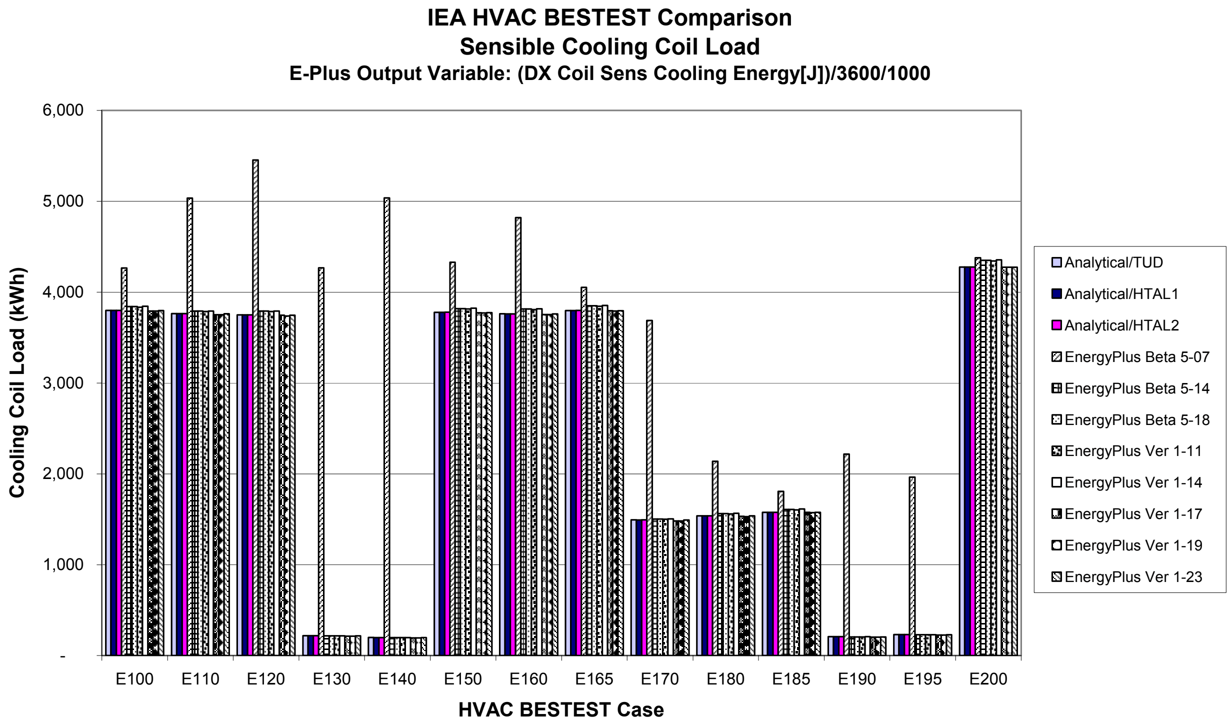

Figure 4 Sensible Cooling Coil Load Results for Early Versions of EnergyPlus

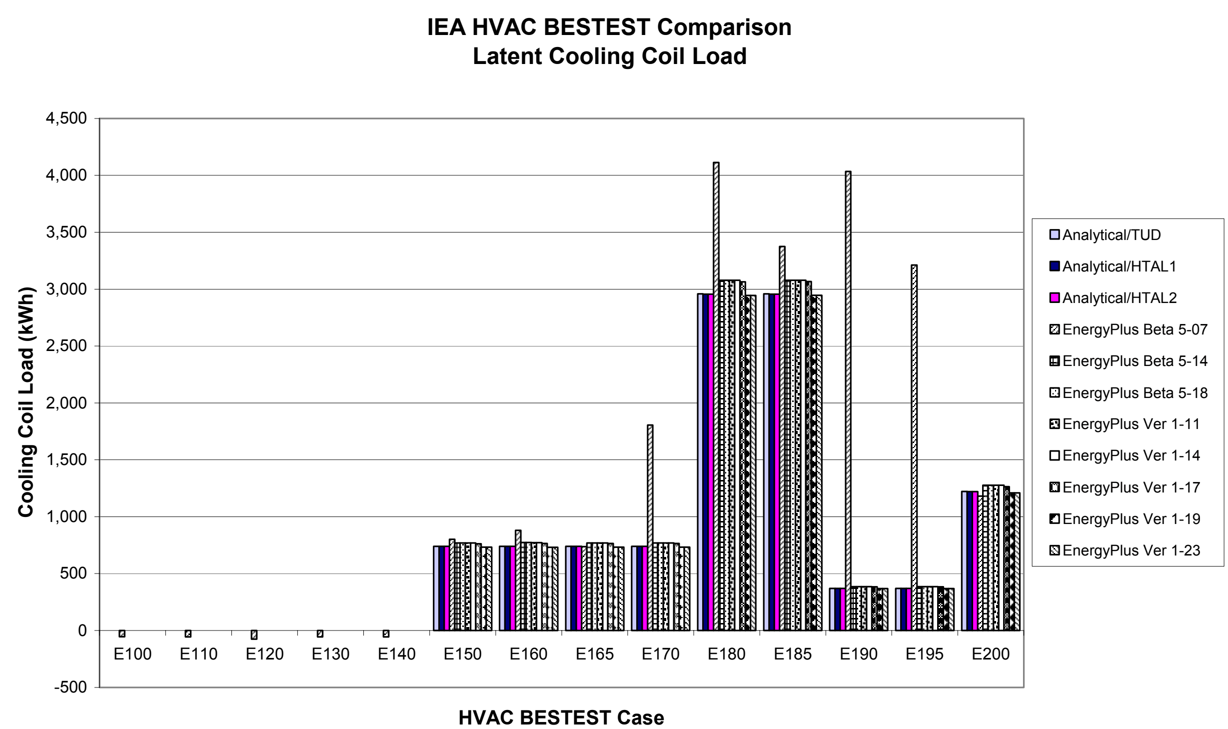

Figure 5 Latent Cooling Coil Load Results for Early Versions of EnergyPlus

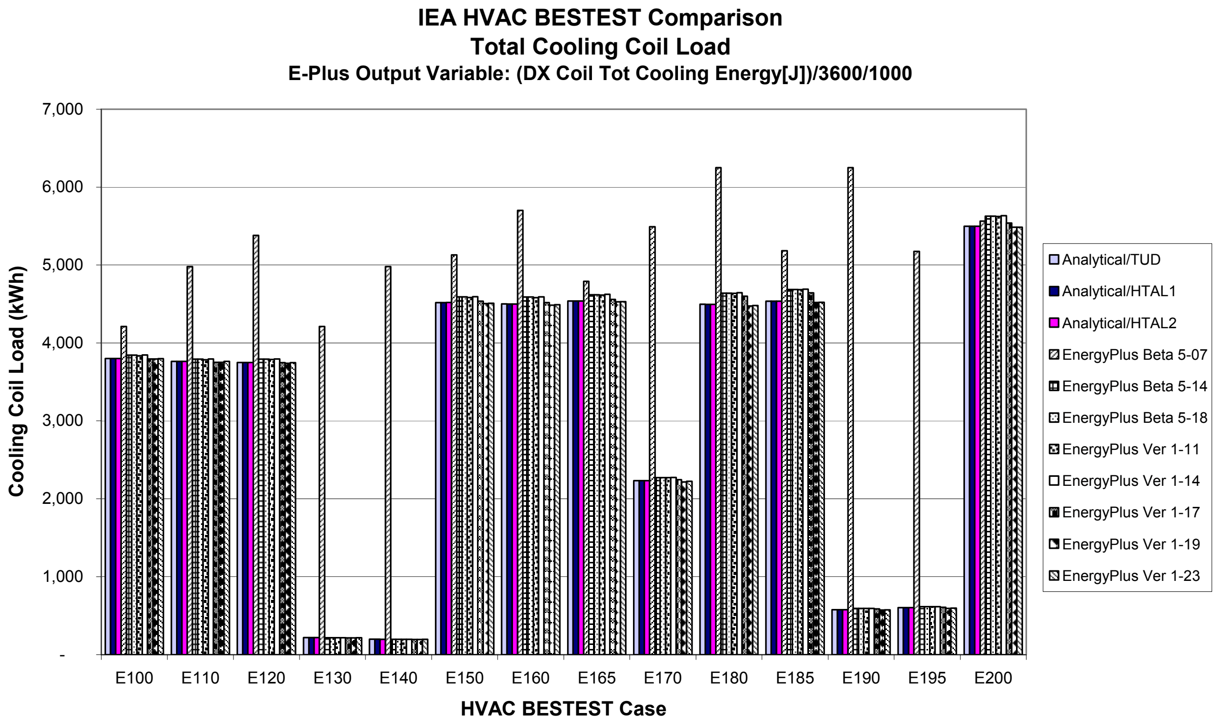

Figure 6 Total Cooling Coil Load Results for Early Versions of EnergyPlus

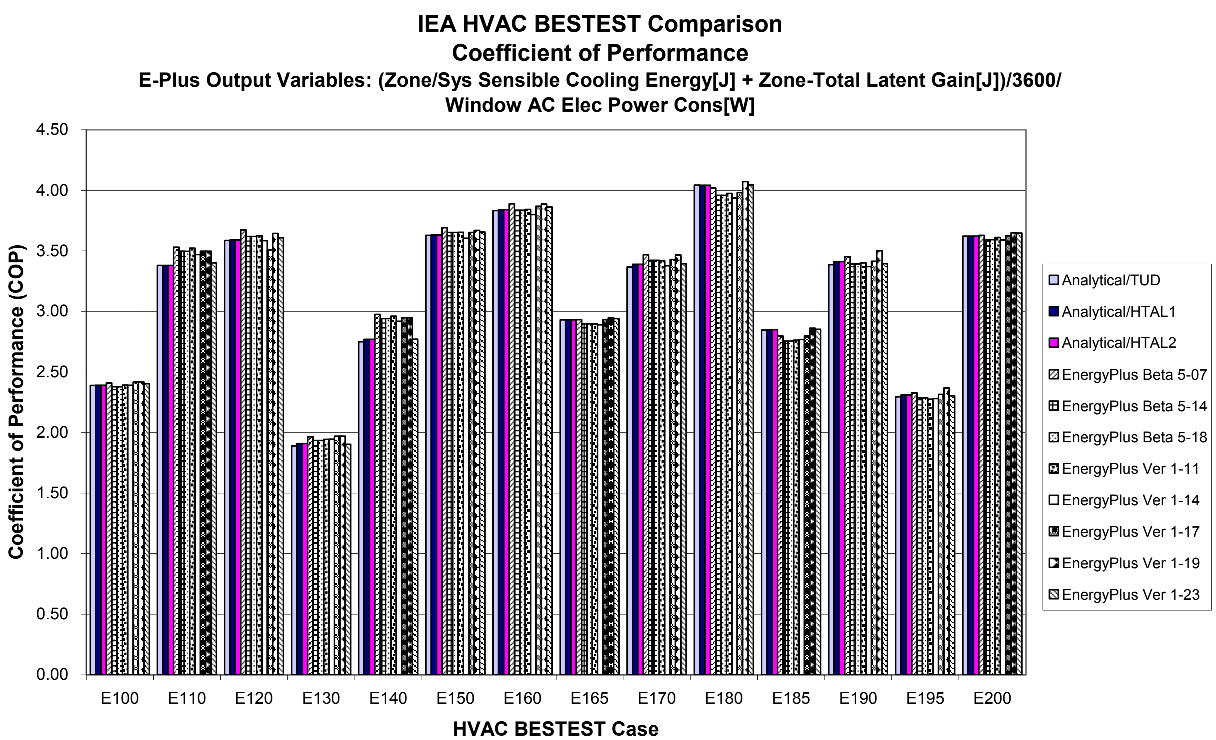

Figure 7 Coefficient of Performance Results for Early Versions of EnergyPlus

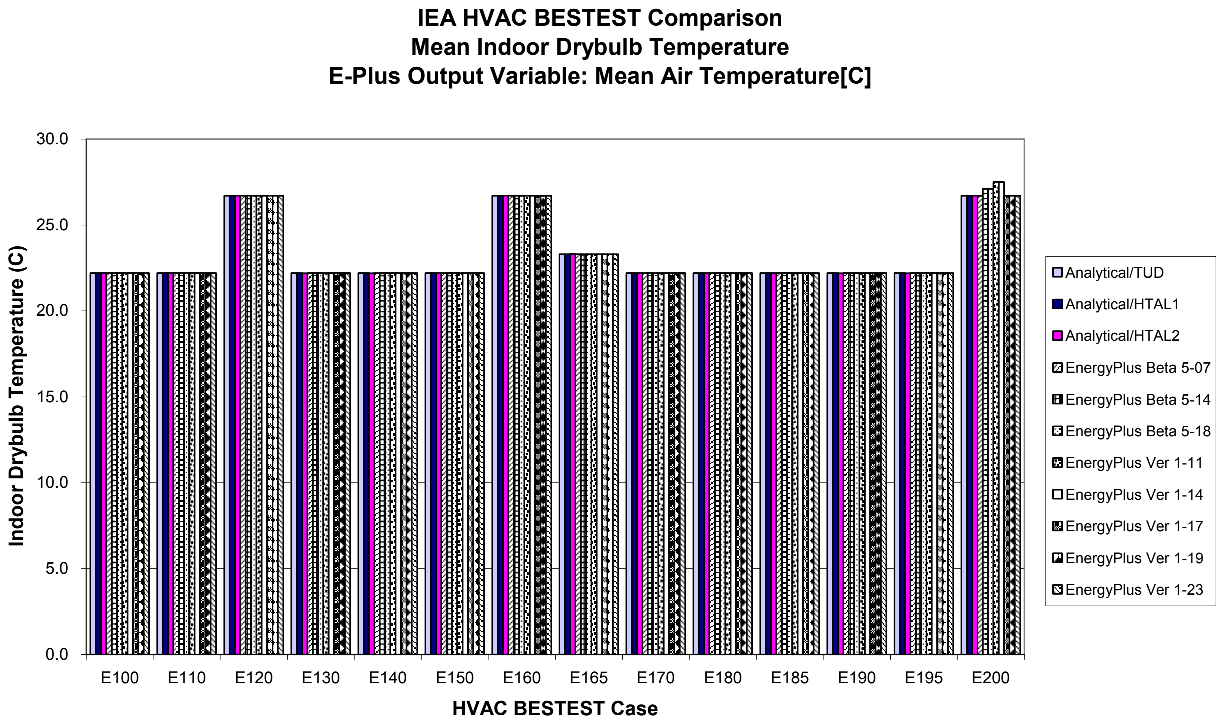

Figure 8 Indoor Dry-Bulb Temperature for Early Versions of EnergyPlus

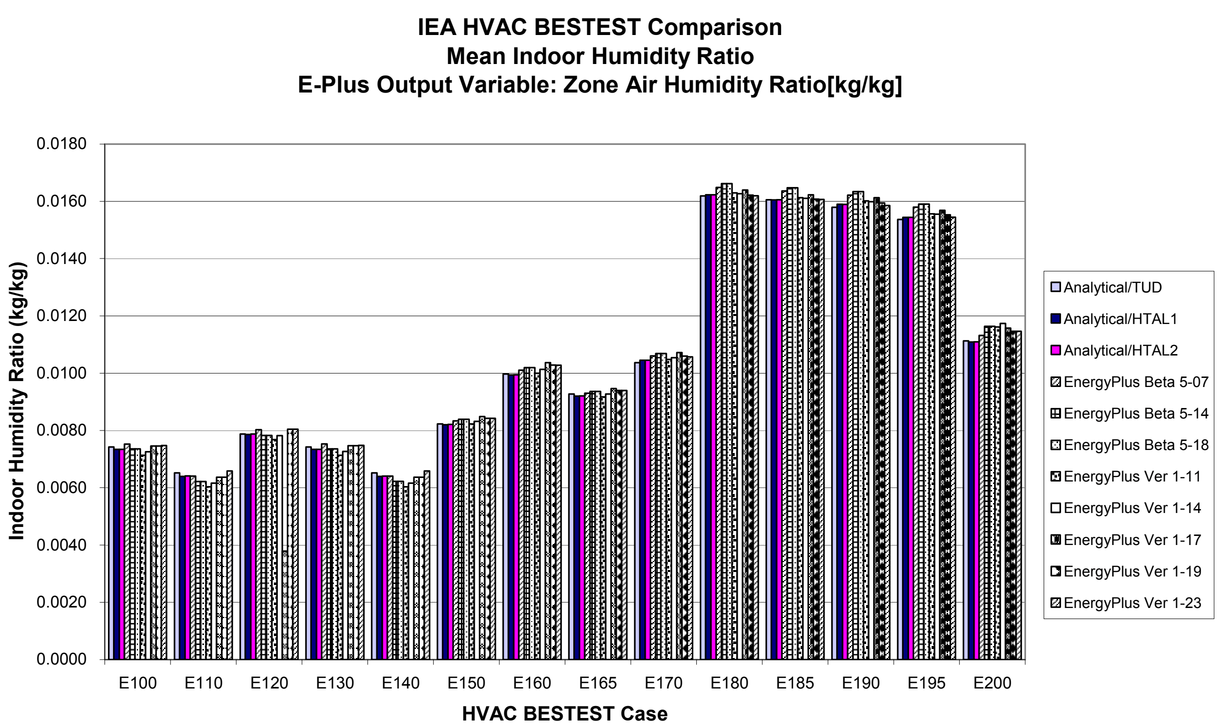

Figure 9 Indoor Humidity Ratio Results for Early Versions of EnergyPlus

2.14 Results with Subsequent Releases of EnergyPlus

The IEA HVAC BESTEST workgroup has completed their activities and final results are recorded in a report authored and released by NREL in January 2002 (Neymark & Judkoff 2002). Since the completion of that study, further capabilities and improvements have been added to EnergyPlus with new releases occurring in June 2002 (version 1.0.1), August 2002 (version 1.0.2), December 2002 (version 1.0.3), April 2003 (version 1.1.0), September 2003 (version 1.1.1) and May 2004 (version 1.2.0). The results for the HVAC BESTEST series with these six new releases of EnergyPlus along with the analytical results and results for the last test series reported in the IEA HVAC BESTEST final report (version 1.0.0.023) are presented in the charts below. Although some minor changes took place in version 1.0.2 and were later reversed in version 1.0.3 (see Table 7), the results for all subsequent releases have remained unchanged.

Table 7 - Summary of Pertinent EnergyPlus Changes that were Implemented After EnergyPlus 1.0.0.023

Version	Input File Changes	Code Changes
1.0.2.003 thru 1.0.2.006		Reformatted and changed the H_{fg} psychrometric function to conform with ASHRAE equations
1.0.3.001 thru 1.0.3.013		Added H_g psychrometric function as per ASHRAE equations and now use this for latent gain conversion to humidity ratio

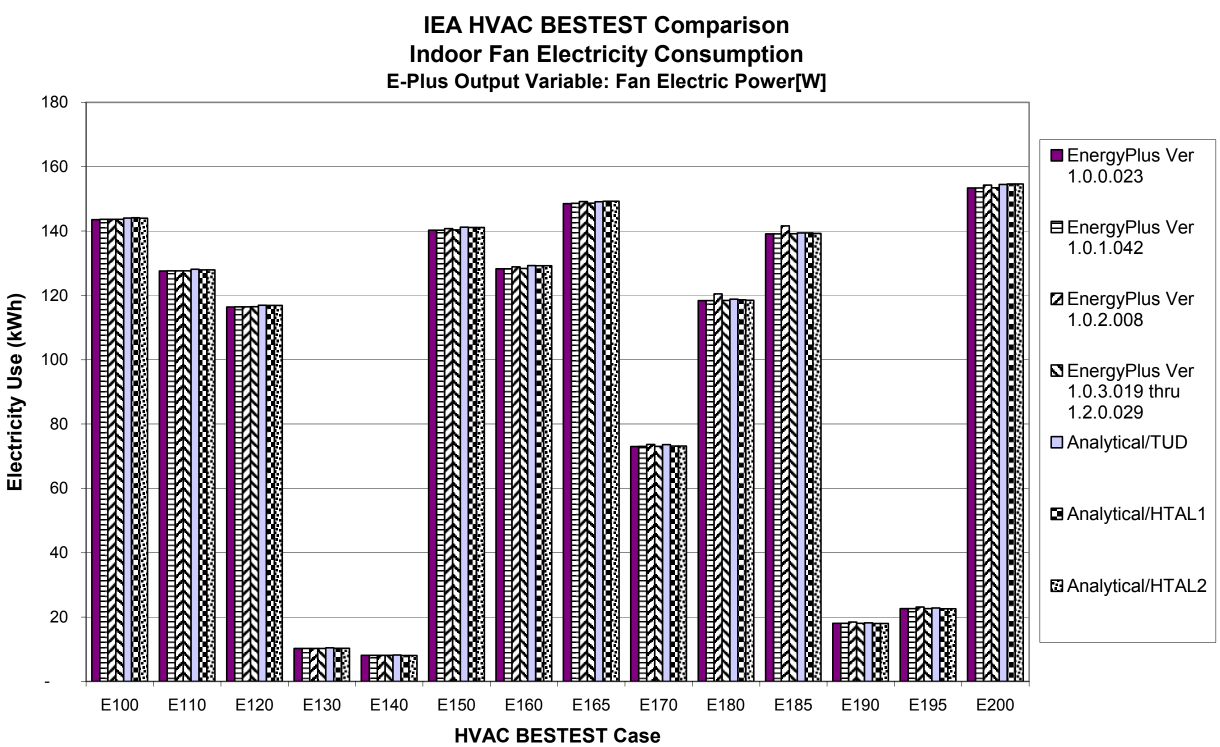

Figure 10 Indoor Fan Power Results for Later Versions of EnergyPlus

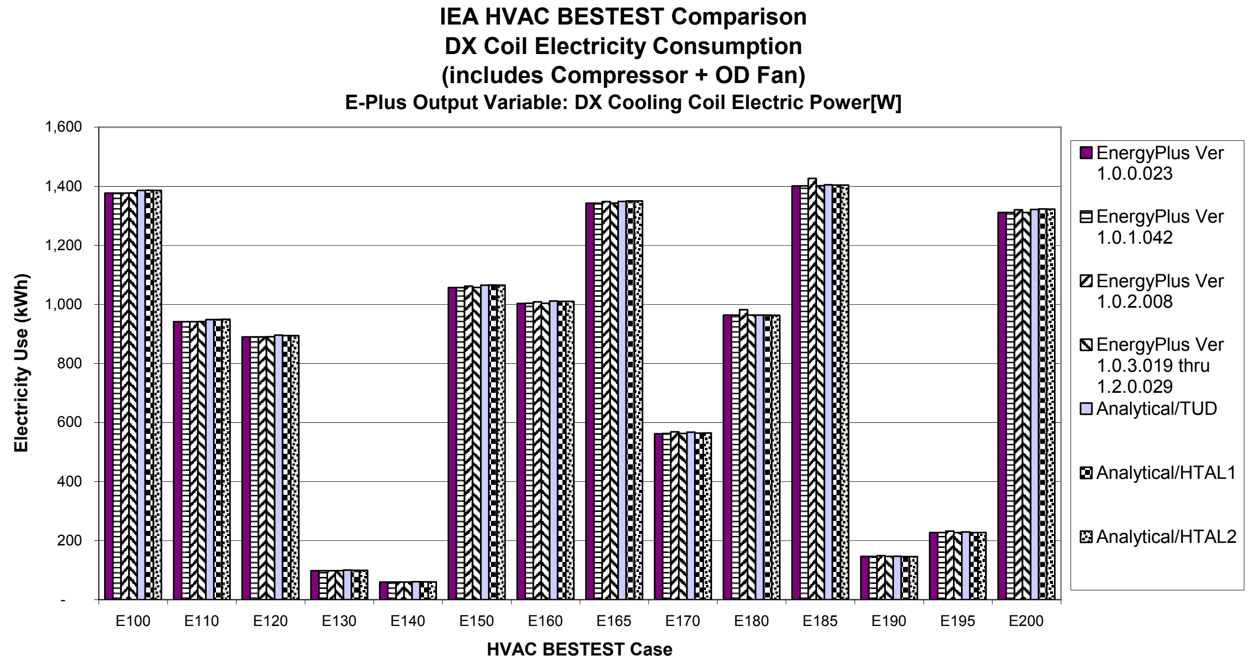

Figure 11 Compressor Plus Outdoor Fan Electricity Consumption Results for Later Versions of EnergyPlus

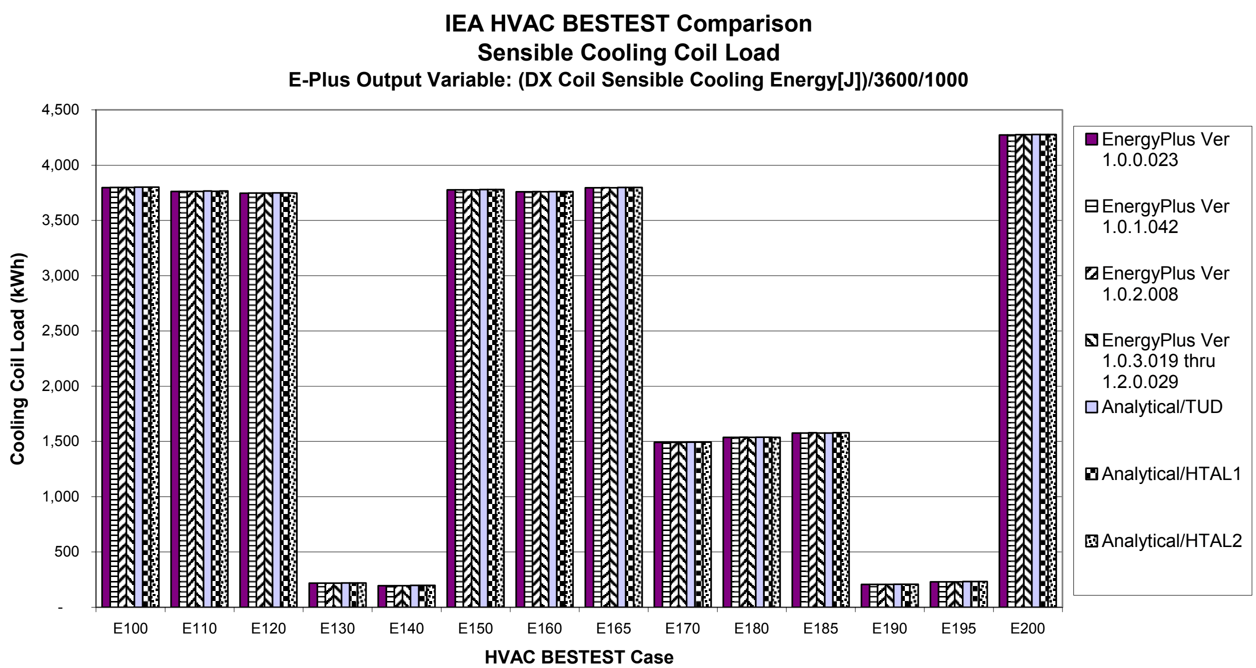

Figure 12 Sensible Cooling Coil Load Results for Later Versions of EnergyPlus

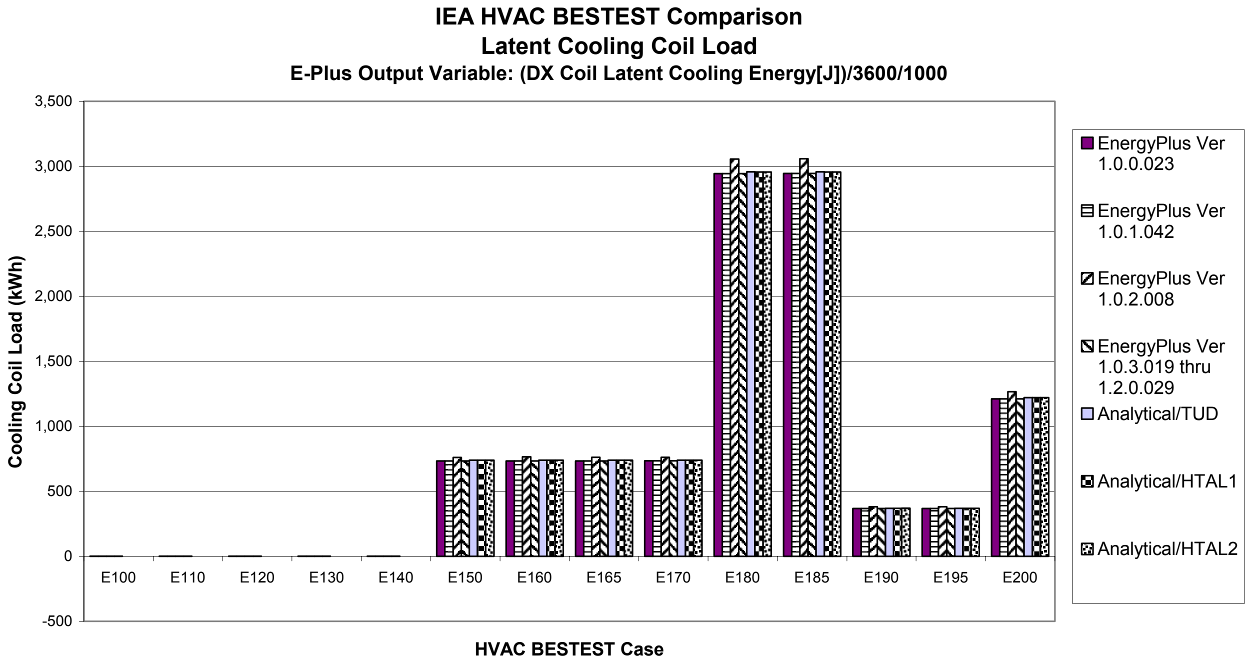

Figure 13 Latent Cooling Coil Load Results for Later Versions of EnergyPlus

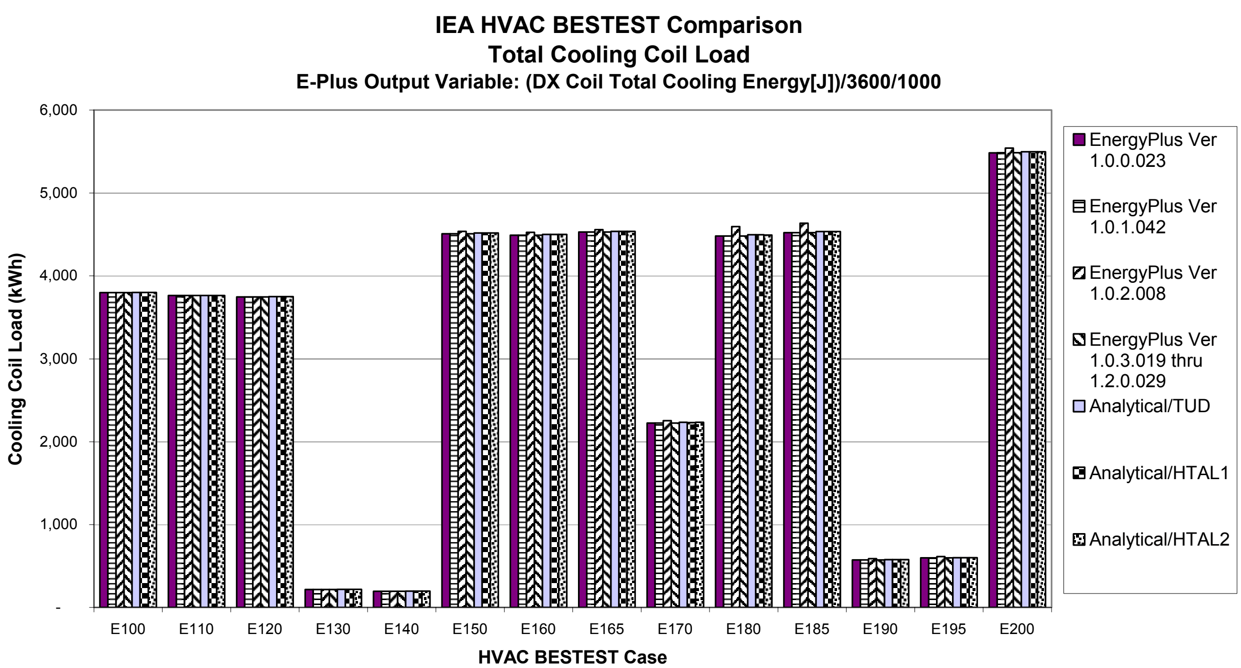

Figure 14 Total Cooling Coil Load Results for Later Versions of EnergyPlus

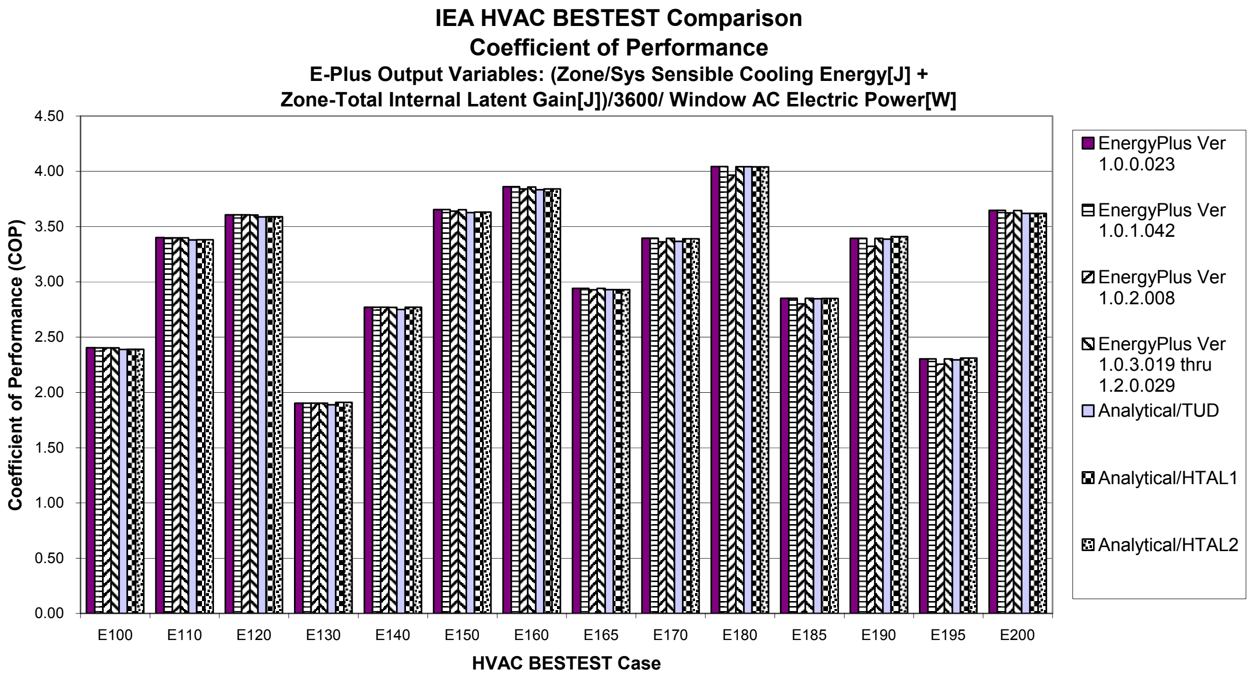

Figure 15 Coefficient of Performance Results for Later Versions of EnergyPlus

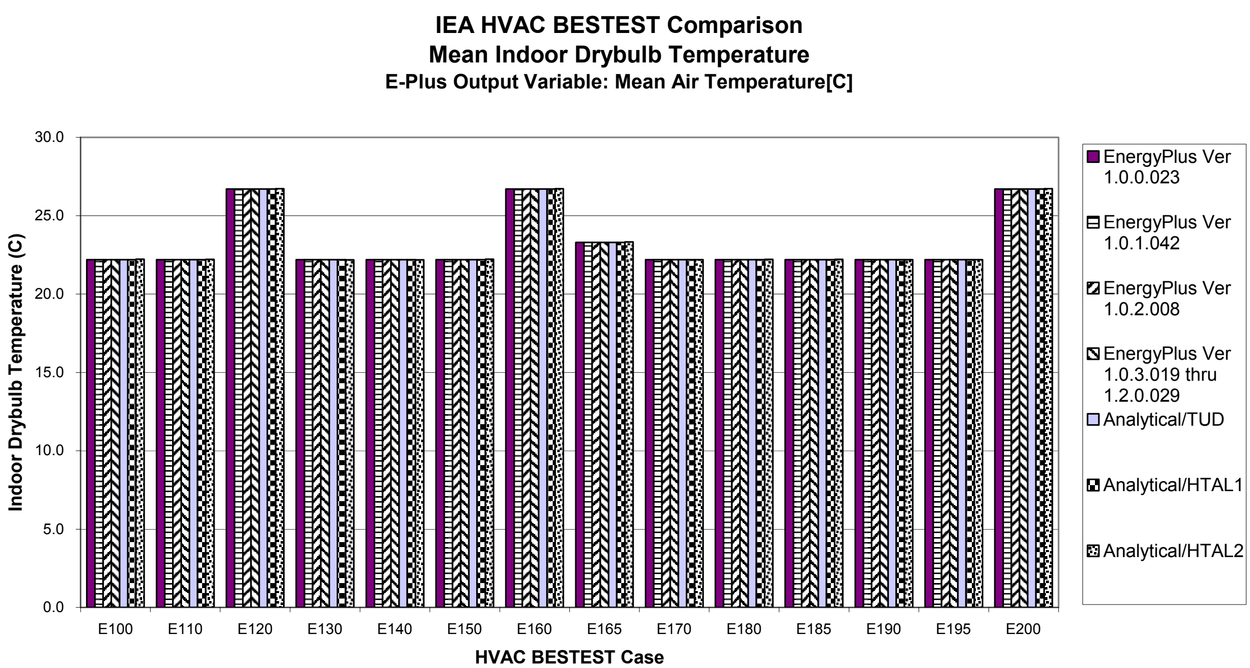

Figure 16 Indoor Dry-Bulb Temperature for Later Versions of EnergyPlus

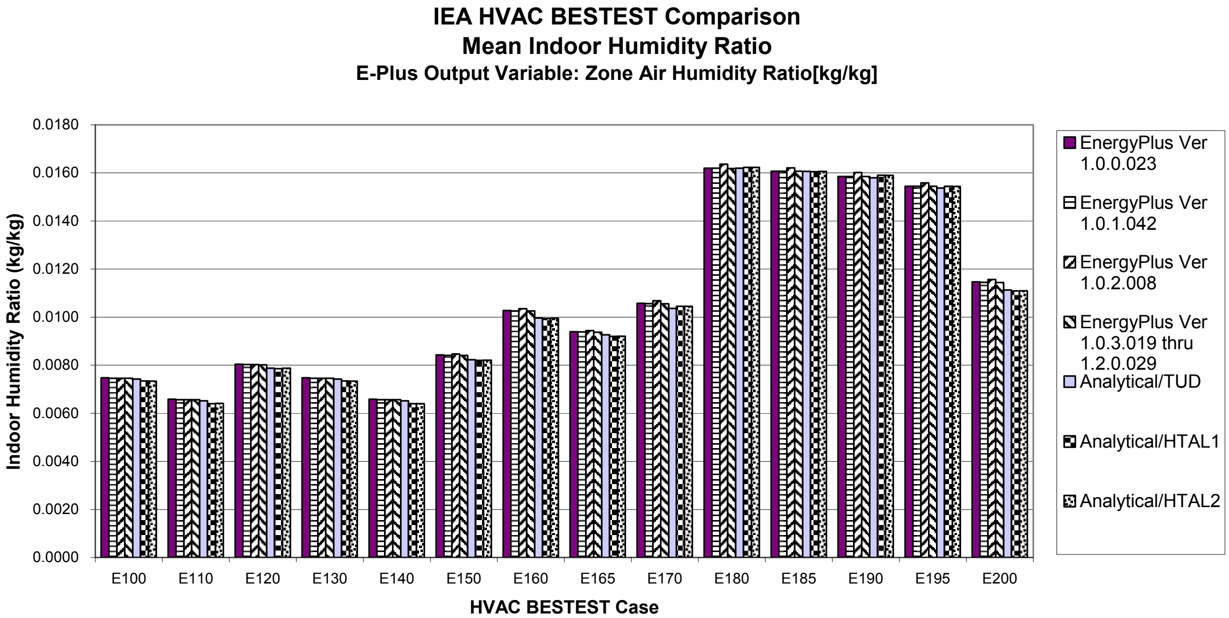

Figure 17 Indoor Humidity Ratio Results for Later Versions of EnergyPlus

3 RESULTS AND DISCUSSION

The results of the EnergyPlus HVAC comparison with other whole building energy analysis programs that participated in the HVAC BESTEST Comparison are summarized on a set of charts which follow in this section. The nomenclature for the various programs referred to on these charts along with the program author and modeler responsible for using the program as part of the HVAC BESTEST project are presented below.

Code Name	Authoring Organization	Implemented by	Abbreviation
CA-SIS V1	Electricite de France, France	Electricite de France, France	CASIS/EDF
CLIM2000 2.1.6	Electricite de France, France	Electricite de France, France	CLIM2000/EDF
DOE-2.1E-088	LANL/LBNL/ESTSC, U.S.	CIEMAT, Spain	DOE21E/CIEMAT
DOE-2.1E-133	LANL/LBNL/JJH, U.S	NREL/JNA, U.S.	DOE21E/NREL
PROMETHEUS	Klimasystemtechnik, Germany	Klimasystemtechnik, Germany	PROKST/KST
TRNSYS 14.2-TUD with ideal controller model	University of Wisconsin, U.S.; Technische Univ. Dresden, Germany	Technische Univ. Dresden, Germany	TRNSYS-ideal/TUD
TRNSYS 14.2-TUD with real controller model	University of Wisc., U.S.; Technische Univ. Dresden, Germany	Technische Univ. Dresden, Germany	TRNYS-real/TUD
Analytical Solution	Hochschule Technik & Architektur, Luzern, Switzerland	Hochschule Technik & Architektur, Luzern, Switzerland	Analytical/HTAL1
Analytical Solution with realistic controller model	Hochschule Technik & Architektur, Luzern, Switzerland	Hochschule Technik & Architektur, Luzern, Switzerland	Analytical/HTAL2
Analytical Solution	Technische Univ. Dresden, Germany	Technische Univ. Dresden, Germany	Analytical/TUD
ENERGYPLUS 1.2.0.029	U.S. Dept. of Energy	GARD Analytics, Inc., U.S.	EnergyPlus Ver 1.2.0.029

LANL/LBNL: Los Alamos National Laboratory/Lawrence Berkeley Laboratory
ESTAC: Energy Science & Technology Software Center (at Oak Ridge National Laboratory)
CIEMAT: Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas
JJH: James J. Hirsch & Associates
NREL/JNA: National Renewable Energy Laboratory/J. Neymark & Associates

Appendix A contains a series of charts that compare the results of EnergyPlus with other programs. The charts are presented in the following order:

Space Cooling Electricity Consumption (compressor + outdoor fan + indoor fan)
Indoor Fan Electricity Consumption
DX Coil Electricity Consumption (compressor + outdoor fan)
Coefficient of Performance
Total Cooling Coil Load
Sensible Cooling Coil Load
Latent Cooling Coil Load
Zone Load (fan heat)
Zone Total Cooling Load
Zone Sensible Cooling Load
Zone Latent Cooling Load
Mean Indoor Dry-bulb Temperature
Mean Indoor Humidity Ratio.

A visual inspection of the charts in Appendix A indicates that EnergyPlus compares very well to the analytical results for all of the charts. Quantitatively, the percent difference between EnergyPlus and average analytical results were as follows:

	Max. % Difference
Space Cooling Electricity Consumption	1.15
Indoor Fan Electricity Consumption	0.78
DX Coil Electricity Consumption	1.16
Coefficient of Performance	0.74
Total Cooling Coil Load	1.04
Sensible Cooling Coil Load	1.04
Latent Cooling Coil Load	0.97
Zone Load	1.19
Zone Total Cooling Load	1.07
Zone Sensible Cooling Load	1.07
Zone Latent Cooling Load	0.0
Mean Indoor Dry-bulb Temperature	0.02
Mean Indoor Humidity Ratio.	3.28

4 CONCLUSIONS

EnergyPlus Version 1.0.0.023 and subsequent versions up through the most recent release, EnergyPlus 1.2.0.029, were used to model a range of HVAC equipment load specifications as specified in *International Energy Agency Building Energy Simulation Test and Diagnostic Method for HVAC Equipment Models (HVAC BESTEST)*. The ability of EnergyPlus to predict zone loads, cooling coil loads, cooling equipment energy consumption and resulting zone environment was tested using a test suite of 14 cases which included varying internal loads and outdoor conditions. The results predicted by EnergyPlus for 14 different cases were compared to results from 7 other whole building energy simulation programs that participated in an International Energy Agency (IEA) project which concluded in January 2002. Comparisons were also made with the results from three analytical solutions. EnergyPlus results generally agreed to within 1% of the analytical results except for the mean zone humidity ratio which agreed to within 3% for high SHR cases but was within 0.20% for low SHR cases.

Although not modeled as part of this exercise, EnergyPlus has another type of applicable system that could have been used, i.e., a unitary furnace with DX cooling coil. This system is currently modeled in EnergyPlus with only a blow-through fan configuration. When the draw-through option becomes available, this system type should also be tested.

For another discussion of EnergyPlus results, please refer to Appendix B where pertinent sections were extracted from the HVAC BESTEST Final Report (Neymark & Judkoff 2001) prepared by Joel Neymark, J. Neymark & Associates, October 2001.

The HVAC BESTEST suite is a very valuable testing tool which provides excellent benchmarks for testing HVAC system and equipment algorithms versus the results of other international building simulation programs. As discussed above, HVAC BESTEST allowed the developers of EnergyPlus to identify errors in algorithms and improve simulation accuracy.

5 REFERENCES

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Taylor, R. D, C. O. Pedersen, and L. K. Lawrie. 1990. "Simultaneous Simulation of Buildings and Mechanical Systems in Heat Balance Based Energy Analysis Programs," in *Proceedings of the 3rd International Conference on System Simulation in Buildings*, December 1990, Liege, Belgium.

Taylor R. D., C. E. Pedersen, D. E. Fisher, R. J. Liesen, and L. K. Lawrie. 1991. "Impact of Simultaneous Simulation of Building and Mechanical Systems in Heat Balance Based Energy Analysis Programs on System Response and Control," in *Proceedings of Building Simulation '91*, August 1991, Nice, France, IBPSA.

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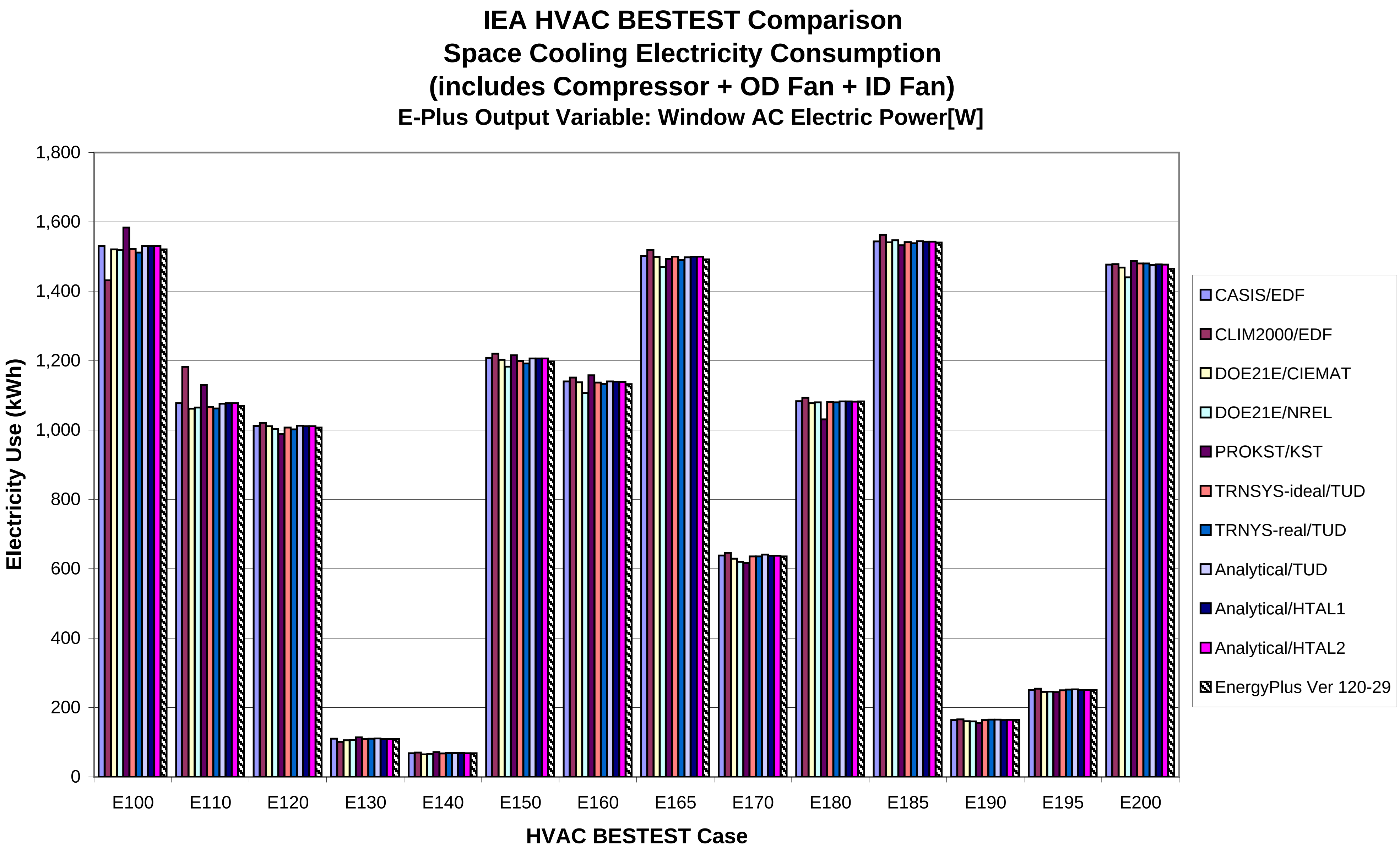
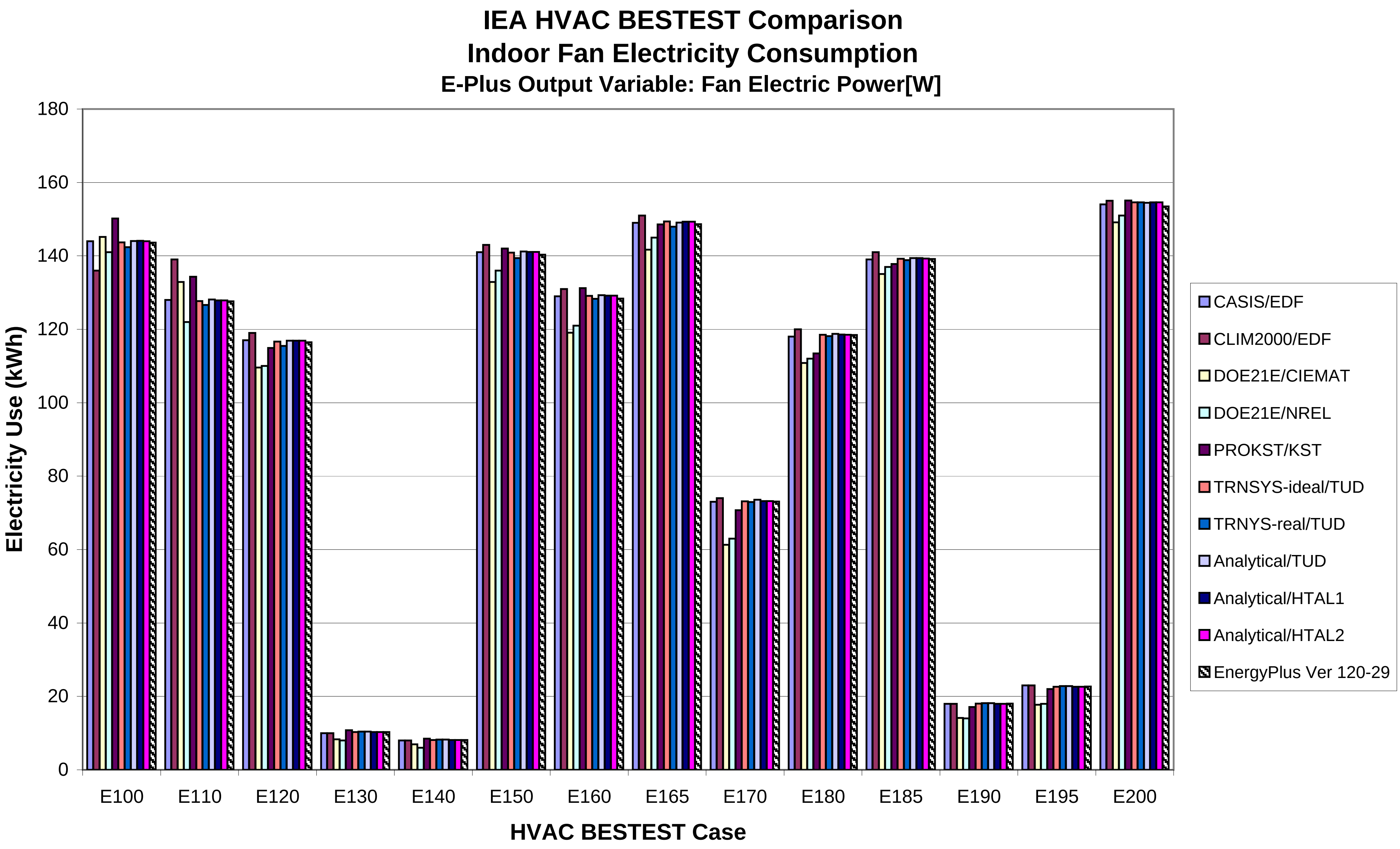
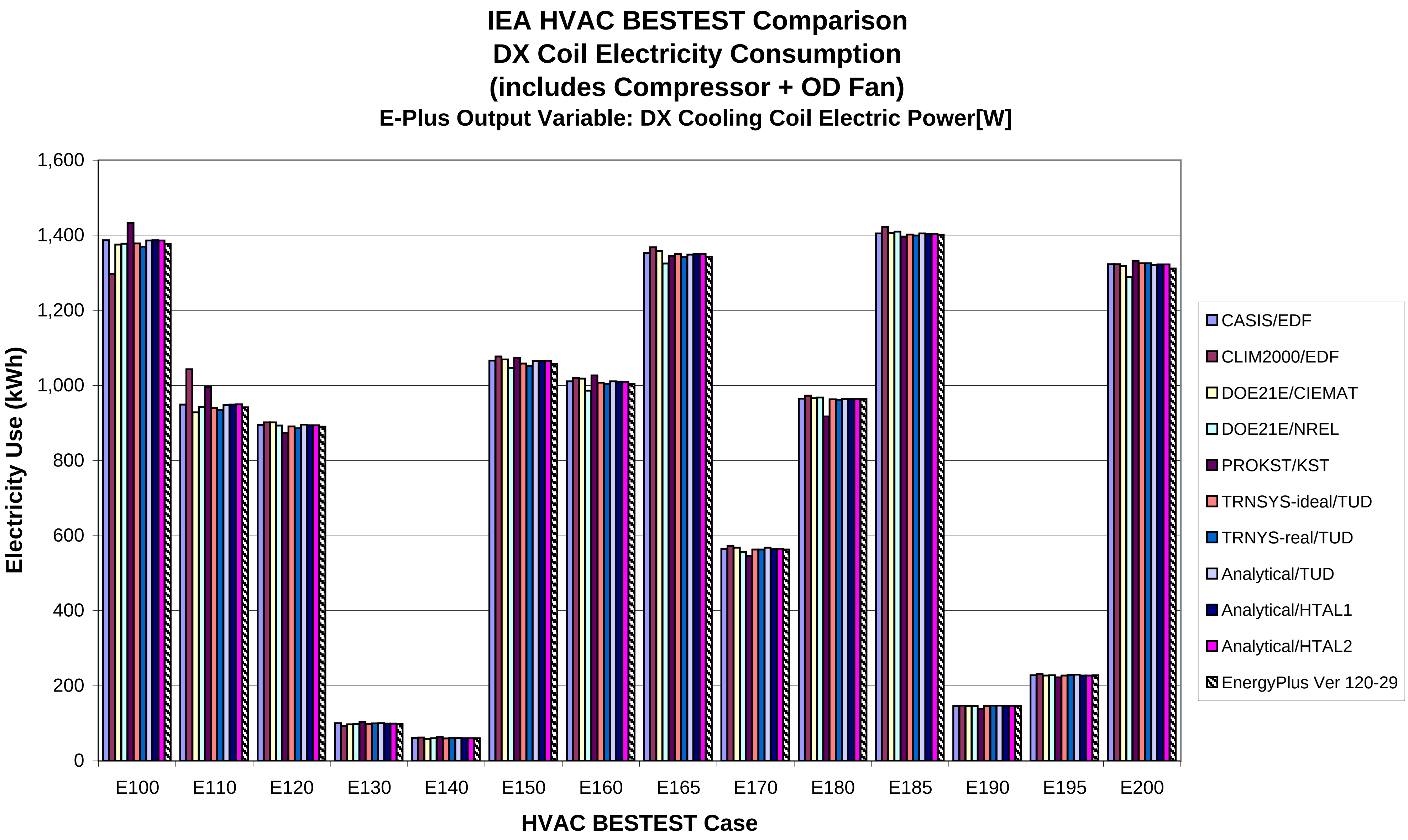
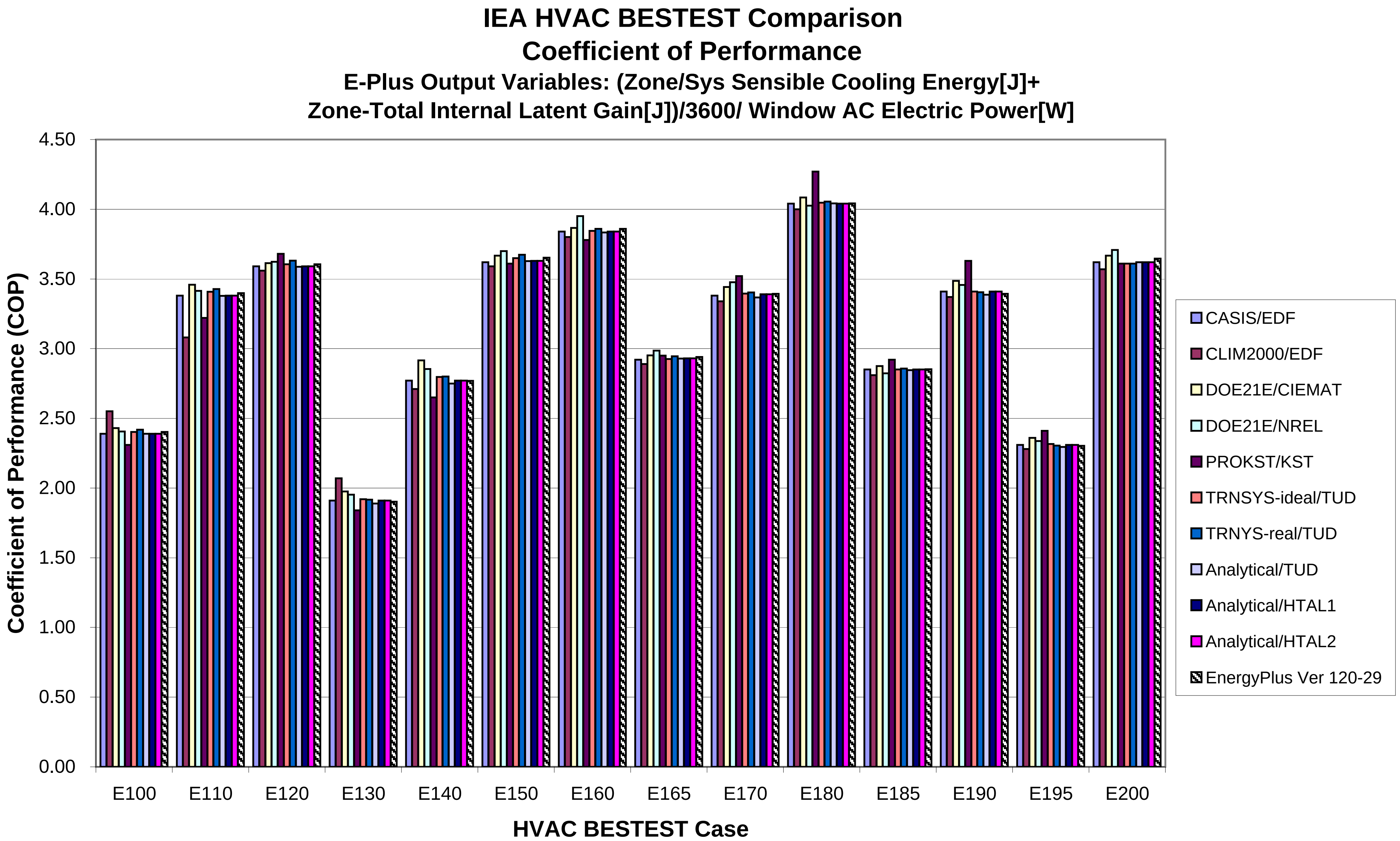
Appendix A

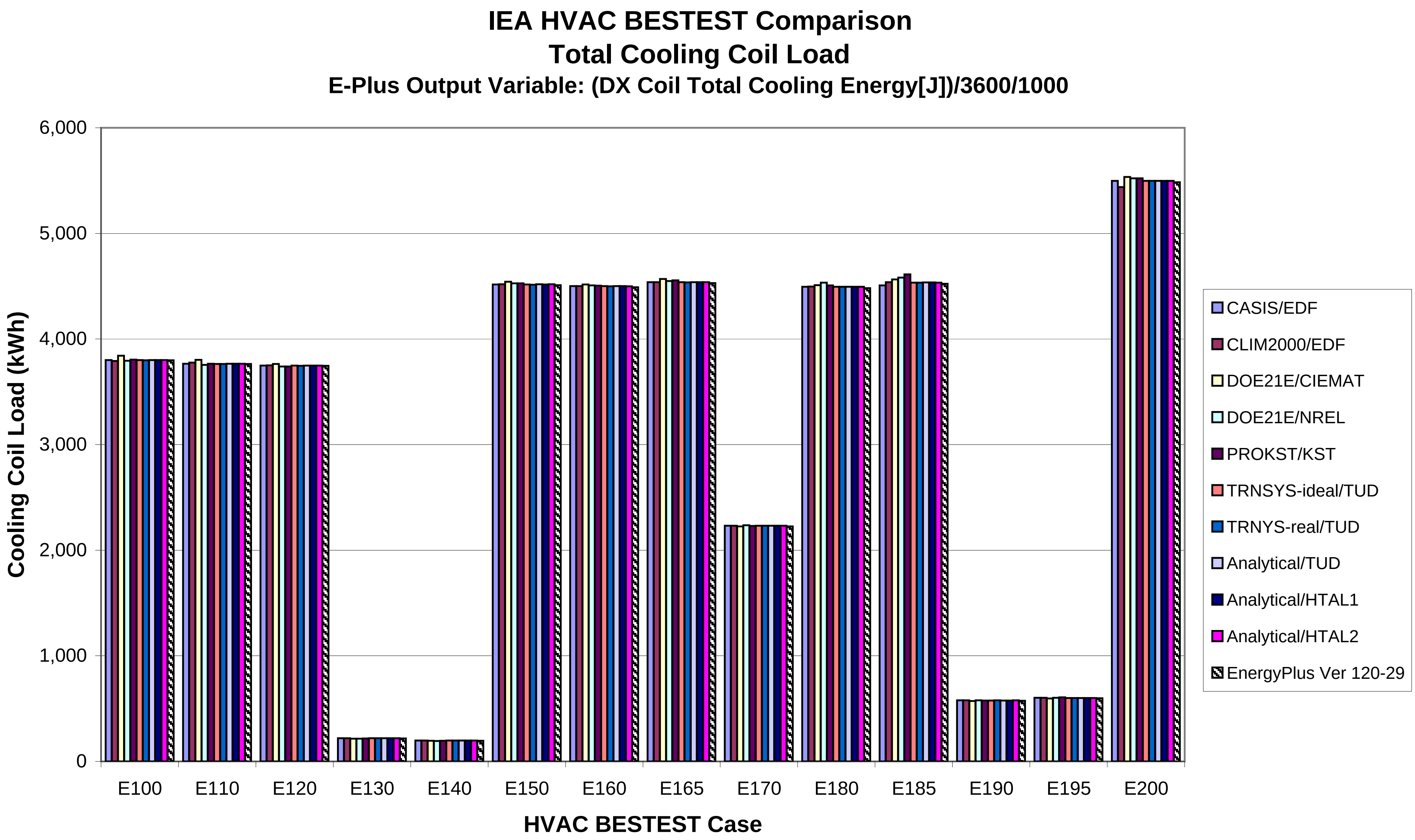
Charts Comparing EnergyPlus Results with Other Whole Building Energy Simulation Programs

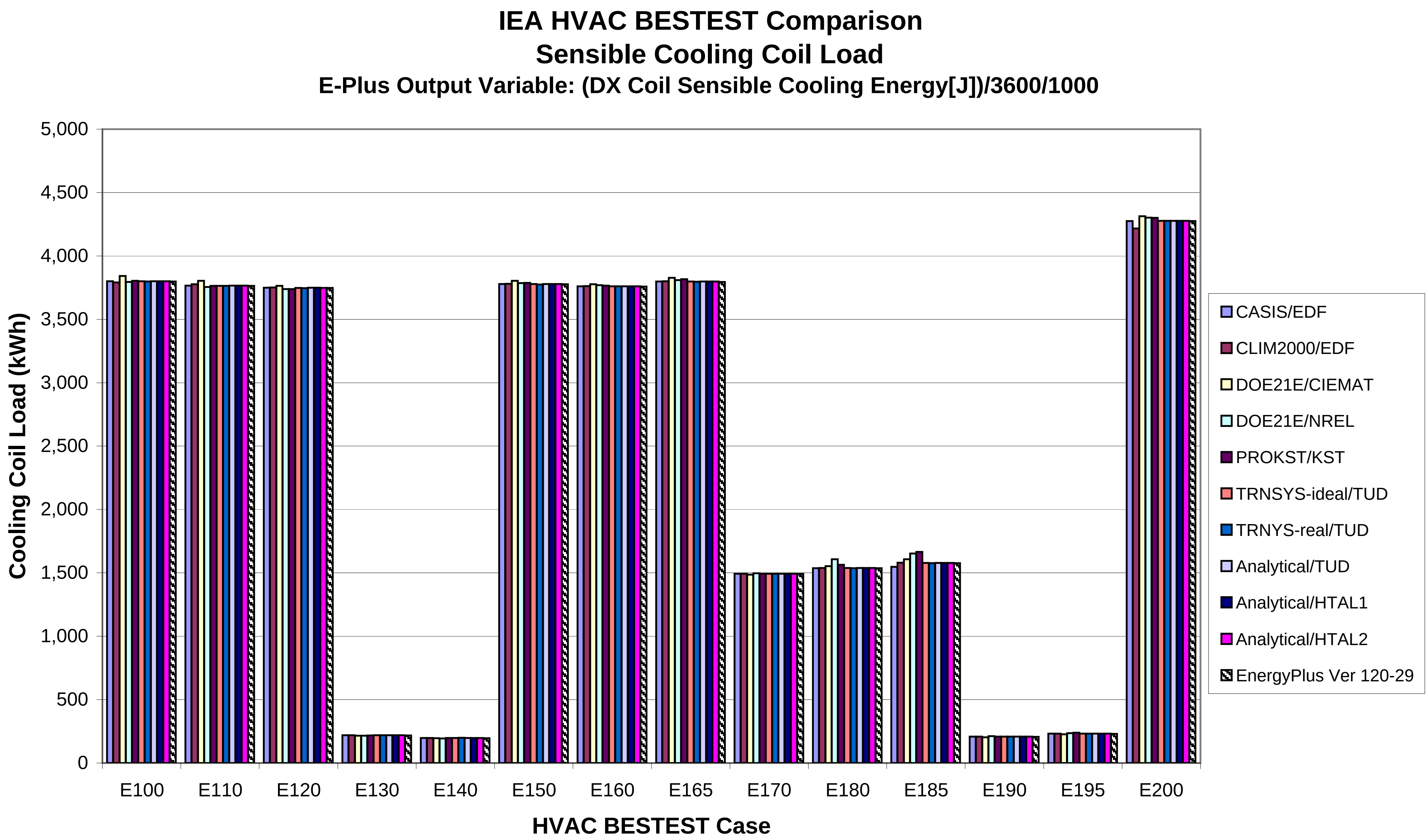

IEA HVAC BESTEST Comparison
Space Cooling Electricity Consumption
(includes Compressor + OD Fan + ID Fan)
E-Plus Output Variable: Window AC Electric Power[W]
Electricity Use (kWh)
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

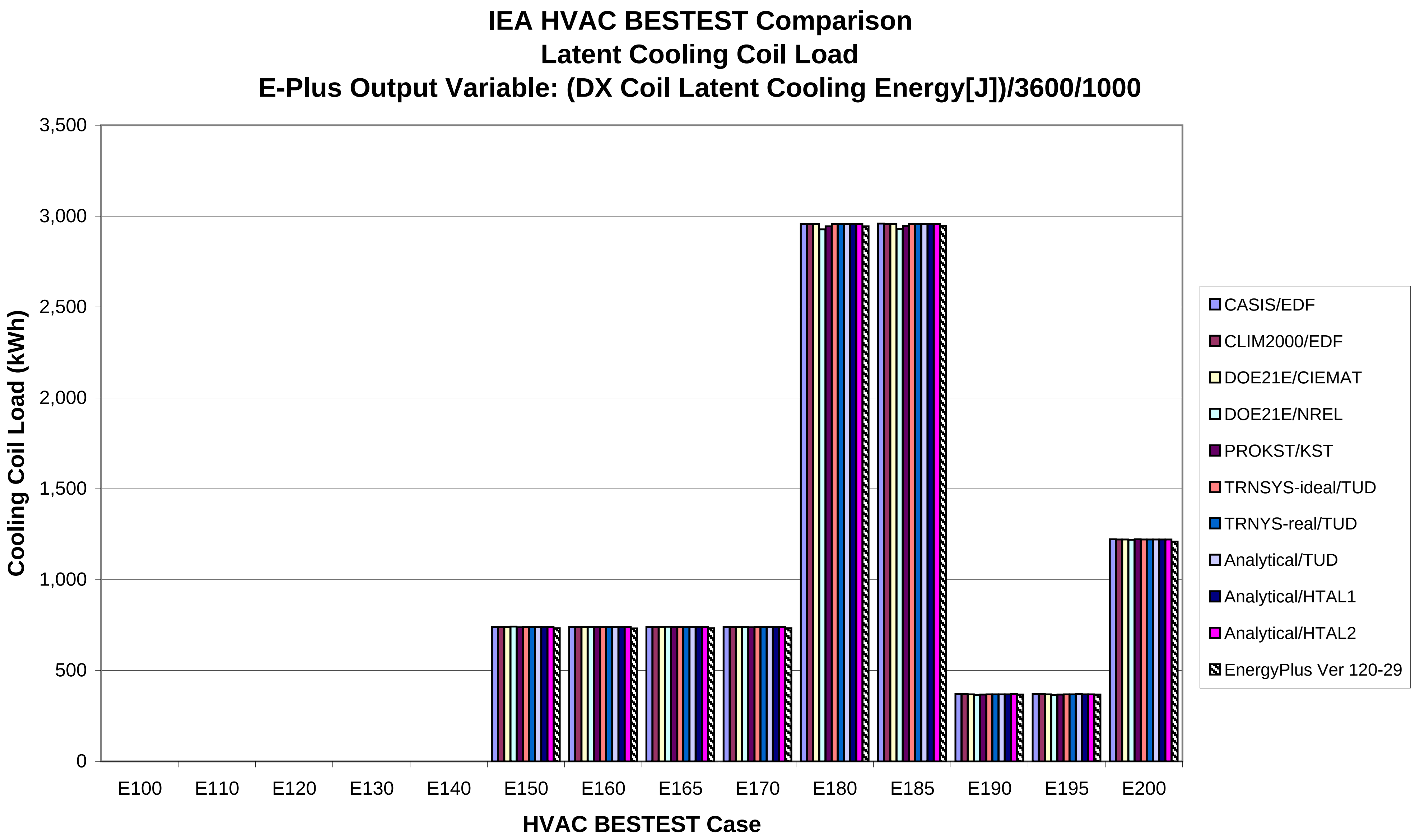

IEA HVAC BESTEST Comparison
Indoor Fan Electricity Consumption
E-Plus Output Variable: Fan Electric Power[W]
Electricity Use (kWh)
0
20
40
60
80
100
120
140
160
180
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

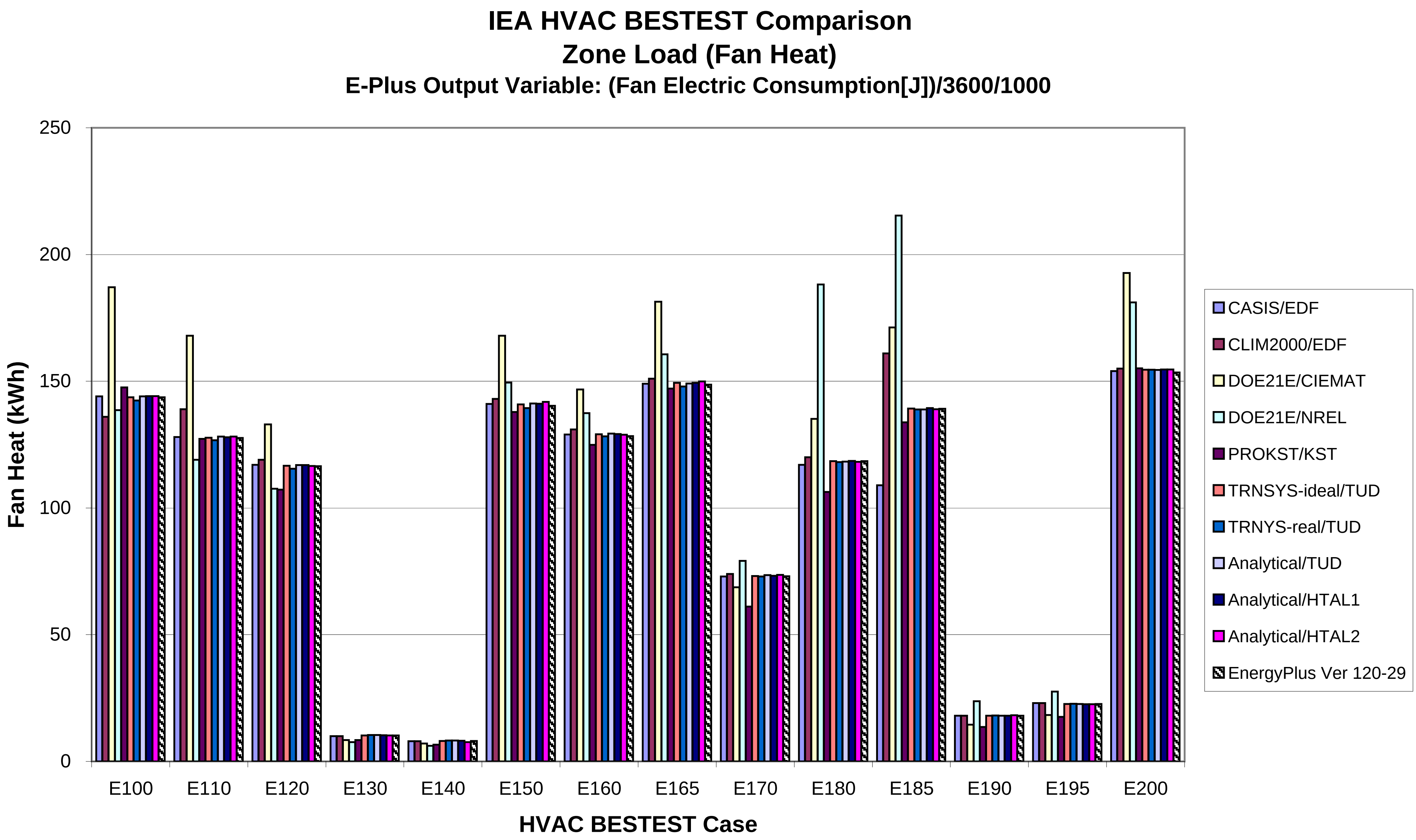

IEA HVAC BESTEST Comparison
DX Coil Electricity Consumption
(includes Compressor + OD Fan)
E-Plus Output Variable: DX Cooling Coil Electric Power[W]
Electricity Use (kWh)
1,600
1,400
1,200
1,000
800
600
400
200
0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

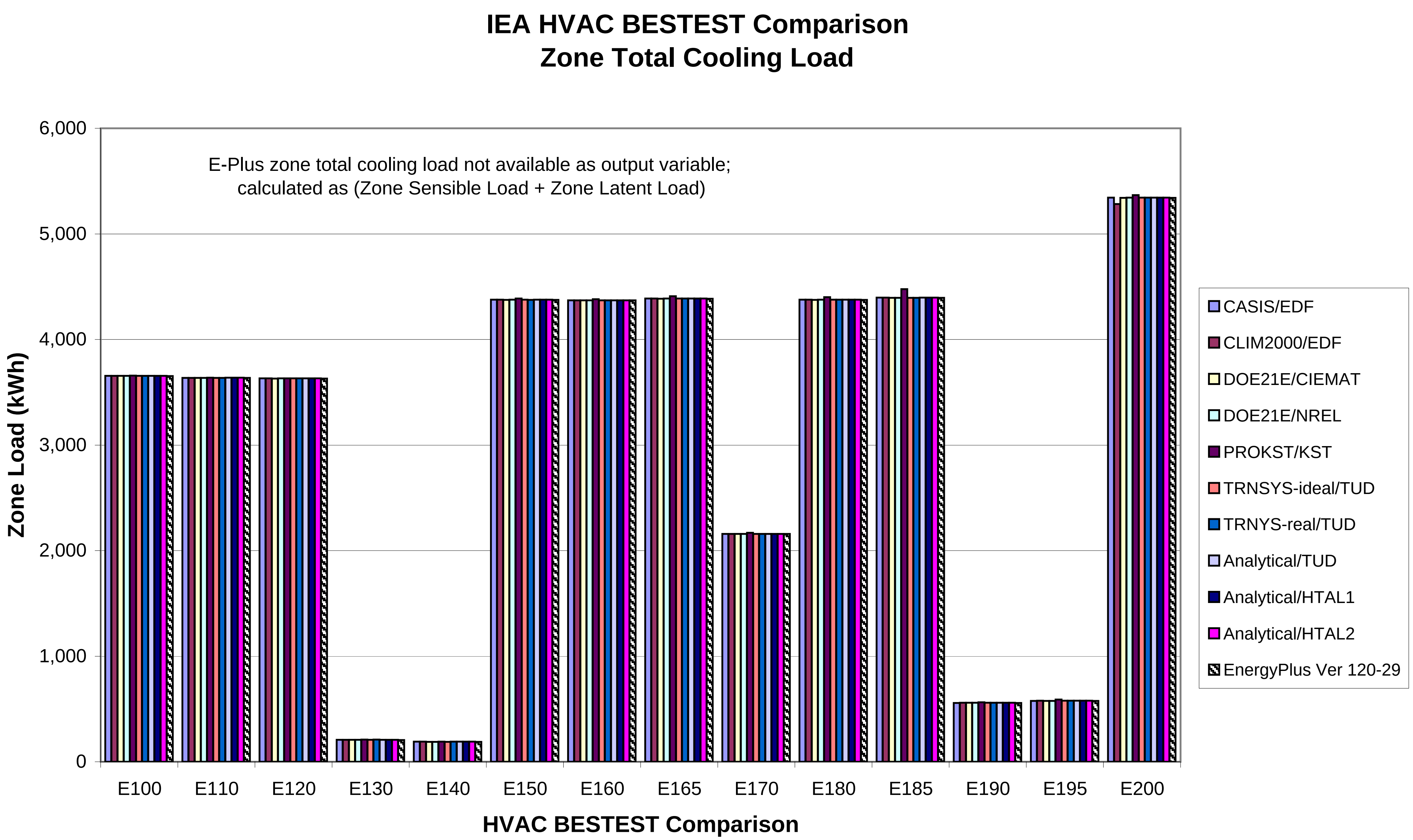

IEA HVAC BESTEST Comparison
Coefficient of Performance
E-Plus Output Variables: (Zone/Sys Sensible Cooling Energy[J]+
Zone-Total Internal Latent Gain[J])/3600/ Window AC Electric Power[W]
Coefficient of Performance (COP)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29


IEA HVAC BESTEST Comparison
Total Cooling Coil Load
E-Plus Output Variable: (DX Coil Total Cooling Energy[J])/3600/1000
Cooling Coil Load (kWh)
6,000
5,000
4,000
3,000
2,000
1,000
0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

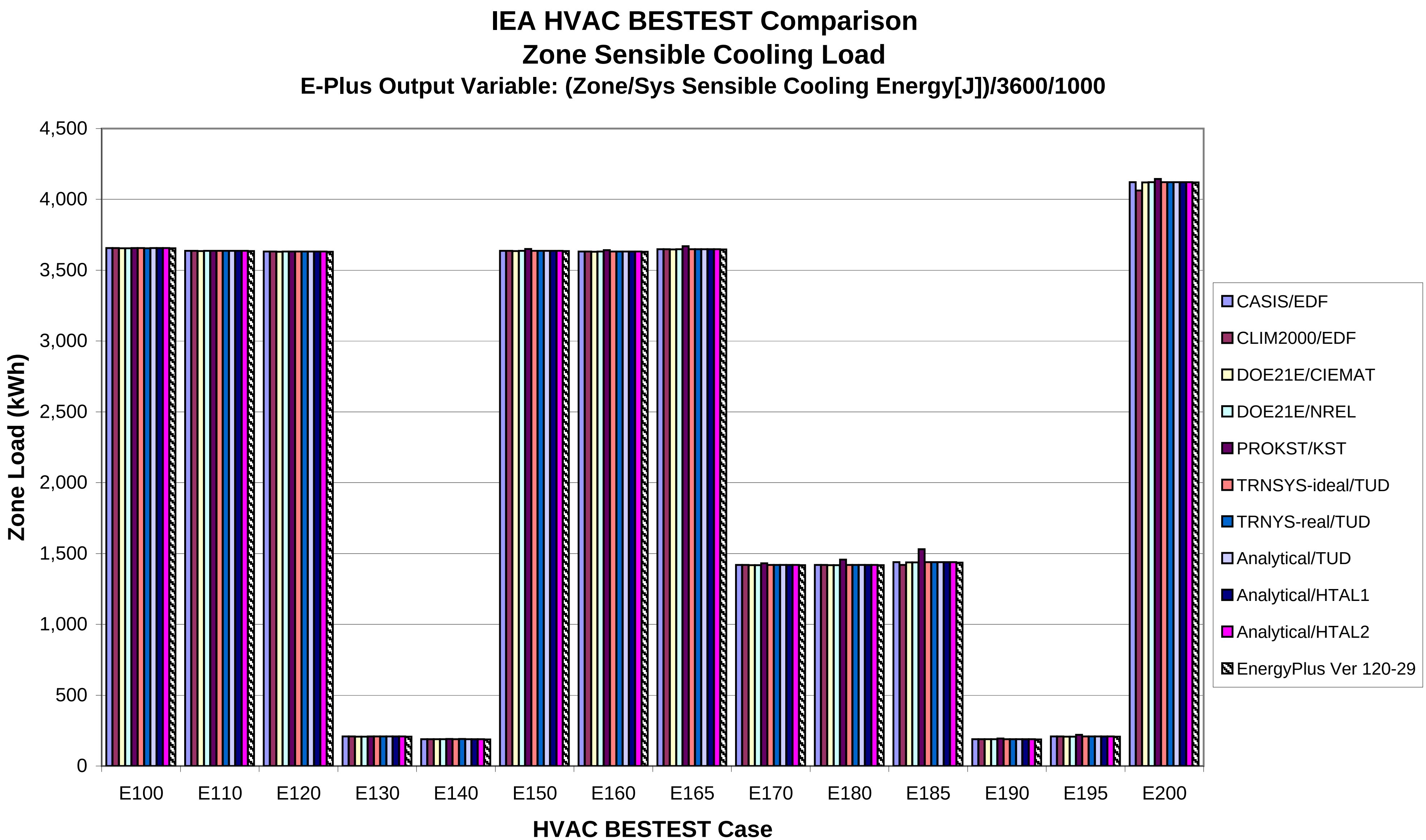

IEA HVAC BESTEST Comparison
Sensible Cooling Coil Load
E-Plus Output Variable: (DX Coil Sensible Cooling Energy[J])/3600/1000
Cooling Coil Load (kWh)
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

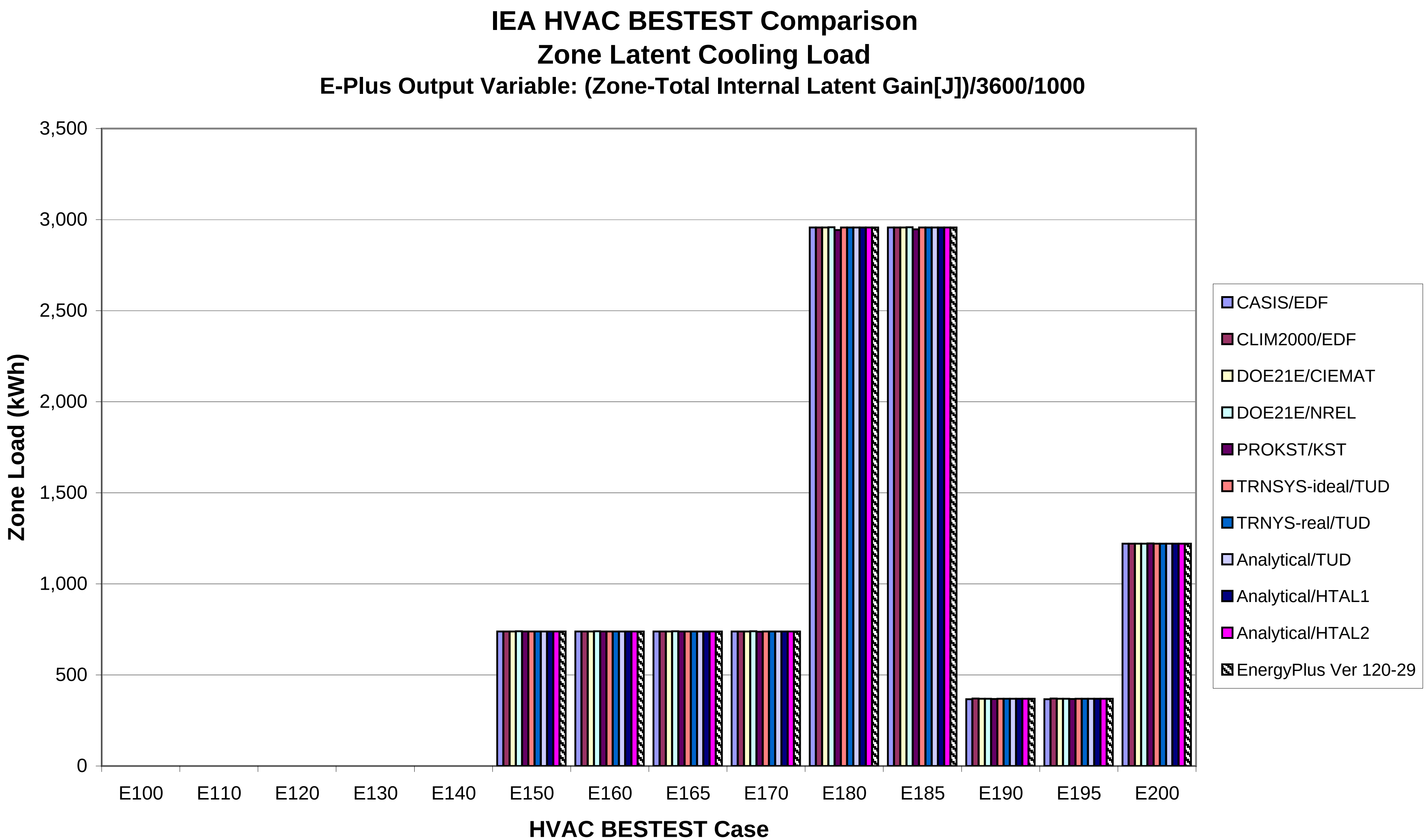

IEA HVAC BESTEST Comparison
Latent Cooling Coil Load
E-Plus Output Variable: (DX Coil Latent Cooling Energy[J])/3600/1000
Cooling Coil Load (kWh)
0
500
1,000
1,500
2,000
2,500
3,000
3,500
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

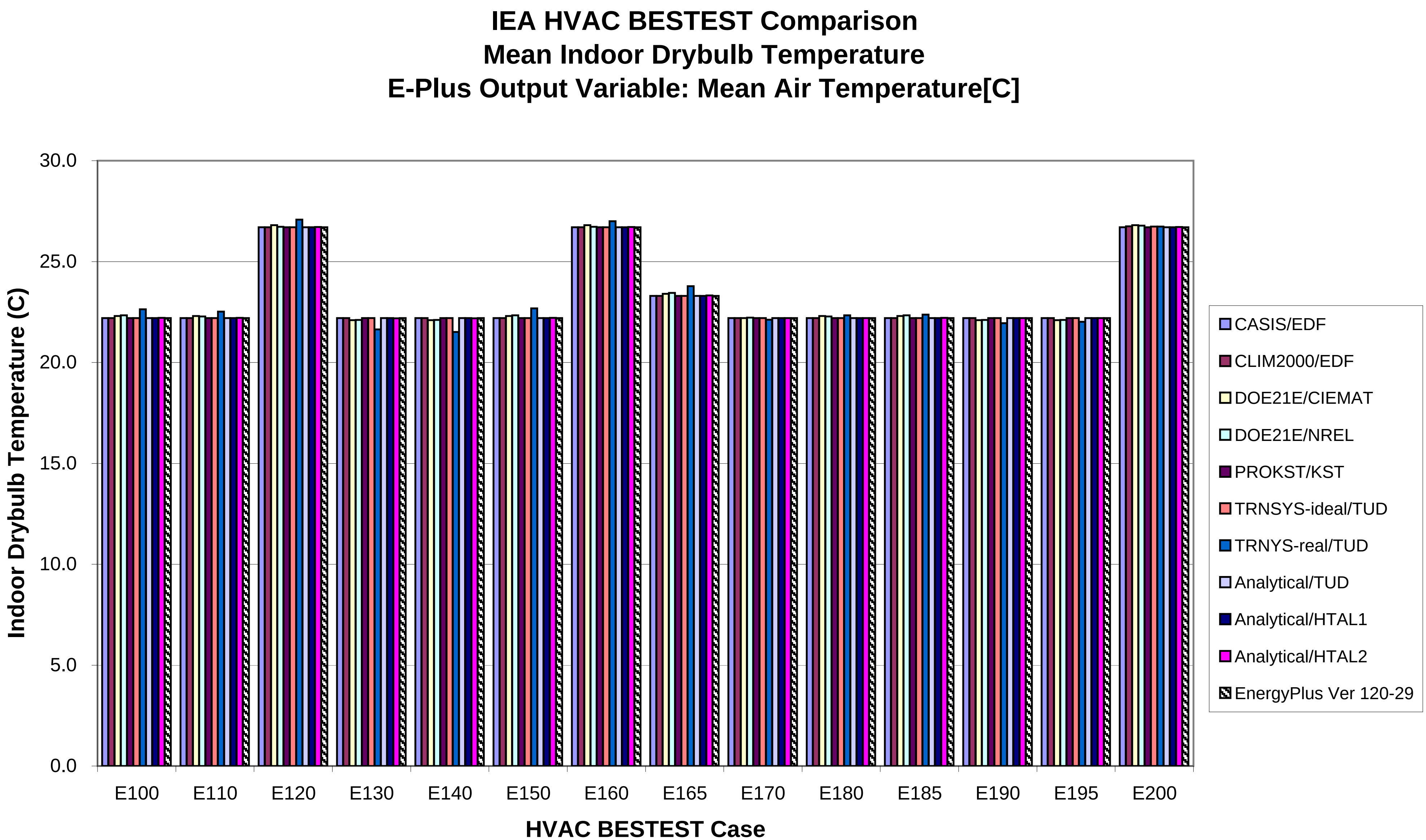

IEA HVAC BESTEST Comparison
Zone Load (Fan Heat)
E-Plus Output Variable: (Fan Electric Consumption[J])/3600/1000
Fan Heat (kWh)
250
200
150
100
50
0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

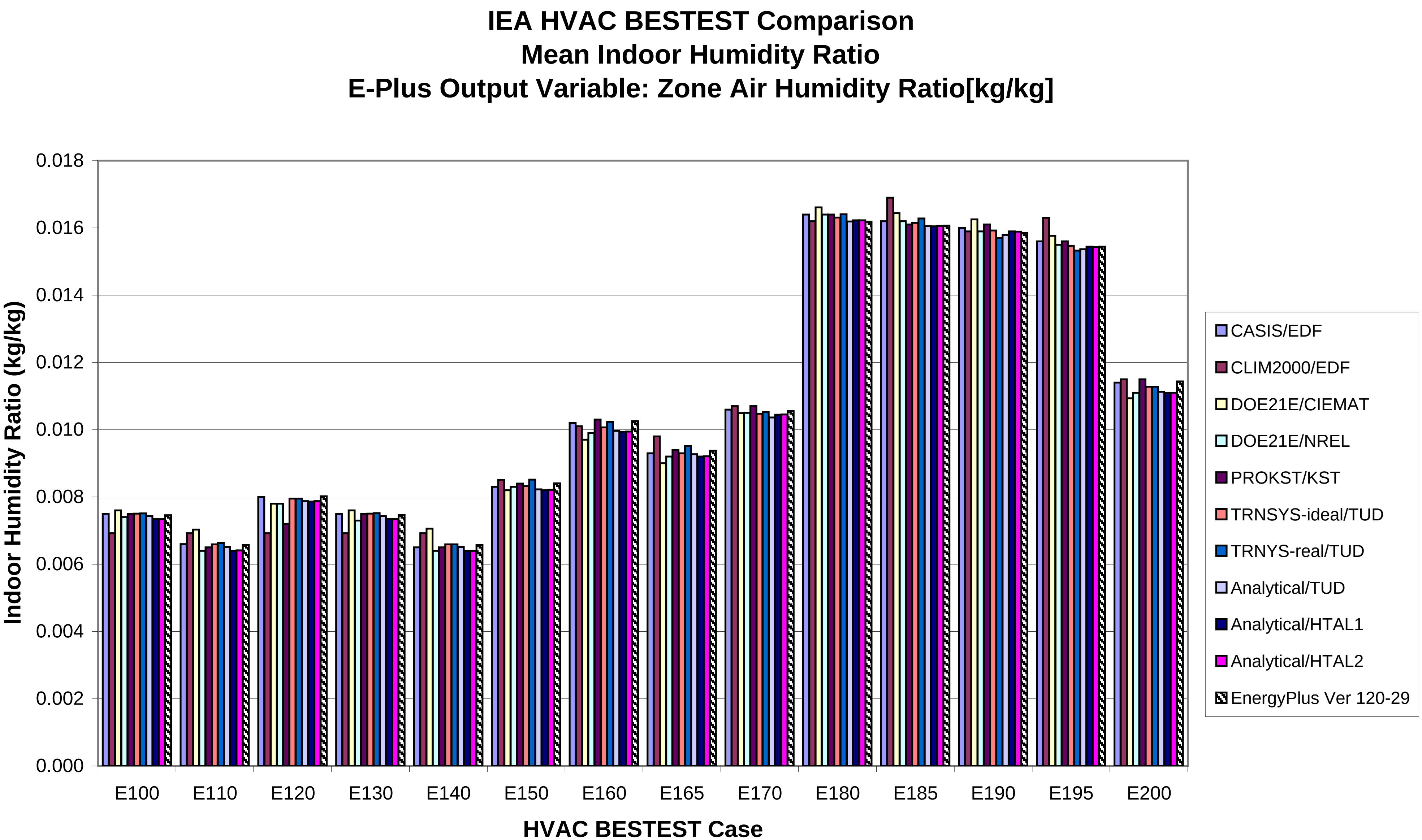


IEA HVAC BESTEST Comparison
Zone Total Cooling Load
E-Plus zone total cooling load not available as output variable;
calculated as (Zone Sensible Load + Zone Latent Load)
Zone Load (kWh)
6,000
5,000
4,000
3,000
2,000
1,000
0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Comparison
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29


IEA HVAC BESTEST Comparison
Zone Sensible Cooling Load
E-Plus Output Variable: (Zone/Sys Sensible Cooling Energy[J])/3600/1000
Zone Load (kWh)
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29


IEA HVAC BESTEST Comparison
Zone Latent Cooling Load
E-Plus Output Variable: (Zone-Total Internal Latent Gain[J])/3600/1000
Zone Load (kWh)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29


IEA HVAC BESTEST Comparison
Mean Indoor Drybulb Temperature
E-Plus Output Variable: Mean Air Temperature[C]
Indoor Drybulb Temperature (C)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29


IEA HVAC BESTEST Comparison
Mean Indoor Humidity Ratio
E-Plus Output Variable: Zone Air Humidity Ratio[kg/kg]
Indoor Humidity Ratio (kg/kg)
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
E100
E110
E120
E130
E140
E150
E160
E165
E170
E180
E185
E190
E195
E200
HVAC BESTEST Case
CASIS/EDF
CLIM2000/EDF
DOE21E/CIEMAT
DOE21E/NREL
PROKST/KST
TRNSYS-ideal/TUD
TRNYS-real/TUD
Analytical/TUD
Analytical/HTAL1
Analytical/HTAL2
EnergyPlus Ver 120-29

Appendix B

EnergyPlus Discussion excerpted from HVAC BESTEST Final Report, (Neymark & Judkoff 2002)

(Note: The excerpted discussion that follows is based on HVAC BESTEST results produced with EnergyPlus 1.0.0.023.)

3.4.7 EnergyPlus (GARD Analytics)

EnergyPlus is the program recently released by DOE, and is the building energy simulation program that will be supported by DOE. GARD Analytics (GARD) used EnergyPlus's "Window Air-Conditioner" system for its model.

GARD submitted eight iterations of simulation results. Table 3-4 describes input file and software modifications for each iteration; a single results set was submitted corresponding to changes described in each row of the table. Version Beta 5-07 was used for the initial results set.

Table 3-4. Summary of EnergyPlus Changes that were Implemented

Version	Input File Changes	Code Changes
Beta 5-07		
Beta 5-12 thru Beta 5-14		DX coil calculations modified to account for cycling Modified method of calculating SHR and coil bypass factor
Beta 5-15 thru Beta 5-18	Changed DX coil object names	Changed name of DX coil object from to better represent its algorithmic basis (no impact on results)
Ver 1-01 thru Ver 1-11	Changed from blow-thru to draw-thru fan configuration	Changed to double precision Modified method of calculating coil outlet conditions Added draw-thru fan option to WindowAC model
Ver 1-12 thru Ver 1-14	New equipment performance curves Adjusted fan mass flow and efficiency to achieve desired mass flow and fan power	
Ver 1-15 thru Ver 1-17	Went back to specified values for fan mass flow and efficiency	Partial implementation of moist c_p Fan power calculated using a standard initial density for volume to mass flow conversion
Ver 1-18 thru Ver 1-19	Changed basis of CDF curve from net to gross Opened up min/max limits for performance curves	Complete implementation of moist c_p h_{fg} calculation modified for latent loads
Ver 1-20 thru Ver 1-23	Went back to original CDF curve (modified curve used with Ver 1-19 was incorrect) Changed from FAN:SIMPLE:CONSTVOLUME to FAN:SIMPLE:ONOFF Used CDF curve for fan power to account for cycling	Implemented optional PLR curve for fan cycling Changed moisture initializations to use outdoor humidity ratio

The COP results for selected cases are summarized in Figure 3-9 for the EnergyPlus simulations and the TUD/HTAL analytical solution results. Note that the differences in results have been magnified in this figure by increasing the minimum value on the y-axis. Figure 3-10 includes specific results used to diagnose the causes of various disagreements. For the initial run with Beta 5-07, a number of disagreements with the analytical solution results were identified:

- Low indoor fan electrical power and fan heat; see Figure 3-10 results labeled "E170 Q ID Fan x 50"
- Reported cooling coil loads apparently not adjusted for part load cycling (although actual load removed from the zone appears to have been adjusted); see Figure 3-10 results labeled "E140 Q Coil Total"
- Sensible coil load about 1% higher than total coil load in the dry-coil cases.

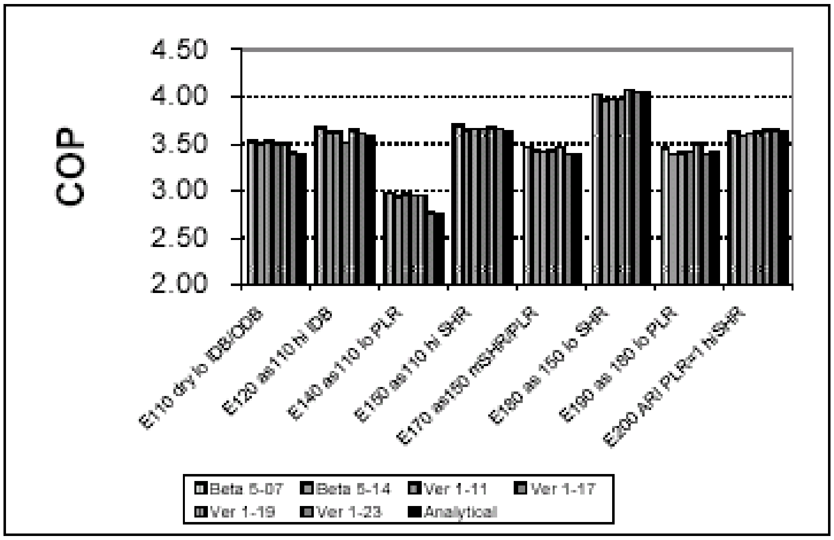


Figure 3-9. COP improvements to EnergyPlus models

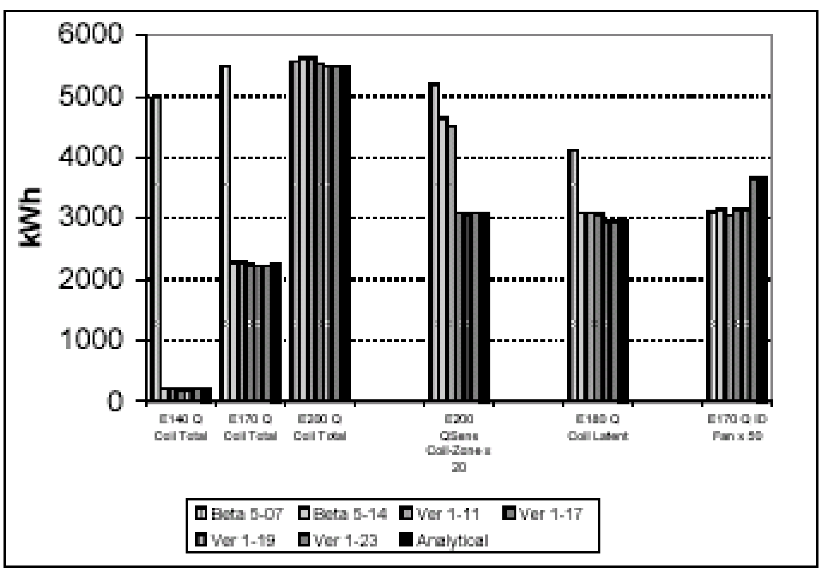


Figure 3-10. EnergyPlus fixes: various results

The process of correcting these disagreements engendered the improvements to EnergyPlus described below.

3.4.7.1 Reported Cooling Coil Loads Not Adjusted for Part Load Operation (up to 2500% effect on total coil load, negligible effect on energy consumption)

In Figure 3-10 it is apparent from the Beta 5-07 results for total coil load (designated by the results labeled “Q Coil Total” for cases E140, E170, and E200) that the total cooling coil load is in error, with the greatest error found in cases with lower PLR. For Beta 5-14 the reporting of cooling coil loads was corrected to account for run time during cycling operation. Because for Beta 5-07 the actual load extracted from the space was already being adjusted for cycling (similar magnitude disagreements do not exist for COP of cases E140 and E170 in Figure 3-9), it appears that this problem had a negligible effect on COP and energy consumption.

3.4.7.2 Modified Calculation of SHR and BF (1%–2% total consumption effect)

The problem of sensible coil loads being greater than total coil loads was addressed by modifying the methods of calculating SHR and BF. With the reasonable assumption that the coil load reporting error had negligible effect on energy consumption, the difference in COP between Beta 5-14 and Beta 5-07 (shown in Figure 3-9) illustrates the 1%–2% energy consumption effect of this modification, with a similar degree of change for all cases.

Along with the remaining differences in COP that are apparent from Figure 3-9 for Beta 5-14, GARD noted a number of other disagreements that were previously masked:

- Total coil loads were generally greater than for the analytical solutions (see “E200 Q Coil Total” results in Figure 3-10), and were 1%–2% greater than the sums of total zone load plus fan energy consumption
- The mean IDB for E200 moved from 26.7°C (good) to 27.1°C (high)
- Previous Beta 5-07 disagreements in terms of low ID fan power remain (see “E170 Q ID Fan × 50” results in Figure 3-10).

These disagreements with the analytical solutions prompted further improvements, described below.

3.4.7.3 Draw-through Fan, Double-Precision Variables, and Modified Calculation of Coil Outlet Conditions (0.1%–0.7% total consumption effect)

Changes leading up to Version 1-11 included:

- Modified method for calculating coil outlet conditions
- Use of double precision throughout EnergyPlus (this change was prompted by other issues not related to HVAC BESTEST)
- Addition of draw-through fan option to the window air-conditioner system.

Unfortunately, the effects of each of these changes were not disaggregated in the testing. The combined effects of these changes are illustrated in Figure 3-10, where the results for Beta 5-14 are compared to those from Ver 1-11 for the set of results labeled “E200 Qsens Coil-Zone × 20” (the difference between sensible coil loads and sensible zone loads, magnified by a factor of 20). This set of results indicates a 5% change in the loads-based calculated fan heat. The overall effect of these changes on COP (and consumption) is <1% as illustrated in Figure 3-9 comparing the difference between results of Ver 1-11 and Beta 5-14.

Along with remaining differences in COP apparent for Ver 1-11 in Figure 3-9, GARD noted other remaining disagreements:

- Total coil load remained 1%–2% greater than total zone load plus fan heat; similarly, the latent coil loads were 3% greater than for the analytical solution results—see "E180 Q Coil Latent" results in Figure 3-10
- The mean IDB for E200 moved from 27.1°C (high) to 27.5°C (higher)
- Previous Beta 5-07 disagreements of low ID fan power became worse compared with analytical solution results (see "E170 Q ID Fan × 50" results in Figure 3-10).

3.4.7.4 Change to Standard Air Density for Fan Power Calculation (1% decrease in sensible coil load)

For versions 1-12 through 1-17, results for changes to the software were aggregated with input file changes (notably the revision of system performance curves) so that assessing the effect of software revisions—including the implementation of moist air specific heat and the use of standard air properties for calculating supply air mass flow rates—was difficult. However, in Figure 3-10 (for the set of results labeled "E200 Qsens Coil-Zone × 20" for Ver 1-17 versus Ver 1-11), the bulk of the remaining fan heat discrepancy appears to have been addressed in version 1-17 when the fan power calculation was changed to incorporate standard air density. This change appears to have resulted in a 1% change in sensible and total coil load (see results for "E200 Q Coil Total" in Figure 3-10). The effect on ID fan energy appears to be about 3% (see results for "E170 ID Fan Q × 50" for Ver 1-17 versus Ver 1-11 in Figure 3-10), which translates to a 0.3% total power effect. The total electricity consumption effect would be greater in cases where the fan is running continuously (e.g. because of outside air requirements) even though the compressor is operating at lower part loads.

3.4.7.5 Modified Heat of Vaporization for Converting Zone Latent Load into HVAC

System Latent Load (0.4%–2.5% total consumption effect for wet coil cases only) For versions 1-18 and 1-19, the effects of input file changes were likely negligible (CDF curve revision), or the changes may have only affected specific cases. Enabling extrapolation of performance curves appears to have had the greatest effect in E120—see Figure 3-9 results for E120, Ver 1-19 versus Ver 1-17. Therefore, changes in results for the wet coil cases are likely caused primarily by changes to the software. Versions 1-18 through 1-19 include the following changes to the software:

- Changed heat of vaporization (hfg) used for converting a zone latent load into a coil load
- Changed airside HVAC-model specific heat (cp) from dry air to moist air basis.

From Figure 3-10, the case E180 latent coil load results (designated by “E180 Q Coil Latent”) for Ver 1-19 versus Ver 1-17 indicate that the fixes to the software improved the latent coil load results, with a 4% effect on latent coil load for E180 and the other wet coil cases (not shown here). In Figure 3-9, the difference between Ver 1-19 and Ver 1-17 illustrates the effect on COP, with the greatest effect (2.2%–2.5%) seen for cases with the lowest SHR (e.g., cases E180 and E190). GARD also noted that changing the airside HVAC model specific heat (cp) from a dry air to a moist air basis improved consistency between coil and zone loads and removed other small discrepancies.

3.4.7.6 ID Fan Power Did Not Include COP f(PLR) Degradation (2% total consumption effect at mid PLR)

In Figure 3-10, using the set of results labeled “E170 Q ID Fan × 50” (fan energy use magnified by a factor of 50), it is apparent that indoor fan consumption was about 15% lower than the analytical solution results for case E170. This difference was traced to CDF not being accounted for in the ID fan consumption. Application of COP=f(PLR) was implemented by Ver 1-23, and better agreement with the analytical solution indoor fan energy consumption was the result. The difference in results for Ver 1-23 and Ver 1-19 in Figure 3-9 indicates a 2% effect on total energy consumption for the mid-PLR case E170, with a higher percentage of effect as PLR decreases (e.g., see Figure 3-9 results for case E140 or E190).

3.4.7.7 General Comment About Improvements to EnergyPlus

Each individual error found in EnergyPlus by itself did not have >3% effect on consumption results. However, these multiple errors do not necessarily compensate each other, and may be cumulative in some cases. Furthermore, some errors that have small effect on total consumption for these cases (e.g. fan model errors when the indoor fan is cycling with the compressor) could have larger effects on total consumption for other cases (e.g., if the indoor fan is operating continuously while the compressor cycles). Therefore, correcting these errors was important.

Appendix C

EnergyPlus Program Characteristics Summary "Proforma" as prepared for HVAC BESTEST Final Report (Neymark & Judkoff 2002)

Program name (please include version number)

EnergyPlus Version 1.2.0.029

Your name, organisation, and country

Michael J. Witte, GARD Analytics, Inc., United States

Program status

	Public domain
	Commercial:
	Research
x	Other (please specify): *Government-sponsored, end-user license is no charge, other license types have fees associated with them*

Solution method for unitary space cooling equipment

x	Overall Performance Maps
	Individual Component Models
	Constant Performance (no possible variation with entering or ambient conditions)
	Other (please specify)

Interaction between loads and systems calculations

x	Both are calculated during the same timestep
	First, loads are calculated for the entire simulation period, then equipment performance is calculated separately
	Other (please specify)

Time step

	Fixed within code (please specify time step):
x	User-specified (please specify time step): *one hour for envelope*
x	Other (please specify): *program automatically adjusts HVAC time step, <= envelope time step*

Timing convention for meteorological data : sampling interval

	Fixed within code (please specify interval):
x	User-specified: *one hour*

Timing convention for meteorological data : period covered by first record

x	Fixed within code (please specify period or time which meteorological record covers): *0:00 - 1:00*
	User-specified

Meteorological data reconstitution scheme

	Climate assumed stepwise constant over sampling interval
x	Linear interpolation used over climate sampling interval
	Other (please specify)

Output timing conventions

	Produces spot predictions at the end of each time step
	Produces spot output at end of each hour
x	Produces average outputs for each hour (please specify period to which value relates): *user-specified, hourly data is average or sum for previous hour, can specify output at each time step*

Treatment of zone air

x	Single temperature (i.e. good mixing assumed)
	Stratified model
	Simplified distribution model
	Full CFD model
	Other (please specify)

Zone air initial conditions

x	Same as outside air
	Other (please specify)

Internal gains output characteristics

	Purely convective
	Radiative/Convective split fixed within code
x	Radiative/Convective split specified by user: *100% convective for these tests*
	Detailed modeling of source output

Mechanical systems output characteristics

x	Purely convective
	Radiative/Convective split fixed within code
a	Radiative/Convective split specified by user: *for types of equipment not used in these tests*
	Detailed modeling of source output

Control temperature

x	Air temperature
	Combination of air and radiant temperatures fixed within the code
	User-specified combination of air and radiant temperatures
	User-specified construction surface temperatures
	User-specified temperatures within construction
	Other (please specify)

Control properties

x	Ideal control as specified in the user's manual
	On/Off thermostat control
	On/Off thermostat control with hysteresis
	On/Off thermostat control with minimum equipment on and/or off durations
	Proportional control
	More comprehensive controls (please specify)

Performance Map: characteristics

	Default curves
x	Custom curve fitting
	Detailed mapping not available
	Other (please specify)

Performance Map: independent variables

	Entering Drybulb Temperature: *program calculates adjustments internally*
x	Entering Wetbulb Temperature
x	Outdoor Drybulb Temperature
x	Part Load Ratio
a	Indoor Fan Air Flow Rate: *always=1, because fan always operates at rated conditions*
	Other (please specify)

Performance Map: dependent variables

x	Coefficient of Performance (or other ratio of load to electricity consumption)
x	Total Capacity
	Sensible Capacity: *program calculates internally based on user-specified nominal SHR*
	Bypass Factor: *program calculates internally based on nominal SHR and current conditions*
x	Other (please specify): *indoor fan power (function of PLR)*

Performance Map: available curve fit techniques

x	Linear, f(one independent variable): *flow fraction curves set to constant=1*
x	Quadratic, f(one independent variable) : *PLF-FPLR (cycling loss)*
a	Cubic, f(one independent variable):
a	Bi-Linear, f(two independent variables)
x	Bi-Quadratic, f(two independent variables): *CAP-FT, EIR-FT*
	Other (please specify)

Performance Map: extrapolation limits

x	Limits independent variables: *27.4 <= ODB <=48.1; 13.0 <= EWB <= 23.7, 0.0 <= PLR <= 1.0*
	Limits dependent variables
	No extrapolation limits

	Extrapolation not allowed
	Other (please specify)

Cooling coil and supply air conditions model

	Supply air temperature = apparatus dew point (ADP); supply air humidity ratio = humidity ratio of saturated air at ADP
	Bypass factor model using listed ADP data
x	Bypass factor model with ADP calculated from extending condition line: *nominal BF is calculated from user-specified nominal SHR*
x	Fan heat included
	More comprehensive model (please specify)

Disaggregation of fans' electricity use directly in the simulation and output

x	Indoor fan only
	Outdoor fan only
	Both indoor and outdoor fans disaggregated in the output
	None - disaggregation of fan outputs with separate calculations by the user

Economizer settings available (for E400 series)

a	Temperature *(E400 series not run)*
a	Enthalpy *(E400 series not run)*
a	Compressor Lockout *(E400 series not run)*
	Other (please specify)