LBNL-6034E

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Comparison of Building Energy Modeling Programs: Building Loads

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June 2012

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, the U.S.-China Clean Energy Research Center for Building Energy Efficiency, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. It was co-sponsored by Energy Foundation under the China Sustainable Energy Program.

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A joint effort between Lawrence Berkeley National Laboratory, USA
and Tsinghua University, China

Under the U.S.-China Clean Energy Research Center for Building Energy Efficiency

Co-sponsored by Energy Foundation

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Executive Summary

This technical report presented the methodologies, processes, and results of comparing three Building Energy Modeling Programs (BEMPs) for load calculations: EnergyPlus, DeST and DOE-2.1E. This joint effort, between Lawrence Berkeley National Laboratory, USA and Tsinghua University, China, was part of research projects under the US-China Clean Energy Research Center on Building Energy Efficiency (CERC-BEE). Energy Foundation, an industrial partner of CERC-BEE, was the co-sponsor of this study work.

It is widely known that large discrepancies in simulation results can exist between different BEMPs. The result is a lack of confidence in building simulation amongst many users and stakeholders. In the fields of building energy code development and energy labeling programs where building simulation plays a key role, there are also confusing and misleading claims that some BEMPs are better than others. In order to address these problems, it is essential to identify and understand differences between widely-used BEMPs, and the impact of these differences on load simulation results, by detailed comparisons of these BEMPs from source code to results.

The primary goal of this work was to research methods and processes that would allow a thorough scientific comparison of the BEMPs. The secondary goal was to provide a list of strengths and weaknesses for each BEMP, based on in-depth understandings of their modeling capabilities, mathematical algorithms, advantages and limitations. This is to guide the use of BEMPs in the design and retrofit of buildings, especially to support China's building energy standard development and energy labeling program. The research findings could also serve as a good reference to improve the modeling capabilities and applications of the three BEMPs. The methodologies, processes, and analyses employed in the comparison work could also be used to compare other programs.

The load calculation method of each program was analyzed and compared to identify the differences in solution algorithms, modeling assumptions and simplifications. Identifying inputs of each program and their default values or algorithms for load simulation was a critical step. These tend to be overlooked by users, but can lead to large discrepancies in simulation results. As weather data was an important input, weather file formats and weather variables used by each program were summarized. Some common mistakes in the weather data conversion process were discussed.

ASHRAE Standard 140-2007 tests were carried out to test the fundamental modeling capabilities of the load calculations of the three BEMPs, where inputs for each test case were strictly defined and specified. The tests indicated that the cooling and heating load results of the three BEMPs fell mostly within the range of spread of results from other programs. Based on ASHRAE 140-2007 test results, the finer differences between DeST and EnergyPlus were further analyzed by designing and conducting additional tests. Potential key influencing factors (such as internal gains, air infiltration, convection coefficients of windows and opaque surfaces) were added one at a time to a simple base case with an analytical solution, to compare their relative impacts on load calculation results.

Finally, special tests were designed and conducted aiming to ascertain the potential limitations of each program to perform accurate load calculations. The heat balance module was tested for both single and double zone cases. Furthermore, cooling and heating load calculations were compared between the three programs by varying the heat transfer between adjacent zones, the occupancy of the building, and the air-conditioning schedule.

Based on the results of the test cases, the main research findings are summarized as follows:

1. EnergyPlus, DOE-2.1E, and DeST all had the fundamental capabilities and appropriate modeling assumptions for load simulations. The results of the simple test cases, such as ASHRAE Standard 140-2007 tests, demonstrated small differences in results between the three programs. The differences were mainly due to different default values or algorithms used by each program. The load results from DeST and EnergyPlus could be very close, within less than 7.5% of annual heating or cooling loads, if the surface convection coefficients in EnergyPlus models were specified the same as the DeST defaults. It was found that the main influencing factors on load discrepancies between DeST and EnergyPlus were not the load solution algorithms, but rather the surface convection coefficient assumptions, the solar position calculation, and the sky diffuse solar models.

2. DeST and EnergyPlus both employed a zone heat balance method that included surface heat balance and air heat balance. But DOE-2 did not perform a zone heat balance due to the simplification of the heat flux calculations between adjacent zones. This was illustrated in the special tests. For modeling assumptions and simplifications, EnergyPlus allowed users to choose from various algorithms, while DOE-2 and DeST used mostly constant values and algorithms that were given as defaults by the program or user-specified. DOE-2 had the most comprehensive set of default inputs.

3. DOE-2 had limitations in accurately calculating the heat balance between multiple zones, especially for nighttime air-conditioning cases. This is because DOE-2 estimates the long-wave radiation between interior surfaces by using combined radiative and convective coefficients, then using the adjacent zone temperature from the previous time step to determine the heat transfer from the surfaces of the adjacent zones. Therefore, DOE-2 was not appropriate for use in radiant cooling or heating applications due to the lack of surface heat balance calculations. DOE-2 should be used cautiously when modeling multiple zones with very different operating conditions in adjacent spaces.

This report summarized comparisons of load calculations for three BEMPs. The comparison of HVAC system modeling and whole building performance is as important, and will be covered by a separate report.

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1 Introduction

1.1 Background

Building simulation has developed rapidly since the 1960s. It is a very important tool to analyze and predict the thermal performance and energy consumption of buildings. Currently, there are more than one-hundred Building Energy Modeling Programs (BEMPs) available, including DOE-2 (DOE-2 1980) and EnergyPlus (Crawley et al. 2001) developed by the U.S. Department of Energy, ESP-r (ESRU 1999) by the University of Strathclyde, United Kingdom, and DeST (Yan et al. 2008; Zhang et al. 2008) by Tsinghua University, China. BEMPs play a significant role in designing the envelop and HVAC system of new buildings, energy-saving retrofitting of existing buildings, developing codes and standards for building energy efficiency design, and building energy rating/labeling programs.

However, large discrepancies in simulation results exist between different BEMPs, even when the same building is modeled by the same person. As most users simply attribute these discrepancies to the simulation programs, they lack confidence in the results. This can lead to a lack of confidence in building simulation which hinders the development and application of BEMPs. It is very difficult to achieve completely equivalent inputs for different BEMPs, because different BEMPs generally use different solution algorithms and modeling assumptions. A large number of default parameters are given automatically by programs, which are then rarely changed by the user. Therefore, both the programs calculation routines and their input parameters contribute to the discrepancies in simulation results from different BEMPs. The influence of both on simulation results needs to be quantified and analyzed.

To achieve low energy goals in the building industry, BEMPs are essential to support the development of building energy codes, building energy rating and labeling programs, and the integrated design of buildings. The problem of large discrepancies in simulation results causes confusion and disputation. Some BEMPs are also claimed wrongly to be better than others. Thus, the functions and limitations of the commonly-used BEMPs need to be compared, analyzed, and documented.

The comparison of commonly-used BEMPs, by focusing on identifying key drivers to the large discrepancies in simulation results, is fundamental and significant for the development of simulation tools and their application. It is of equal importance to compare and tabulate the functions of BEMPs, such as their modeling capabilities, strengths, weaknesses and limitations, in order to guide application in scientific research and engineering practice.

1.2 Objectives

EnergyPlus, DeST and DOE-2 were compared in this study because they are widely used in the U.S.

and China. As previously mentioned, both the calculation routines and the default input parameters have differences, which can result in large discrepancies in simulation results from different programs. User-defined input parameters for different programs were usually not equivalent for the same building. This contributed to the large discrepancies in simulation results. In this study, we focused on how the different simulation engines and energy model inputs affected the simulation results from the three BEMPs.

The thermal loads, HVAC systems, and energy consumption of buildings can be simulated by EnergyPlus, DeST and DOE-2. For this study, we focused on the thermal load calculations as they are the foundation of building energy simulations. The comparison of HVAC systems and energy consumption will be covered by another report.

The objectives of the comparison work included:

- Gaining a better understanding of each BEMP, including its modeling capabilities, strengths, weakness and limitations;
- Identifying major differences between EnergyPlus, DeST and DOE-2, including the algorithms and modeling assumptions used for load calculations;
- Analyzing the impacts of key influencing factors on the discrepancies in the simulation results;
- Providing a list of strengths and weaknesses of each program to guide its use in design and operation of buildings; especially to support China's building energy standards development and energy labeling programs.

1.3 Methodology

Previous efforts to validate and compare the three BEMPs are summarized in Table 1.1, where three common test methods were used: analytical tests, comparative tests, and empirical tests (Judkoff et al. 2006):

- Analytical tests

In analytical tests, simple test cases that can be solved analytically and that can also be simulated in BEMPs are used to test the fundamental heat transfer mechanisms that have the greatest impact on building thermal performance. This is the basic approach for program validation.

- Comparative tests

In comparative tests, a direct comparison of the results obtained from other programs using equivalent inputs is used to test the accuracy of modeling simplifications and assumptions. The comparative approach has the least input uncertainty and can deal with any level of complexity in building energy simulation, but there is no absolute judgment of good or bad results even if results from tested programs are within small ranges.

- Empirical tests

In empirical tests, a real building or test cell is monitored and the calculated results from BEMPs and measured results are compared to test the ability of BEMPs to simulate the real world. As empirical tests need a real building and lots of instruments for measuring, this approach is expensive and time consuming. Some degree of input uncertainty exists due to measurement uncertainty.

Table 1.1 Previous Validation Works for DOE-2, EnergyPlus and DeST

Tests	**DOE-2**	**DeST**	**EnergyPlus**
Analytical Tests	Release and executable tests	Release and executable tests (DeST 2006)	Building fabric tests, based on ASHRAE Research Project 1052 (Henninger et al. 2011a); HVAC tests, based on ASHRAE Research Project 865
Comparative Tests	IEA Annex 21 BESTEST (Judkoff et al. 1995); ASHRAE Standard 140-2004 (Henninger et al. 2006)	IEA Annex 21 BESTEST, (Judkoff et al. 1995); ASHRAE Standard 140-2001 (limited test cases, DeST 2006)	ASHRAE Standard 140-2007 (Henninger et al. 2011a); IEA Annex 21 BESTEST EnergyPlus HVAC Component Comparative tests (Henninger et al. 2011c); EnergyPlus Global Heat Balance tests (Henninger et al. 2011d)
Empirical Tests	Comparison of DOE-2 with Measurements in the Pala Test Houses (Winkelmann et al. 1995) DOE-2 Verification Project (Vincent et al. 1996; Lomas et al. 1994)	Case studies of residential and commercial buildings (DeST 2006)	Case studies of residential and commercial buildings

There still lacks comparisons of EnergyPlus, DeST and DOE-2 based on the same building models though lots of validation studies have been carried out. The differences between the three BEMPs and their effect on simulation results are not analyzed in detail (Huang et al. 2006; Andolsun et al. 2010; Waddell et al. 2010). Thus, in-depth and systematic comparisons of the three BEMPs have to be conducted to achieve the research objectives. Three steps are designed for the comparative tests:

Step 1: Focus on the differences of the load calculations including the solution algorithms, modeling assumptions and simplifications for the three BEMPs. This is the key to identifying the inter-program discrepancies.

Step 2: Compare simulation results of the three BEMPs with other programs based on ASHRAE Standard 140-2007 tests. Further identify differences in the load calculations between DeST and

EnergyPlus and evaluate their effects on results quantitatively by an in-depth comparison.

Step 3: Take into account cases when adjacent zones have very different conditions or when a zone is conditioned part-time (representing the usage style of AC systems in China's buildings), and find out the strengths and weaknesses of the three BEMPs for their applications.

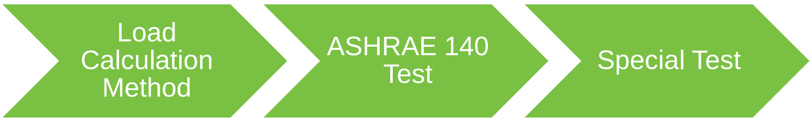

Figure 1.1 Three Steps to compare EnergyPlus, DeST and DOE-2

2 Overview of the three programs

2.1 DOE-2

DOE-2 was developed by LBNL and J.J. Hirsch & Associates in the late 1970s, and is still the most widely used BEMP in the U.S. There are two versions, DOE-2.1E and DOE-2.2. Although DOE-2 is just a simulation engine, various graphical user interfaces are available, such as eQuest (eQuest 2009), VisualDOE (VisualDOE 2004), and EnergyPro (EnergyPro 2011). DOE-2.1E version 124, developed by LBNL, was used for this study.

The DOE-2 simulation engine has four parts (DOE-2 1980) as shown in Figure 2.1: one program for translation of inputs called 'BDL Processor', and three simulation subprograms that are executed in sequence, with outputs from the previous subprogram serving as inputs to the next subprogram.

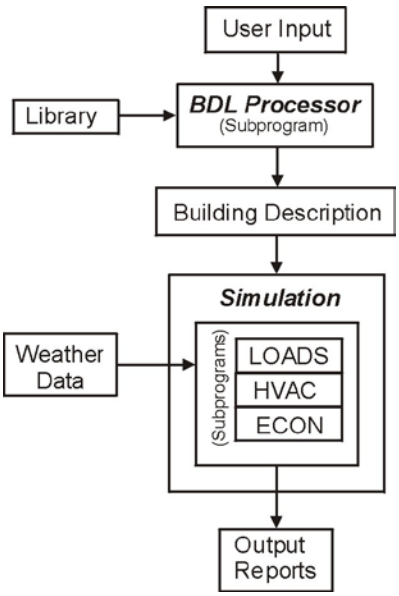

Figure 2.1 the Program Structure of DOE-2 (DOE-2 1980)

- **BDL**

BDL is the Building Description Language processor, which reads the flexibly formatted data supplied by the user and translates them into computer recognizable form. It also calculates response factors for the transient heat flow in walls, and weighting factors for the thermal response of building spaces.

- **LOADS**

LOADS is the loads simulation subprogram, which calculates the sensible and latent components of the hourly heating or cooling load for each user-designated space in the building, assuming that each space is kept at a constant temperature selected by the user. LOADS is responsive to weather and solar conditions, occupancy schedules, lighting and equipment, infiltration, the time delay of heat transfer through walls and roofs, and to the effect of building shades on solar radiation.

- **HVAC**

HVAC can be divided into two parts, SYSTEMS and PLANT. LOADS produces a first approximation of the energy demands of a building. SYSTEMS corrects this approximation by taking into account outside air requirements, hours of equipment operation, HVAC equipment control strategies, and the transient response of the building when neither heating nor cooling is required to maintain the temperature and humidity set-points. The output of SYSTEMS is a list of heating and cooling loads at the zone and system levels. PLANT simulates the behavior of boilers, turbines, chillers, cooling towers, storage tanks, etc., in satisfying the secondary systems heating and cooling coil loads. PLANT takes into account the part-load characteristics of the primary equipment in order to calculate the fuel and electrical demands of the building.

- **ECONOMICS**

ECONOMICS calculates the energy cost of buildings. It can be used to compare the costs of different building designs or to calculate retrofit savings for existing buildings.

DOE-2.1E can model 28 pre-defined HVAC system types, which allow some flexibility of activating optional components, but it does not provide an easy way for users to model new HVAC system types. Advanced users familiar with the user function feature of DOE-2.1E can write computer code to modify or add algorithms that can be used during the simulations.

2.2 DeST

DeST (Designer’s Simulation Toolkits) was developed by Tsinghua University for the purposes of teaching, research and practical use of HVAC related applications in China. The development of DeST began in 1989. Initially it was just a simulation engine for handling building thermal calculations called BTP (Building Thermal Performance, Hong T et al. 1997a). HVAC simulation modules were added and BTP became a prototype suite of integrated building simulation tools called IISABRE (Hong T et al. 1997b). Considering the various stages in practical HVAC design, based on IISABRE, an extensive version called DeST was developed from 1997. Since then, a structure map of the development of DeST has been established.

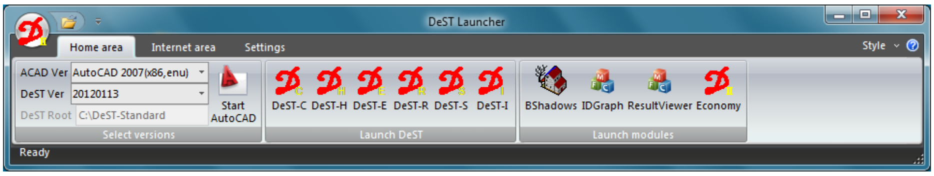

Figure 2.2 DeST Launcher

Practical building design process includes various stages with different design objectives and focuses for each stage. With the design progress from initial to detail, information will be increased to assist the design but at the same time its design flexibility will be reduced. For the different stages in the design process, design parameters of the simulated buildings are limited and uncertain. For example, in the preliminary design stage, the thermal properties of the building are undetermined; in the scheme design stage, these thermal properties are determined but parameters of HVAC systems are not determined. Thus, DeST is developed to assist data analysis and design of building environment and its control systems for different design stages, that is, “simulation by stage” (Yan D et al. 2008). To implement the objective of “simulation by stage”, DeST uses base temperatures (space temperature under no cooling or heating) to couple buildings with systems, and uses ideal controls for systems. Unlike DOE-2 and EnergyPlus, DeST is not a stand-alone simulation engine; instead it is coupled with a graphical user interface based on Autodesk’s AutoCAD platform.

DeST comprises of a number of modules for handling different functions, shown in Figure 2.3. BAS (Building Analysis & Simulation) is the core module for the building thermal performance calculations. It can perform hourly calculations for indoor air temperatures and cooling/heating loads for buildings. BAS uses a ‘state-space’ method to solve building thermal heat balance equations. Its stability and errors are independent of the simulation time step (Jiang Y et. al 1982). One advantage of DeST is that it can calculate the heat balance of multiple rooms. DeST takes into account the thermal processes of a space affected by adjacent spaces. DeST benchmarked well in the IEA Annex 21 BESTEST.

DeST is the prevalent program for building energy modeling in China, and also is used increasingly in other regions and countries such as Hong Kong, Japan, and Italy etc.

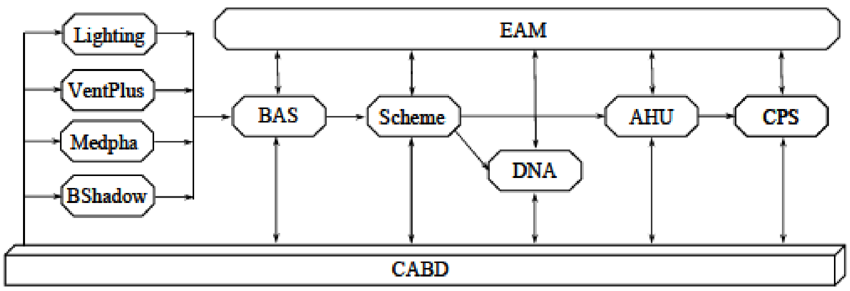

Figure 2.3 the Program Structure of DeST (Yan et al. 2008)

Note:
“CABD” stands for Computer Aided Building Description;
“BAS” stands for Building Analysis & Simulation;

"Scheme" stands for HVAC scheme design;
"DNA" means Duct Network Analysis;
"AHU" means Air Handling Unit;
"CPS" means Combined Plant Simulation (cooling/heating source and water system);
"EAM" means Economic Analysis Model.

2.3 EnergyPlus

EnergyPlus is a new building energy modeling program based on both BLAST and DOE-2. Similar to its parent programs, EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building including the building's physical make-up, associated mechanical systems, etc., EnergyPlus can calculate the heating and cooling loads necessary to maintain thermal control set-points, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment. EnergyPlus is intended to be a stand-alone simulation engine around which a third-party user interface can be wrapped.

As a new BEMP, EnergyPlus has some significant advantages. One of these is the integration of all parts of the building simulation — loads, systems, and plants, as shown in Figure 2.4. Based on a research version of the BLAST program called IBLAST, the system and plant output is allowed to directly impact the building thermal response, rather than calculating all loads first and then simulating systems and plants. The coupled simulation allows the designer to more accurately investigate the effect of under-sizing fans and equipment, and what impact that might have on the thermal comfort of occupants within the building. Figure 2.4 gives a basic overview of the integration of these important elements of a building energy simulation.

Different from the fixed time step used by most programs, EnergyPlus has sub-hourly, user-definable time steps for the interaction between the thermal zones and the environment, and variable time steps for interactions between the thermal zones and the HVAC systems. EnergyPlus is used in various simulation situations due to its elaborate solution and numerous modules. In the calculation of building thermal loads, it allows for the simultaneous calculation of radiant and convective effects for both interior and exterior surfaces during each time step. Unlike DOE-2 and DeST, EnergyPlus has various algorithms for users to choose, such as thermal comfort models, anisotropic sky models, and atmospheric pollution models, etc. For systems, EnergyPlus allows users to construct HVAC systems by adding and linking components, and modify the system operation and controls using the Energy Management System feature without the need to recompile the program source code.

Starting with version 7.0, EnergyPlus is open source allowing users to inspect source code as necessary during the debugging and quality control process.

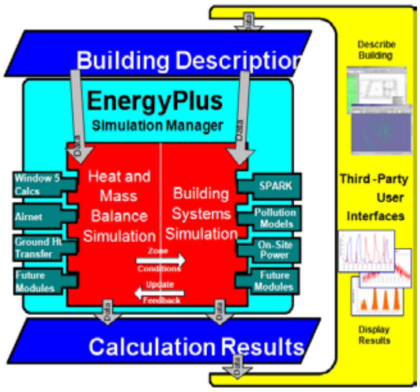

Figure 2.4 the Program Structure of EnergyPlus (EnergyPlus 2011a)

2.4 Summary of features

The main features of the three programs are summarized in Table 2.1.

Table 2.1 Main Features of DOE-2, DeST and EnergyPlus

Features	**DOE-2**	**DeST**	**EnergyPlus**
Inputs	Text, BDL	Database, MS Access	Text, IDF/IDD
Outputs	Summary & hourly reports	Summary & hourly reports	Extensive summary & detailed reports with user specified time steps
GUI	Simulation engine only; 3rd party GUIs available: eQuest, VisualDOE, EnergyPro, etc.	Coupled with AutoCAD;	Simulation engine only; 3rd party GUIs: Open Studio, DesignBuilder, etc.
Algorithms	Surface heat balance: Response Factor, CTF; Zone Weighting Factors	Zone heat balance: State Space Method	Surface heat balance; Zone air heat balance
Limitations	Lacks zone air heat balance, linear systems	Linear systems	Potentially long run time for detailed models
Time Step	1 hour, fixed	1 hour fixed	1 to 60 minutes
Weather Data	Hourly	Hourly	Hourly or sub-hourly
HVAC	28 pre-defined systems	A few pre-defined systems	User configurable with some limitations
User customization	User functions	N/A	EMS (Energy Management System), External Interface, FMI (Functional Mockup Interface)
Interoperability	gbXML	XML	gbXML, IFC (Industry Foundation Classes)
Language	Fortran	C++	Fortran
Copyright	Free download; Open source	Free download;	Free download; Open source

3 Comparison of load calculation methods

The differences between the load calculation methods for the three BEMPs include the solution algorithms, modeling assumptions, and simplifications. The solution algorithm is the unchangeable kernel for each BEMP. The modeling assumptions and simplifications are usually based on default values or algorithms that can be changed by the user.

3.1 Solution algorithms

DOE-2 (DOE-2 1980) uses the 'CTF' (Conduction Transfer Function) module for processing the conduction through the wall and the 'Weighting Factor' module for the calculation of thermal loads and room air temperatures. In a strict sense, DOE-2 has no ability to perform a zone heat balance because DOE-2 performs no air heat balance. It calculates the long-wave radiation exchange by using combined convective and radiative surface coefficients rather than explicitly calculating the convection from surface to zone air, and long-wave radiation between zone surfaces. DOE-2 uses the adjacent zone temperature from the previous time step for multiple zone solutions. There are two steps for performing the load calculation. First, the LOADS sub-program calculates the sensible and latent hourly heating or cooling load, assuming that each space is kept at a constant temperature selected by the user. The output of the LOADS sub-program is a first approximation of the energy demands of a building. Second, The SYSTEM sub-program modifies the output of the LOADS sub-program to produce actual thermal loads based on an hourly variable zone temperature with HVAC system related, which are very different from DeST and EnergyPlus load calculations. Due to the assumptions of Weighting Factor, the natural convection and radiation must be approximated linearly, and system properties that influence the weighting factors are constant, that is, they are not functions of time or temperature. The distribution of the solar radiation incident on the interior walls of a room may vary hourly, surface convection coefficients may vary with the direction of heat flow or air velocity, and wall properties may also vary hourly (such as phase change materials). Thus, DOE-2 is limited to linear systems for load calculations.

DeST can perform a zone heat balance solved by the state space method. The state space solution method is continuous in time, but discrete in space (Jiang Y et. al 1982). Each material layer of the building constructions (such as walls, roofs and floors) is divided into multi-section with a temperature node for each section. Based on the functions of the surface and the air heat balance, the zone temperature can be obtained as a function of time and other influencing factors. Thus, a smaller time step can be achieved by adding more temperature nodes for each material layer. By solving a set of energy balance equations for each temperature node, all of the response factors for all heat disturbances can be obtained. These response factors are the thermal properties of the room itself. This method also requires a linear system. DeST performs the heat balance of multiple rooms. It takes into account the thermal processes affecting adjacent rooms by simultaneously iterating for all zones. DeST simulates an ideal HVAC system in the calculation of zone temperatures and loads in the BAS module.

EnergyPlus (EnergyPlus 2011b) splits the zone heat balance calculations into surface and air components. When calculating the conduction through a wall, the Conduction Transfer Function (CTF) or Conduction Finite Difference (CondFD) Solution Algorithm can be selected by the user. A disadvantage of using CTF algorithms is that conduction transfer function series become progressively more unstable as the time steps get shorter. This phenomenon was most apparent for thermally massive constructions with long characteristic times, requiring a large number of terms in the CTF series. This indicates that the problem is related to rounding and truncation errors and is not an indictment of the CTF method itself. CTF has all the usual restrictions of a transformation-based solution i.e. constant properties, and fixed values of some parameters. CondFD has no restrictions and can handle phase change materials (PCM) or variable thermal conductivity. CondFD does not replace the CTF solution algorithm, but complements it for cases where the user needs to simulate PCMs (phase change materials) or variable thermal conductivity. It is also possible to use the finite difference algorithm for time steps as short as one minute. EnergyPlus usually integrates the LOAD and SYSTEM sub-programs when calculating zone temperatures and loads. The IdealLoadsAirSystem can control both temperature and humidity specified by the user. This works similarly to the Ideal HVAC system in DeST.

In both DOE-2 and DeST the time step for load calculations is 1 hour. EnergyPlus allows the user to select a time step length from 1 to 60 minutes (has to be a factor of 60). The default time step length in version 7.0 is 10 minutes. In DOE-2 and EnergyPlus, a day is from hour 1 to hour 24 and hour 1 presents the time interval 00:00:01AM to 1:00:00AM. In DeST, a day is from hour 0 to hour 23 and hour 0 presents the time interval 00:00:00AM to 00:59:59AM. So hour 0 in DeST can be regarded as the same time interval as hour 1 in DOE-2 and EnergyPlus.

In summary, both DeST and EnergyPlus perform a zone heat balance for the load calculations. DOE-2 does not perform a zone heat balance in a strict sense due to its simplifications for long-wave radiation exchange and multiple zone solutions. DeST and DOE-2 have the usual restrictions of a linear system, while EnergyPlus has more powerful functions as it can handle PCMs or variable thermal conductivity by using the CondFD method.

Table 3.1 Comparison of Solution Algorithms

	DOE-2	**DeST**	**EnergyPlus**
Heat balance method	Surface heat balance: CTF. Response Factor; Zone Weighting Factors	Zone heat balance: State Space Method	Surface heat balance: CTF, CondFD; Air heat balance
Temperature & load calculation	HVAC system related; Ideal HVAC system: SUM	Ideal HVAC system; Control both temperature and humidity as required	HVAC system related; Ideal HVAC system: IdealLoadsAirSystem
Solution method	Sequential iteration; **LOADS:** assume each space is always conditioned at a constant temperature **SYSTEMS:** produce actual thermal loads based on an hourly variable temperature setpoint and actual operating schedules	Simultaneous iteration for all zones; Trial for zone and ideal system integration	Sequential iteration; Predictor-Corrector for zone and system integration
Time step	Hourly	Hourly, can be sub-hourly	Sub-hourly, Default: 10 minutes

3.2 Modeling assumptions and simplifications

In the following, the main differences of modeling assumptions and simplifications between DOE-2, DeST and EnergyPlus are discussed. For detailed information of the algorithms, the engineering manuals can be used as a reference (DOE-2 1980; DeST 2006; EnergyPlus 2011b).

3.2.1 Surface convection coefficients

Many models are available for calculating the surface convection coefficients, with much disparity between them. EnergyPlus, DeST and DOE-2 use different models and their disparity impacts building load calculation results significantly.

DOE-2 does not calculate the long-wave radiation exchange between different surfaces based on surface temperature precisely. Instead it uses combined convective and radiative surface coefficients to estimate this part of the heat transfer flux. For exterior surfaces, the combined convective and radiative surface coefficient varies hourly by wind speed. For interior surfaces, it is a user-specified constant value (the default is 8.3 $W/(m^2 \cdot K)$). Thus, the surface convection coefficient is a part of a combined convective and radiative surface coefficient in DOE-2.

In DeST, surface convection coefficients are specified by the user as constant values for both exterior and interior surfaces. The default values are shown in Table 3.2.

EnergyPlus provides a broad range of options for algorithms that calculate exterior and interior surface coefficients. The values can vary by time-step. The exterior convection coefficient is predominantly determined by wind speed, wind direction, the roughness index, and the temperature difference between the surface and the air. The default algorithm in DOE-2 is 'TARP'. It is a comprehensive natural convection model used for interior surfaces. It correlates the convective heat transfer coefficient to the surface orientation and the difference between the surface and zone air temperatures.

Table 3.2 Comparison of Surface Convection Coefficients

	DOE-2	**DeST**	**EnergyPlus**
Exterior surface	Combined convective and radiative surface coefficients, varies hourly by wind speed	Specific constant value Default: 23.3 W/(m^2·K)	Vary by time step based on various algorithms Default algorithm: DOE-2
Interior surface	Specific constant value for combined convective and radiative surface coefficient Default: 8.3 W/(m^2·K)	Specific constant values Default: Vertical surface: 3.5 W/(m^2·K) Upward on horizontal surface: 4 W/(m^2·K) downward on horizontal surface: 1 W/(m^2·K)	Vary by time-step based on various algorithms Default algorithm: TARP

In summary, surface convection coefficients vary by time-step in EnergyPlus. They are set as constant values in DeST. In DOE-2, the exterior surface convection coefficients are variable and the interior ones are constant. In order to compare the difference of surface convection coefficients between DeST and EnergyPlus, using the default values or algorithms, hourly values from Case 195 in ASHRAE Standard 140-2007 are shown in Figure 3.1 and Figure 3.2.

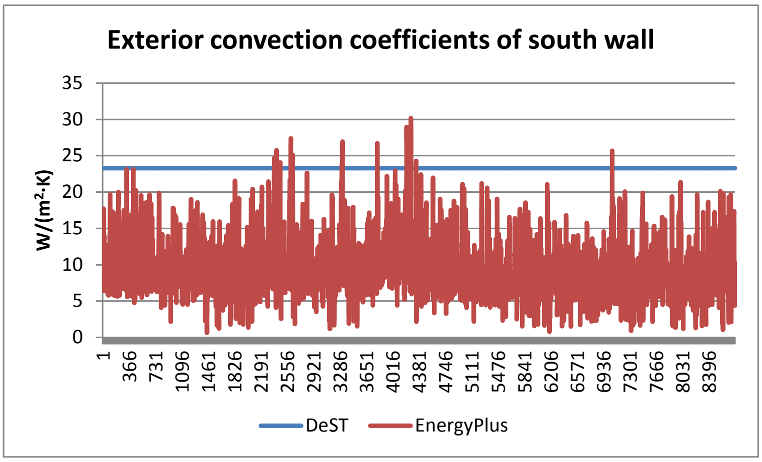

Figure 3.1 Comparison of Hourly Exterior Convection Coefficients

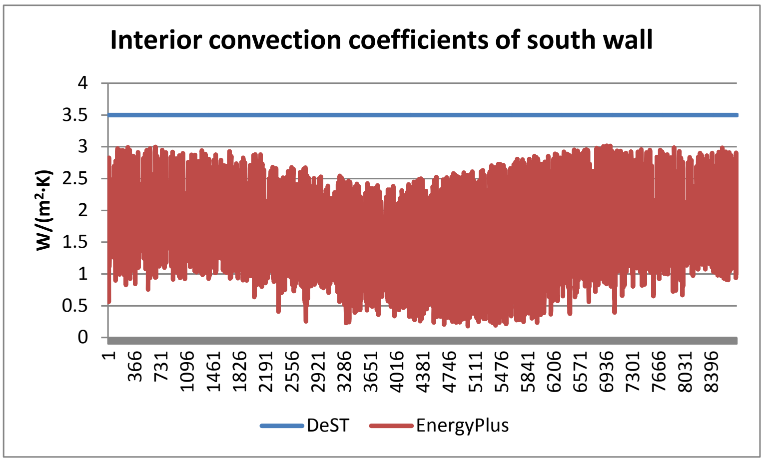

Figure 3.2 Comparison of Hourly Interior Convection Coefficients

3.2.2 Long-wave radiation exchange

Long-wave radiation exchange occurs between different interior surfaces (walls, roofs and floors) due to different surface temperatures. Exterior surfaces have long-wave radiation exchange with the sky, the ground and surrounding building exterior surfaces. The total long-wave radiative heat flux is the sum of three.

In DOE-2, the long-wave radiation exchange between different interior surfaces is not calculated using surface temperatures, rather it is estimated using combined convective and radiative surface coefficients. For exterior surfaces, the long-wave radiation exchange with the air is calculated using combined convective and radiative coefficients. The long-wave radiation exchange with the ground is calculated using the ground surface temperature and the building surface temperature, under the assumption that the ground surface is at the same temperature as the outside air. The long-wave radiation exchange with the sky is estimated by assuming that the clear sky radiation from a horizontal surface should be 20 Btu/hr-ft^2 (63.1 W/m^2). When the sky is covered by clouds, it is assumed that no sky radiation exchange occurs i.e. the clouds and building exterior surfaces are at approximately the same temperature. For partial cloud coverage, a linear interpolation is made.

In DeST, the long-wave radiation exchanged between different interior surfaces is part of the zone heat balance. It is related to the thermal emissivity and view factor (approximated as area weighted). Furthermore, the 4th power correlation for long-wave radiation is simplified into a linear one by assuming interior surface temperatures vary in a small range. For exterior surfaces, only the long-wave radiation exchange with the sky is considered at present. The 4th power correlation of the sky temperature and exterior surface temperature is also converted into a linear relationship between the temperature difference between building exterior surfaces and the sky. The sky radiation heat transfer coefficient can be user-specified.

In EnergyPlus, the internal long-wave radiation exchange is part of the interior surface heat balance. The radiation heat flux is calculated from the surface, sky and ground temperatures, the surface absorptivity, and the sky and ground view factors. For exterior surfaces, the long-wave radiation is also part of the exterior surface heat balance. EnergyPlus considers an enclosure consisting of the building exterior surface, the surrounding ground surface, and the sky. Thus, the long wave radiative heat flux at the building exterior surface is determined as the sum of components due to radiation exchange with the ground, the sky, and the air. The sky temperature is calculated using the horizontal infrared radiation intensity from the EnergyPlus weather file. The ground surface temperature is assumed to be the same as the outside air temperature.

Table 3.3 Comparison of Long-wave Radiation Exchange

	DOE-2	**DeST**	**EnergyPlus**
Exterior surface	**Air:** combined convective and radiative surface coefficients; **Ground:** varies by surface temperature and ground surface temperature; **Sky:** varies by cloud cover	**Sky:** varies by surface temperature and the sky temperature (linearized); Sky radiation heat transfer coefficient	**Sky, air and ground**: varies by surface, air, ground, and sky temperature; Thermal absorptance
Interior surface	Combined convective and radiative surface coefficients	$q_{i,j} = hr_{i,j}(T_i - T_j)$ Linearized	$q_{i,j} = A_i F_{i,j}\left(T_i^4 - T_j^4\right)$ 4^{th} power

3.2.3 Solar radiation on surfaces

Modeling assumptions and simplifications for calculating solar radiation on surfaces in DOE-2, DeST and EnergyPlus are described in their engineering manuals (DOE-2 1980; DeST 2006; EnergyPlus 2011b), showing that the discrepancies mainly come from solar radiation models and the time point selected for the solar position calculation.

Solar radiation on surfaces can be divided into three components: direct solar radiation, sky diffuse radiation, and ground reflected diffuse radiation. The most significant difference in direct solar radiation calculations is that the three BEMPs use different time points for the solar position calculations. Specifically, DOE-2 uses the middle point of the hour, DeST uses the beginning of the hour, and EnergyPlus uses multiple time points per hour (selected by the user). Solar radiation data values in the EnergyPlus weather files are hourly. So, sub-hourly values are obtained via linear interpolation. It is assumed that the hourly data from the weather file is the value of the midpoint. In DOE-2 and DeST, the hourly solar data values from the weather file are used directly as inputs for the direct solar radiation calculations. Models for the sky diffuse radiation calculations also differ greatly. EnergyPlus assumes the anisotropic radiance distribution of the sky, which is more complex than the isotropic radiance distribution used in DOE-2 and DeST. Ground reflected diffuse radiation is calculated as the product of the ground reflectivity and the global horizontal radiation, so the model of the three BEMPs has no difference but the results have discrepancies due to different global horizontal radiation calculated from the results of direct solar calculation and sky diffuse radiation.

Table 3.4 Comparison of Reported Solar Radiation on Surfaces

	DOE-2	DeST	EnergyPlus
Solar data variables	Global horizontal radiation; Direct normal radiation	Global horizontal radiation; Diffuse horizontal radiation;	Diffuse horizontal radiation; Direct normal radiation
Time point for solar position	The middle of the hour	The beginning of the hour	The end of every time step (10 minute in time step default)
Composition	Direct solar; Sky diffuse: isotropic model; Ground reflected diffuse	Direct solar; Sky diffuse: isotropic model; Ground reflected diffuse	Direct solar; Sky diffuse: anisotropic model; Ground reflected diffuse
Exterior surface	Solar absorptance	Solar absorptance	Solar absorptance Visible absorptance
Interior surface	Solar absorptance	Solar absorptance	Solar absorptance Visible absorptance

In order to estimate the differences in results caused by the different time points used in the solar position and sky diffuse radiation models, the solar radiation on east/west/south/north/horizontal surfaces were exported from Case 195 using modified solar data in the weather file. In Figures 3.3 and 3.4, the value of direct solar radiation in the weather file was always zero, i.e. there was only diffuse solar radiation. The results show that there was a big difference in sky diffuse radiation, especially during the hours of sunrise (see Figure 3.4). This is because EnergyPlus uses an anisotropic model while DeST uses an isotropic one. In Figures 3.5 and 3.6, the value of diffuse solar radiation in the weather file was always zero, i.e. there was only direct solar data. Due to different time points and time steps for the solar position calculations, the direct solar radiation on exterior surfaces was also different. From the annual solar radiation results shown in Figure 3.7, where the weather data was the same as the ASHRAE 140 weather file, we could see that the biggest discrepancy occurred first on the west wall, and then the north and south walls.

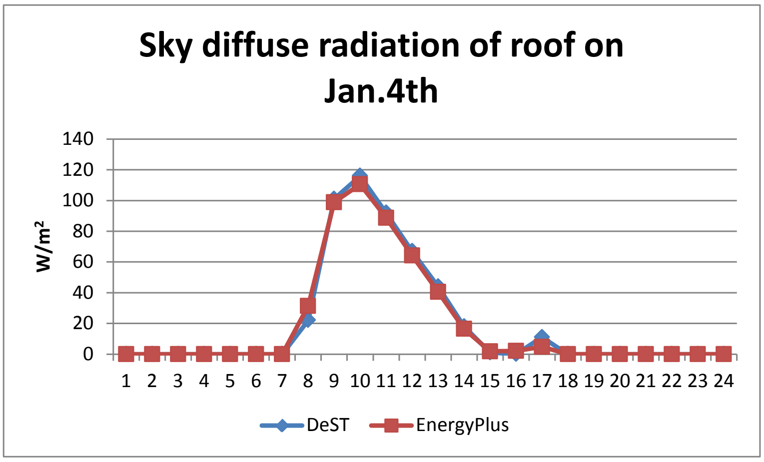

Figure 3.3 Comparison of the Sky Diffuse Radiation on Roof between EnergyPlus and DeST

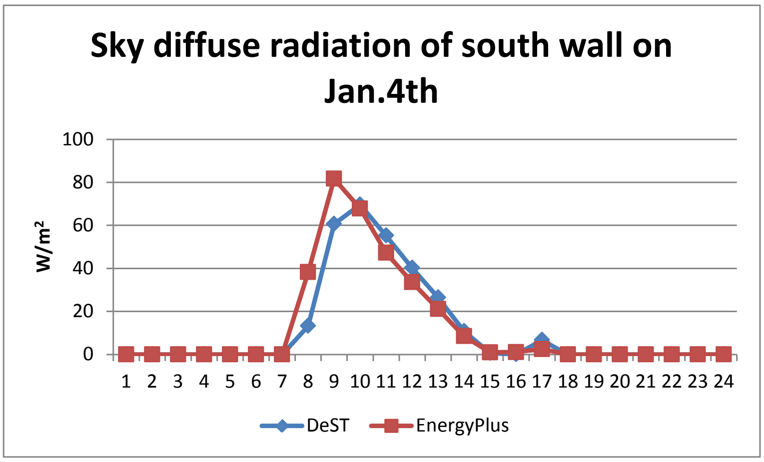

Figure 3.4 Comparison of the Sky Diffuse Radiation on South Wall between EnergyPlus and DeST

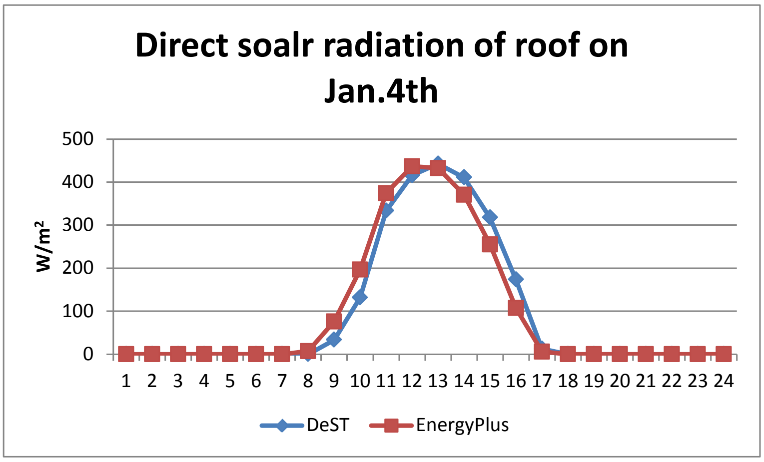

Figure 3.5 Comparison of the Direct Solar Radiation on Roof between EnergyPlus and DeST

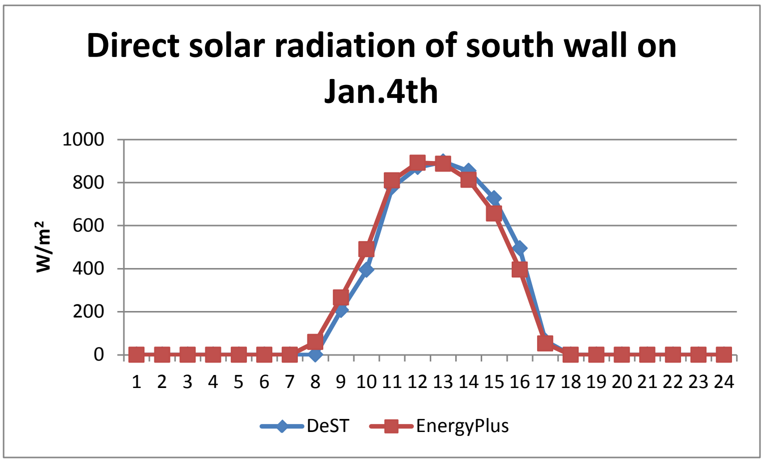

Figure 3.6 Comparison of the Direct Solar Radiation on South Wall between EnergyPlus and DeST

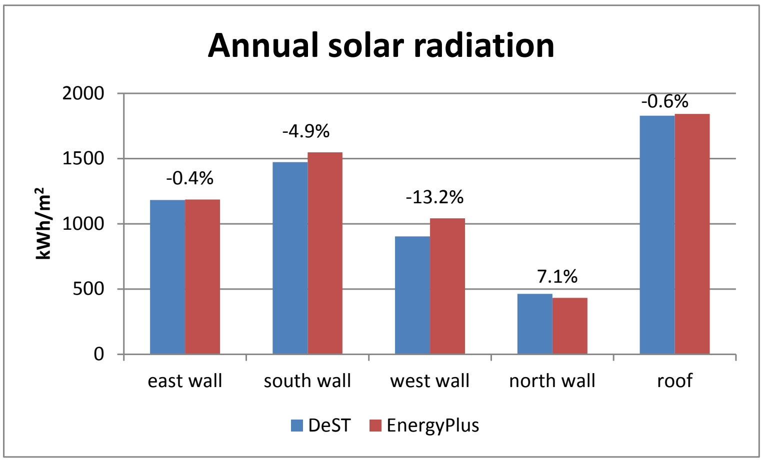

Figure 3.7 Annual Solar Radiation on Surfaces with Different Orientations

3.2.4 Solar distribution

The three BEMPs take a different approach to how solar radiation is transmitted through windows, distributed to interior surfaces, and then reflected back out through windows.

DOE-2 uses a user-defined fraction for all exterior (excluding windows) and interior surfaces to calculate the distribution of the incident direct solar radiation and diffuse radiation in the space. By default, DOE-2 assumes that 60% of direct and diffuse solar radiation is absorbed by the floor, and 40% is distributed to the remaining surfaces based on their areas.

DeST also uses a user-defined fraction for space air and interior surfaces (excluding windows) to calculate the distribution of the incident direct solar radiation and diffuse radiation in the space. The default values for the solar distribution fractions are shown in Table 3.5.

In EnergyPlus, the distribution of the incident direct solar radiation is calculated by various algorithms. The "ScriptF" algorithm is used to calculate the diffuse solar radiation distribution.

Table 3.5 Comparisons of Solar Distribution

DOE-2	**DeST**	**EnergyPlus**
User specified constant values Defaults: floor 60%, other interior surfaces split the 40% weighted by area	User specified constant values Default: Air=0.150, walls=0.255, floor=0.510, roof=0.085	Auto-calculated values. **Direct solar radiation:** various algorithms. Default: FullExterior **Diffuse solar radiation:** "ScriptF" algorithm

3.2.5 Internal gains

Internal gains affecting the building thermal load calculations for convective and radiative heat flux mainly include heat from people, lighting, and equipment.

All of the three BEMPs adopt a traditional model which defines a radiative/convective split for the heat introduced into a zone from lighting and equipment. The radiative part is then distributed over the surfaces within the zone in some prescribed manner. For the people, users can define the value of the sensible and latent heat ratio in both DOE-2 and DeST. EnergyPlus uses an activity level (the total heat output from people) as the input, and then the sensible heat fraction can be calculated automatically or specified as a constant value by the user.

Table 3.6 Comparison of Internal Heat Gains

	DOE-2	**DeST**	**EnergyPlus**
People	Sensible heat: Convective/Radiant fraction; Latent heat;	Sensible heat: Convective/Radiant fraction; Latent heat;	Activity level (total heat); Sensible heat fraction: constant value or auto-calculate; Convective/Radiant fraction
Lighting	Light type (default: SUS-FLUOR) or Convective/Radiant fraction	Convective/Radiant fraction	Convective/Radiant/Return air fraction
Equipment	Sensible heat; Latent heat;	Sensible heat: Convective/Radiant fraction; Latent heat;	Sensible heat: Convective/Radiant fraction; Latent heat;
Radiant distribution	No user input	Fraction, user input	Based on surface absorptance

3.2.6 Internal thermal mass

Furniture in a zone has the effect of increasing the amount of surface area that can participate in radiation and convection heat exchange. It also adds thermal mass to the zone. These two changes both affect the response to temperature changes in the zone and also affect the heat extraction characteristics. Modeling assumptions and simplifications for internal thermal mass in DOE-2, DeST and EnergyPlus are described in their engineering manuals (DOE-2 1980; DeST 2006; EnergyPlus 2011b).

In DOE-2, the internal thermal mass is described by the furniture model which is defined by furniture type, furniture fraction, and furniture weight. When the value of the floor weight in models is set to zero, custom weighting factors will be used. Otherwise, the weighting factors are calculated based on the actual value of the floor weight.

In DeST, a furniture coefficient is used to account for the effect of furniture, which is defined as a multiplier of zone air capacity.

EnergyPlus uses the 'Internal Mass' object to describe furniture surface area and thermal mass.

3.2.7 Windows

Modeling assumptions and simplifications for window thermal calculation in DOE-2, DeST and EnergyPlus are described in their engineering manuals (DOE-2 1980; DeST 2006; EnergyPlus 2011b).

In DOE-2, the user can select window templates from its window library as well as build window models using the K-SC method, where K is the heat transfer coefficient of the window excluding the outside film coefficient, and SC is the shading coefficient. For indirect normal incidence, the transmittance of the direct solar radiation is calculated as a polynomial, using the cosine of the solar incidence angle.

The approach to build window model in DeST is very similar as in DOE-2, including window templates and the K-SC method. But the K-SC method has difference between DeST and DOE-2. In DeST K is the heat transfer coefficient including the outside film coefficient. Besides, in DeST a window of the required layers of glass is built to meet the value of K and SC. Then the performance at non-direct normal incidence is calculated by the layer-by-layer approach basing on the built window.

In EnergyPlus, the window model is more complex. Two approaches are available: layer-by-layer construction or a simple glazing model. With the layer-by-layer approach, users provide properties of the glazing (such as the solar and visible transmittance at normal incidence) and the air gap (such as its thickness). The glazing optical and thermal calculations are based on window algorithms from the WINDOW 4 and WINDOW 5 programs. The simple glazing approach determines an equivalent single layer of glazing based on user specified U-factors, SHGCs, and optional VT.

Table 3.7 Comparison of Window Models

	DOE-2	**DeST**	**EnergyPlus**
Method 1	Window library	Window library	Layer-by-layer construction
Method 2	K-SC model	K-SC model	U-SHGC model

In order to compare the results from window models in EnergyPlus and DOE-2, a double-pane window, as defined in ASHARE Standard 140, was simulated (Figure 3.8). The window transmittance is calculated under the condition of only direct solar radiation. From the results, we can see that the difference of window transmittance between DeST and EnergyPlus is very small for various angles of incidence.

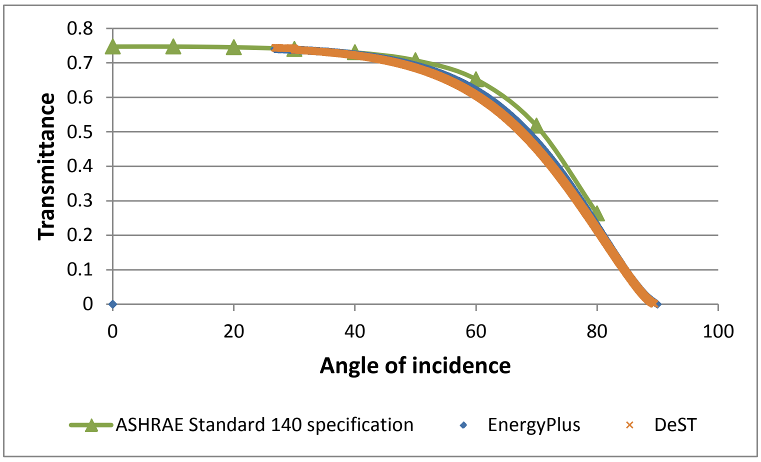

Figure 3.8 Window Solar Transmittance under Various Incident Angles

3.2.8 Ventilation

The ventilation involved in load calculations includes two parts: air infiltration and inter-zone airflows. Modeling assumptions and simplifications for ventilation calculations in DOE-2, DeST and EnergyPlus are described in their engineering manuals (DOE-2 1980; DeST 2006; EnergyPlus 2011b).

In DOE-2, the infiltration rate is calculated by the air-change method and schedule as follows:

Actual air changes per hour = (AIR-CHANGES/HR) × (wind-speed)/(10 mph)

In EnergyPlus, the infiltration rate can be specified as a design level which is modified by a schedule fraction, temperature difference and wind speed as follows:

Actual infiltration = design rate × Schedule × (A+B×(Tzone-Todb)+C×WindSpd+D× WindSpd^2)

When coefficients B, C and D are set to zero and A is set to one, the hourly infiltration rate only depends on the infiltration schedule defined by the user.

Table 3.8 Comparison of Ventilation Models

	DOE-2	**DeST**	**EnergyPlus**
Infiltration	Schedule; Correlation	Schedule;	Schedule; Correlation
Zone mixing	No	Schedule	DeltaT control
Airflow network	No	Yes	Yes

Airflows between zones ("Zone mixing") are ignored by DOE-2. DeST uses a simple schedule to define hourly flow rates. EnergyPlus has a more complex model to handle inter-zone airflow which allows temperature controls. Both EnergyPlus and DeST implement an airflow network model to calculate inter-zone air flows in details.

3.3 Summary of inputs

From the comparisons above, we can see that a large number of inputs are required for simulating building thermal loads. In DOE-2 and DeST, most inputs are assigned default values by the program automatically, and rarely specified by the user. Examples of these inputs are surface convection coefficients, solar distribution fractions, internal gain radiant heat fractions and distributions, etc. EnergyPlus requires the user to specify most inputs or algorithms.

In order to compare inputs better, we can classify all inputs into two types: one is user inputs that are specified by the user (these tend to vary by simulation cases); the other is default values or algorithms provided by the program automatically, which are rarely changed by the user. The summary of both user inputs and default values or algorithms is shown in Table 3.9 and Table 3.10. From the summary of user inputs, we can conclude that there are mostly no differences between the three BEMPs for building load calculations, i.e. equivalent values for these inputs can be specified in each program. However, default values or algorithms for the three programs differ greatly due to different modeling assumptions and simplifications. In EnergyPlus, many inputs used as default values in DOE-2 and DeST, such as solar absorptance, visible absorptance and thermal emissivity etc., have to be specified by the user. In DeST, the default values listed in Table 3.10 are set as constant values and it is very easy to change their values. In DOE-2, most default values have to be changed by program variables in input files. This is more difficult compared with EnergyPlus and DeST, and usually the user does not try to change these default settings.

In summary, it is not easy to make all the default values or algorithms equivalent, some even cannot be changed without modifying and recompiling the source code of the program.

Table 3.9 Summary of User Inputs

	DOE-2	**DeST**	**EnergyPlus**
Weather data	Weather file	Weather database	Weather file
Construction	Specify material properties layer-by-layer		
People	Number, heat rate, schedule, sensible/latent split		
Lighting	Power level, schedule, distribution fractions, convective/radiative split		
Equipment	Power level, schedule, distribution fractions, convective/radiative split		
Infiltration	Design flow rate, schedule, and correction by indoor and outdoor conditions		
AC on/off	Schedule		
Thermostat setpoints	Heating setpoint, Cooling setpoint		

Table 3.10 Summary of Default Values or Algorithms

	DOE-2	**DeST**	**EnergyPlus**
Time steps per hour	1	1	6
Exterior surface convection coefficients	Combined radiative and convective coefficients varied by wind speed	Constant convection coefficients	DOE-2 algorithm
Interior surface convection coefficients	Constant combined radiative and convective coefficients	Constant convection coefficients	TARP algorithm
Exterior surface radiative property	Solar absorptance=0.7 Thermal emissivity=0.9	Solar absorptance=0.55 Thermal emissivity=0.85	User inputs: solar absorptance, visible absorptance, and thermal absorptance
Interior surface radiative property	Solar absorptance=0.7	Solar absorptance=0.55 Thermal emissivity=0.85	User inputs: solar absorptance, visible absorptance, and thermal absorptance
Roughness	Medium rough	None	User input
Solar distribution	floor 60%, other interior surfaces split the 40% weighted by area	Air=0.15, walls=0.255, floor=0.51, roof=0.085	FullExterior algorithm
People heat level	Sensible heat=67W Latent heat=56W	Sensible heat=66W Latent heat=0.102kg/h	User inputs: activity level, sensible heat fraction
People heat distribution	Default weighting factor	Convective=0.5, radiative=0.5(walls=0.5, floor=0.1, ceiling=0.4)	User inputs: convective/Radiative fraction; radiation distribution
Lighting heat distribution	Lighting types Default: SUS-FLUOR	Convective=0.3, radiative=0.7(walls=0.4, floor=0.5, ceiling=0.1)	User inputs: convective/Radiative fraction; radiation distribution
Equipment heat distribution	Default weighting factor	Convective=0.7, radiative=0.3(walls=0.33, floor=0.33, ceiling=0.33)	User inputs: convective/Radiative fraction; radiation distribution
Ground reflectance	0.2	0.3	User input

4 Weather data

4.1 Weather variables

Weather data is one of the important user inputs to BEMPs. Each of the three BEMPs has its specific weather file format for building thermal load simulations. DOE-2 accepts weather files in FMT format (ASCII text format), and then converts them into BIN format (binary format) using its weather data processor. EnergyPlus uses weather files in EPW format (text format) and has a powerful weather data processor, which can convert from various raw data formats, including TMY2, IWEC, CSV, WYEC2, FMT (DOE-2 format), CLM (ESP-R ASCII format), ASC (BLAST ASCII format), etc. DeST has its own weather database consisting of thousands of China cities and other important cities around the world, though it has no weather data processor. The weather file format for DeST is MDB format (Microsoft Access Database) that can be re-written directly by the "CLIMATE_DATA" object.

DOE-2 weather variables in IP units are summarized in Table 4.1, including hourly and monthly variables (Fred Buhl 1999). DeST weather variables in SI units are described in Table 4.2 (DeST 2006). EnergyPlus weather variables in SI units are described in Table 4.3 (EnergyPlus 2011c). When there are missing values, they are replaced by an initial default value or the value from the previous time step. Although there are numerous variables in the weather file, some are not used in program currently.

Table 4.1 DOE-2 Weather Variables in the Processed Weather File

Field No.	Name	Description	Unit	Missing Value	Currently Used
1	**month**	The month (1-12) of the year		N/A	√
2	**day**	The day of the month		N/A	√
3	**hour**	The hour of the data (1-24). Hour 1 is 00:01 to 01:00.		N/A	√
4	**Wet-bulb temperature**	The wet-bulb temperature	°F	N/A	√
5	**Dry-bulb temperature**	The dry-bulb temperature	°F	N/A	√
6	**atmospheric pressure**	The atmospheric pressure	Inches of Mercury	N/A	√
7	**Cloud amount**	0=perfectly clear, 10=completely overcast		N/A	√
8	**Rain flag**	0=no, 1=yes		N/A	√
9	**Snow flag**	0=no, 1=yes		N/A	√
10	**Wind direction**	Compass point 0-15,0=N,1=NNE, etc.		N/A	√
11	**Humidity ratio**	lb of water per lb of dry air		N/A	√
12	**Air density**	Density of air	lb/ft^3	N/A	√
13	**enthalpy**	Specific enthalpy of the air	Btu/lb	N/A	√
14	**Total horizontal solar radiation**	The total horizontal solar radiation	$Btu/hr\text{-}ft^2$	N/A	√
15	**Direct normal radiation**	The direct normal solar radiation	$Btu/hr\text{-}ft^2$	N/A	√
16	**Cloud type**	0=cirrus,1=cirrus/stratus,2=stratus		N/A	√
17	**Wind speed**	The wind speed	knots	N/A	√
18	**Clearness number**	Monthly variables		N/A	√
19	**Ground temperature**	Monthly variables	Rankine	N/A	√

Table 4.2 DeST Weather Variables in the Weather File

Field No.	**Name**	**Description**	**Unit**	**Missing Value**	**Currently Used**
1	**HOUR**	The hour of the data (0-8759). Hour 0 is 00:01 to 01:00, Jan 1st.		N/A	√
2	**T**	Dry bulb temperature	°C	N/A	√
3	RH	Relative humidity in percent		N/A	
4	**D**	Humidity ratio	g/kg	N/A	√
5	**RT**	Total horizontal solar radiation	W/m^2	N/A	√
6	**RR**	Diffuse horizontal radiation	W/m^2	N/A	√
7	TS	Wet bulb temperature	°C	N/A	
8	TD	Dew point temperature	°C	N/A	
9	PW	Partial pressure of water vapor	Pa	N/A	
10	**P**	Atmospheric pressure	Pa	N/A	√
11	I	Enthalpy	kJ/kg	N/A	
12	RNORM	Direct normal radiation	W/m^2	N/A	
13	RE	Total radiation on eastern vertical plane	W/m^2	N/A	
14	RS	Total radiation on southern vertical plane	W/m^2	N/A	
15	RW	Total radiation on western vertical plane	W/m^2	N/A	
16	RN	Total radiation on northern vertical plane	W/m^2	N/A	
17	**T_SKY**	Effective sky temperature	K	N/A	√
18	**T_GROUND**	Ground temperature	°C	N/A	√
19	CLOUD	Opaque sky cover (tenths of coverage)		N/A	
20	**WS**	Wind speed	m/s	N/A	√
21	**WD**	Wind direction in 16 directions where the convention is 0=C, 1=N, 2=NNE, 3=NE, 4=ENE, 5=E, 6=ESE, 7=SE, 8=SSE, 9=S,…13=W,…16=NNW.		N/A	√

Table 4.3 EnergyPlus Weather Variables in the Weather File

Field No.	Name	Description	Unit	Missing Value	Currently Used
1	year	The year of the data. Not really used in EnergyPlus. Used in the Weather Converter program for display in an audit file.			
2	**month**	The month (1-12) for the data.		N/A	√
3	**day**	The day (dependent on month) for the data.		N/A	√
4	**hour**	The hour of the data. (1 – 24). Hour 1 is 00:01 to 01:00.		N/A	√
5	**minute**	The minute field.		0	
6	data source and uncertainty flag	See EnergyPlus Documentation: Auxiliary Programs			
7	**dry bulb temperature**	The dry bulb temperature at the time indicated.	°C	99.9	√
8	**dew point temperature**	The dew point temperature at the time indicated.	°C	99.99	√
9	**relative humidity**	The Relative Humidity in percent at the time indicated.		999	√
10	**atmospheric station pressure**	The station pressure at the time indicated.	Pa	999999	√
11	extraterrestrial horizontal radiation	The Extraterrestrial Horizontal Radiation.	Wh/m^2	9999	
12	extraterrestrial direct radiation	The Extraterrestrial Direct Normal Radiation.	Wh/m^2	9999	
13	**horizontal infrared radiation intensity**	The Horizontal Infrared Radiation Intensity. If it is missing, it is calculated from the Total and Opaque Sky Cover fields.	Wh/m^2	9999	√
14	global horizontal radiation	The Global Horizontal Radiation.	Wh/m^2	9999	
15	**direct normal radiation**	The Direct Normal Radiation.	Wh/m^2	9999	√
16	**diffuse horizontal**	The Diffuse Horizontal Radiation.	Wh/m^2	9999	√

	radiation				
17	global horizontal illuminance	The Global Horizontal Illuminance.	lux	999999	
18	direct normal illuminance	The Direct Normal Illuminance.	lux	999999	
19	diffuse horizontal illuminance	The Diffuse Horizontal Illuminance.	lux	999999	
20	field zenith luminance	The Zenith Illuminance.	Cd/m^2	9999	
21	**wind direction**	The Wind Direction in degrees where the convention is that North=0.0, East=90.0, South=180.0, West=270.0. Values can range from 0 to 360. If calm, direction equals zero.		999	√
22	**wind speed**	The wind speed.	m/s	999	√
23	**total sky cover**	The value for total sky cover (tenths of coverage). This is not used unless the field for Horizontal Infrared Radiation Intensity is missing.		99	√
24	**opaque sky cover**	The value for opaque sky cover (tenths of coverage). This is not used unless the field for Horizontal Infrared Radiation Intensity is missing.		99	√
25	visibility	The value for visibility in km. (Horizontal visibility at the time indicated.)		9999	
26	ceiling height	The value for ceiling height in m.		99999	
27	**present weather observation**	The primary use of these fields (Present Weather Observation and Present Weather Codes) is for rain/wet surfaces. A missing observation field or a missing weather code implies “no rain”.		9	√
28	**present weather codes**	A text field of 9 single digits. The most important fields		999999999	√

		are those representing liquid precipitation – where the surfaces of the building would be wet.			
29	precipitable water	The value for Precipitable Water.	mm	999	
30	aerosol optical depth	The value for Aerosol Optical Depth in thousandths.		999	
31	snow depth	The value for Snow Depth.	cm	999	
32	days since last snowfall	The value for Days Since Last Snowfall.		99	
33	albedo	The ratio (unitless) of reflected solar irradiance to global horizontal irradiance.		999	
34	**liquid precipitation depth**	The amount of liquid precipitation observed at the indicated time for the period indicated in the liquid precipitation quantity field. If this value is not missing, it is used and overrides the "precipitation" flag as rainfall.	mm	0	√
35	liquid precipitation quantity	The period of accumulation (hr) for the liquid precipitation depth field.		0	

Only some of the weather data variables listed in Table 4.4 are essential and influential for building load simulations. The key variables can be sorted into four types. The first includes the temperature, humidity and atmospheric pressure of the outdoor air. These can all be converted into equivalent inputs for the different programs. The second is solar radiation variables including global horizontal, direct normal radiation, and diffuse horizontal radiation. The variables for solar radiation used by each program vary and sometimes there is missing data in the weather files. The third is sky radiation variables. EnergyPlus uses horizontal infrared radiation intensity, while DeST uses sky temperature. The final type of variable consists of wind direction, wind speed, and ground temperature, which are used by all three BEMPs. The major difference is that monthly ground temperatures are used in DOE-2 and EnergyPlus, but hourly values are used in DeST.

Table 4.4 Key Weather Variables used by Each Program

Type	Variable	DOE-2	DeST	EnergyPlus
1	Dry bulb temperature	√	√	√
	Wet bulb temperature	√		
	Dew point temperature			√
	Relative humidity			√
	Humidity ratio	√	√	
	Atmospheric station pressure	√	√	√
2	Global horizontal radiation	√	√	
	Direct normal radiation	√		√
	Diffuse horizontal radiation		√	√
3	Horizontal infrared radiation intensity			√
	Sky temperature		√	
4	Wind direction	√	√	√
	Wind speed	√	√	√
	Ground temperature	√	√	√

4.2 Weather data conversion

Due to different weather file formats used in the three BEMPs, weather data conversion is required as shown in Figure 4.1. As weather variables can be overwritten directly in DeST weather files, it is easy to convert weather variables from DOE-2 or EnergyPlus to DeST. From DeST to DOE-2, weather variables can be overwritten in the FMT format first, and then converted into BIN format by the DOE-2 weather data processor. From DeST to EnergyPlus, weather variables can be overwritten in the CSV format first, and then converted into EPW format by the EnergyPlus weather data processor. From DOE-2 to EnergyPlus, the DOE-2 weather files (FMT format) can be converted into EPW format by the EnergyPlus weather data processor. From EnergyPlus to DOE-2, first, weather variables in the DOE-2 weather file can be overwritten and then converted into BIN format.

Thus, some of the conversions can be done by the weather data processor automatically, and others have to be completed manually.

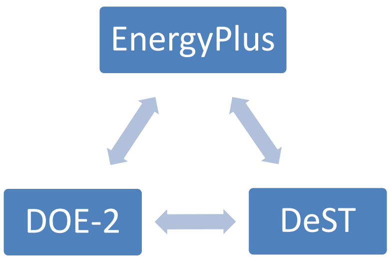

Figure 4.1 Weather Data Conversion

4.2.1 Solar radiation

Weather files sometimes have missing values for solar radiation. Different BEMPs have different methods to deal with this problem, so the conversion of solar radiation data is non-trivial.

First, if every value of the solar radiation data is zero in the weather file, DeST and EnergyPlus use zero as the value, whereas DOE-2 will calculate the hourly value using a specific algorithm based on the ASHRAE Clear Sky model and the clearness number, cloud coverage, and cloud type from the DOE-2 weather file. Thus, a large discrepancy can arise if we convert DOE-2 weather files (FMT format) into EnergyPlus weather files (EPW format) by the EnergyPlus weather processor directly. In order to solve this problem, we have to run DOE-2 to get a report of hourly solar radiation values, and then replace the zero values in the weather file before conversion.

Second, each of the three BEMPs uses a different solar radiation source as shown in Table 4.4. With any two solar components, it is reasonable to use the simple relationship of global, diffuse and direct radiation, such as:

$$Global_{horizontalradiation} = Direct_{horizontalradiation} + Diffuse_{horizontalradiation}$$

Using a known solar position (calculated internally by the weather data processor from latitude, longitude, date and hour), one has:

$$Direct_{normalradiation} = \frac{Direct_{horizontalradiation}}{SIN(Solar_{height})}$$

Due to different time points for the solar position calculations, the actual solar radiation values for building load simulations would be different, though the values in the weather files are equivalent among the three BEMPs.

4.2.2 Sky infrared radiation

In EnergyPlus, horizontal infrared radiation intensity in the weather files is used for sky radiation calculations. If it is missing, it will be calculated from the dry-bulb temperature and Opaque Sky Cover field ((EnergyPlus 2011b: Climate, Sky and Solar/Shading Calculations).

In DeST, the sky temperature is used, which can be calculated from the horizontal infrared radiation intensity as follows:

$$\text{Sky}_{Temperature} = (\frac{Horizontal_{IR}}{Sigma})^{0.25} - Temperature_{Kelvin}$$

Where:
$\text{Sky}_{Temperature}$ =Sky radiative temperature
$Horizontal_{IR}$ =Horizontal infrared radiation intensity

$Sigma$ =Stefan-Boltzmann constant = 5.6697e-8 W/($m^2 \cdot K^4$)
$Temperature_{Kelvin}$ =Temperature conversion from Kelvin to Centigrade, i.e. minus 273.15

5 ASHRAE Standard 140-2007 Tests

5.1 Introduction

This section describes the modeling methods and results of building thermal envelope and fabric tests designated as Cases 195 through 960 in ASHRAE Standard 140-2007 (ANSI/ASHRAE Standard 140 2007) from the three BEMPs (DOE-2.1E, DeST 2011-11-23 and EnergyPlus 7.0). The tests described in Section 5.2 of ASHRAE Standard 140-2007, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, were performed. This suite of tests was based on work previously performed under an earlier project sponsored by the International Energy Agency (IEA) titled Building Energy Simulation Test (BESTEST) and Diagnostic Method (IEA 1995) (Judkoff et al 1995). Standard 140-2007 is a standard test method that can be used for identifying and diagnosing predictive differences from whole building energy simulation software that may possibly be caused by algorithmic differences, modeling limitations, input differences, or coding errors.

5.2 Test suite

The following tests were performed as specified with modeling notes and other reports generated as shown in the Standard:

✓ BASE Case (Case 600, Section 5.2.1 of Standard)

✓ BASIC Tests (Section 5.2.2 of Standard)

Low mass tests (Cases 610 to 650)
High mass tests (Cases 900 to 960)
Free float tests (Cases 600FF, 650FF, 900FF and 950FF)

✓ IN-DEPTH Tests (Section 5.2.3 of Standard)

Cases 195 to 320
Cases 395 to 440
Cases 800 to 810

The test results of the three BEMPs were compared to the results of other programs that completed and reported test results, including ESP, DOE2.1D, TRNSYS and TASE, etc.

A brief description of the BASE Case, BASIC Test Cases and Case 195 are presented in the following sections as examples. For descriptions of the other test cases see ASHRAE Standard 140-2007.

5.2.1 Case 600–Base Case Low Mass Building

The basic test building (Figure 5.1) is a rectangular, single zone (8 m wide × 6 m long × 2.7 m high) with no interior partitions and 12 m^2 of windows on the southern exposure. The building is of lightweight construction with characteristics as described below. For further details refer to Section 5.2.1 of ASHRAE Standard 140-2007.

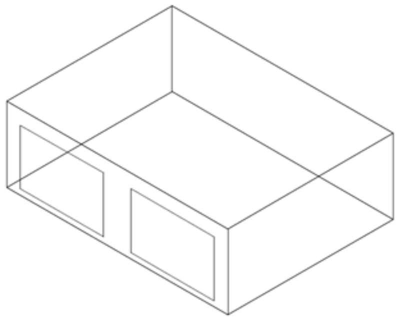

Figure 5.1 Case 600 Described in ASHRAE Standard 140-2007

- Construction (light weight mass)

Table 5.1 Material Specifications Lightweight Case Described in ASHRAE Standard 140-2007

Lightweight Case: Exterior Wall (inside to outside)						
Element	**K (W/m·K)**	**Thickness (m)**	**U (W/m2·K)**	**R (K/W)**	**Density (kg/m3)**	**Cp (J/kg·K)**
Int Surf Coef			8.290	0.121		
Plasterboard	0.160	0.012	13.333	0.075	950	840
Fiberglass quilt	0.040	0.066	0.606	1.650	12	840
Wood Siding	0.140	0.009	15.556	0.064	530	900
Ext Surf Coef			29.300	0.034		
Total air-air			**0.514**	**1.944**		
Total air-surf			**0.559**	**1.789**		
Lightweight Case: Floor (inside to outside)						
Element	**K (W/m·K)**	**Thickness (m)**	**U (W/m2·K)**	**R (K/W)**	**Density (kg/m3)**	**Cp (J/kg·K)**
Int Surf Coef		8.290	0.121			
Timber flooring	0.140	0.025	5.600	0.179	650	1200
Insulation	0.040	1.003	0.040	25.075	**	
Total air-air			**0.039**	**25.374**		
Total air-surf			**0.040**	**25.254**		

Lightweight Case: Roof (inside to outside)						
Element	**K (W/m·K)**	**Thickness (m)**	**U (W/m2·K)**	**R (K/W)**	**Density (kg/m3)**	**Cp (J/kg·K)**
Int Surf Coef			8.390	0.121		
Plasterboard	0.160	0.010	16.000	0.063	950	840
Fiberglass quilt	0.040	0.1118	0.358	2.794	12	840
Roof deck	0.140	0.019	7.368	0.136	530	900
Ext Surf Coef			29.300	0.034		
Total air-air			**0.318**	**3.147**		
Total air-surf			**0.334**	**2.992**		

- Window properties

Table 5.2 Window Properties Described in ASHRAE Standard 140-2007

Property	Value
Extinction coefficient	0.0196/mm
Number of panes	2
Pane thickness	3.175 mm
Air gap thickness	13 mm
Index of refraction	1.526
Normal direct-beam transmittance through one pane in air	0.86156
Thermal conductivity of glass	1.06 W/m·K
Conductance of each glass pane	333 W/m^2·K
Combined radiative and convective heat transfer coef of air gap	6.297 W/m^2·K
Exterior combined surface coefficient	21.00 W/m^2·K
Interior combined surface coefficient	8.29 W/m^2·K
U-value from interior air to ambient air	3.0 W/m^2·K
Hemispherical infrared emittance of ordinary uncoated glass	0.84
Density of glass	2500 kg/m^3
Specific heat of glass	750 (J/kg·K)
Curtains, blinds, frames, spacers, mullions, obstructions inside the window	None
Double-pane shading coefficient (at normal incidence)	0.907
Double-pane solar heat gain coefficient (at normal incidence)	0.789

- Infiltration

0.5 air changes per hour

- Internal load

200 W continuous, 100% sensible, 60% radiative, 40% convective

- Mechanical system

100% convective air system, 100% efficient with no duct losses and no capacity limitation, no latent heat extraction, non-proportional-type dual set-point thermostat with dead-band, heating < 20°C, cooling >27°C

- Soil temperature

10°C continuous

5.2.2 Case 610–South Shading Test for Low Mass Buildings

Case 610 is exactly the same as Case 600 except for 1 m horizontal overhang across the entire length of the south wall, shading the south facing windows at the roof level. This case tests the ability of a program to treat shading of a southerly exposed window.

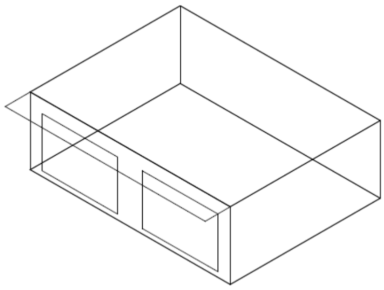

Figure 5.2 Case 610 Described in ASHRAE Standard 140-2007

5.2.3 Case 620–East/West Window Orientation Test for Low Mass Buildings

Case 620 is exactly the same as Case 600 except that the window orientation is modified so that 6 m^2 of window area is facing east, and 6 m^2 of window area is facing west.

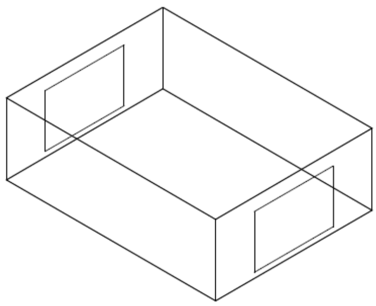

Figure 5.3 Case 620 Described in ASHRAE Standard 140-2007

5.2.4 Case 630–East/West Shading Test for Low Mass Buildings

Case 630 is exactly the same as Case 620 except that a shade overhang and shade fins were added around the east and west window. A 1 m horizontal overhang is located at the roof level and extends across the 3 m width of each window. The 1 m wide right and left vertical shade fins are located on the sides of each window and extend from the roof down to the ground.

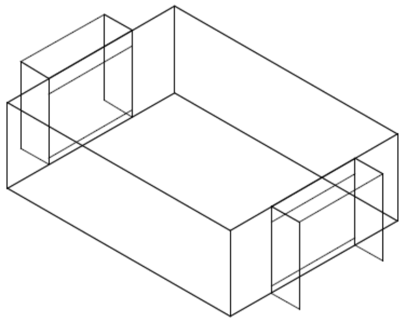

Figure 5.4 Case 630 Described in ASHRAE Standard 140-2007

5.2.5 Case 640–Thermostat Setback Test for Low Mass Buildings

Case 640 is exactly the same as Case 600 except for the change of thermostat control strategy as follows:

- From 2300 hours to 0700 hours, heat = on if temperature < 10°C.
- From 0700 hours to 2300 hours, heat = on if temperature < 20°C.
- All hours, cool = on if temperature > 27°C.

Otherwise, mechanical equipment is off.

5.2.6 Case 650–Night Ventilation Test for Low Mass Buildings

Case 650 is exactly the same as Case 600 except the following scheduled nighttime ventilation and heating and cooling temperature control was used:

- Vent fan capacity = 1703.16 standard m^3/h (13.14 ACH).
- From 1800 hours to 0700 hours, vent fan = on.
- From 0700 hours to 1800 hours, vent fan = off.
- Heating = always off.
- From 0700 hours to 1800 hours, cool = on if temperature > 27°C; Otherwise, cool = off.
- From 1800 hours to 0700 hours, cool = off.

5.2.7 Case 900–Base Case High Mass Buildings

The 900 series of tests use the same building model as the series 600 tests except that the wall and floor construction are changed to use heavier materials.

Table 5.3 Material Specifications Heavyweight Case Described in ASHRAE Standard 140-2007

Heavyweight Case: Exterior Wall (inside to outside)						
Element	**K (W/m·K)**	**Thickness (m)**	**U (W/m2·K)**	**R (K/W)**	**Density (kg/m3)**	**Cp (J/kg·K)**
Int Surf Coef			8.290	0.121		
Concrete Block	0.510	0.100	5.100	0.196	1400	1000
Foam Insulation	0.040	0.0615	0.651	1.537	10	1400
Wood Siding	0.140	0.009	15.556	0.064	530	900
Ext Surf Coef			29.300	0.034		
Total air-air			**0.512**	**1.952**		
Total air-surf			**0.556**	**1.797**		

Heavyweight Case: Floor (inside to outside)						
Element	**K (W/m·K)**	**Thickness (m)**	**U (W/m2·K)**	**R (K/W)**	**Density (kg/m3)**	**Cp (J/kg·K)**
Int Surf Coef		8.290	0.121			
Concrete Slab	1.130	0.080	14.125	0.071	1400	1000
Insulation	0.040	1.007	0.040	25.175	**	
Total air-air			**0.039**	**25.366**		
Total air-surf			**0.040**	**25.246**		

Heavyweight Case: Roof (inside to outside)						
Element	**K (W/m·K)**	**Thickness (m)**	**U (W/m2·K)**	**R (K/W)**	**Density (kg/m3)**	**Cp (J/kg·K)**
Int Surf Coef			8.390	0.121		
Plasterboard	0.160	0.010	16.000	0.063	950	840
Fiberglass quilt	0.040	0.1118	0.358	2.794	12	840
Roof deck	0.140	0.019	7.368	0.136	530	900
Ext Surf Coef			29.300	0.034		
Total air-air			**0.318**	**3.147**		
Total air-surf			**0.334**	**2.992**		

5.2.8 Case 910 through 950

Case 910 (920, 930, 940, 950) is same as Case 610 (620, 630, 640, 650) except for high mass walls and floor.

5.2.9 Case 960–Sunspace Test

Case 960 simulates a passive solar building consisting of two zones (a back-zone and a sun-zone) separated by a common interior wall.

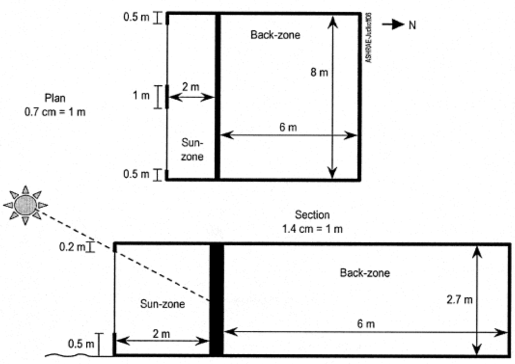

Figure 5.5 Case 960 Described in ASHRAE Standard 140-2007

- Back zone

The geometric and thermal properties of the back zone are exactly the same as for Case 600 except that the south wall and windows are replaced with the common wall. Infiltration and the internal load in the back zone is also the same as in Case 600.

Table 5.4 Thermal and Physical Properties of the Sun-zone/Back-zone Common Wall Described in ASHRAE Standard 140-2007

K (W/m·K)	Thickness (m)	U (W/m2·K)	R (K/W)	Density (kg/m3)	Cp (J/kg·K)	Shortwave Absorptance	Infrared Emittance
0.510	0.20	2.55	0.392	1400	1000	0.6	0.9

- Sun zone

Infiltration = 0.5 ACH

No internal heat gain

No space conditioning system

5.2.10 Case 600FF through Case 950FF

Case 600FF (650FF, 900FF, 950FF) is the same as Case 600 (650, 900, 950) except that there is no mechanical heating or cooling system.

5.2.11 Case 195–In depth Test of Solid Conduction Problem for Low Mass Buildings

Case 195 is the same as case 600 with the following exceptions:

South wall contains no windows and is of the lightweight mass exterior wall construction.
No infiltration, no internal gains.

Thermostat control: heat = on if temperature < 20°C; cool = on if temperature > 20°C.
Infrared emissivity and solar/visible absorptance of all interior and exterior surfaces = 0.1.

5.3 Modeling notes

Test results from DOE-2.1E and EnergyPlus 7.0 were provided by the Lawrence Berkeley National Lab (LBNL) and the EnergyPlus development team (Henninger et al. 2006; Henninger et al. 2011b). When preparing the DeST models for the tests described above, the specifications defined in Section 5 – Test Procedures of ASHRAE Standard 140-2007, were followed. As different programs require different inputs, in some cases the specification provides alternate input values for a particular element of the building. The following notes were presented modeling specifications of DeST models, also compared with DOE-2 and EnergyPlus. For example, ASHRAE Standard 140-2007 tests supply two methods for interior radiative and convective surface properties. If the test program calculates interior surface radiation and convection automatically, the default algorithm of the program is used; otherwise, the combined radiative and convective coefficients from ASHRAE 140 tests are directly used.

Table 5.5 Modeling Notes of the Three BEMPs (using Case 600 as an example)

	Standard 140	**DOE-2**	**DeST**	**EnergyPlus**
Weather file	DRYCOLD.TMY	DRYCOLD.bin	Converted from EnergyPlus 7.0	DRYCOLD.epw
Time step	1 hour	1 hour	1 hour	15 minutes; Outputs reported hourly
Exterior radiative and convective surface properties	Auto-calculated; Combined radiative and convective input values	Auto-calculated	Auto-calculated; Surface convection coefficients: default	Auto-calculated; Surface Convection Algorithm: Outside = DOE-2
Interior radiative and convective surface properties	Auto-calculate; Combined radiative and convective input values	Combined radiative and convective input values = 8.3 W/m^2	Auto-calculated; Surface convection coefficients: default	Auto-calculated; Surface Convection Algorithm: Inside = TARP
Exterior opaque surface radiative properties	Solar absorptance = 0.6 Infrared emittance = 0.9	Solar absorptance = 0.6 Thermal emissivity = 0.9	Solar absorptance = 0.6 Infrared emittance = 0.9	Solar absorptance = 0.6 Visible absorptance = 0.6 Thermal absorptance = 0.9
Interior opaque surface radiative properties		Solar absorptance = 0.6		
Solar distribution	Auto-calculated; Distribution fraction	Distribution fraction	Distribution fraction	Auto-calculated; Algorithm: FullInteriorAndExterior
Infiltration	Constant, 0.5 ACH	Constant, 0.5 ACH	Constant, 0.5 ACH	Constant, 0.5 ACH
Window	A great deal of information provided for different programs	Double-pane window K = 3.5 (excludes exterior film coefficient) SC = 0.91	Double-pane window K = 3 SC = 0.907	Layer by layer construction
Zone HVAC	Ideal load calculation, only sensible load			

5.4 Results and discussion

The summary of BEMPs participating in the ASHRAE 140-2007 tests is listed in Table 5.6. The results of BEMPs except DeST come from LBNL (Henninger et al. 2011b), summarized on a set of charts presented in the Appendix.

Table 5.6 BEMPs Participating in the Comparison Described in (Henninger et al. 2011b)

Code Name	Computer program	Developer	Implemented by
BLAST	BLAST-3.0 level 193 v.1	CERL,U.S.	NREL, U.S. Politecnico, Torino, Italy
DOE2.1D	DOE2.1D 14	LANL/LBL,U.S.	NREL, U.S.
ESP	ESP-RV8	Strathclyde University, U.K.	De Montfort University, U.K.
SRES/SUN	SERIRES/SUNCODE 5.7	NREL/Ecotope, U.S.	NREL, U.S.
SERIRES	SERIRES 1.2	NREL, U.S. and BRE, U.K.	BRE, U.K.
S3PAS	S3PAS	University of Sevilla, Spain	University of Sevilla, Spain
TASE	TASE	Tampere University, Finland	Tampere University, Finland
TRNSYS	TRNSYS 13.1	University of Wisconsin, U.S.	BRE, U.K. Vrije Universiteit, Brussels, Belgium
DOE2.1E	DOE2.1E	LANL/LBL, U.S.	GARD Analytics, U.S. using NREL input files
DOE2.1E-RevWindow	DOE2.1E-RevWindow	LANL/LBL, U.S.	GARD Analytics, U.S. Uses Window 4 data file which more closely matches specification
BLAST3.0-334	BLAST3.0 level 334	CERL, U.S.	GARD Analytics, U.S. using NREL input files
ENERGYPLUS	EnergyPlus ver.7.0.0.036,Nov 2011	U.S Dept. of Energy	GARD Analytics, U.S.
DEST	DeST 2.0	Tsinghua University, China	Tsinghua University, China

The charts showed the annual heating, annual cooling, peak heating, and peak cooling for different cases. One measure of the comparison to see how well DOE-2 (DOE2.1E-RevWindow), DeST (DeST 2011-11-23) and EnergyPlus (EnergyPlus 7.0) predicted building loads was to see if their results fell within the range of spread of results from other programs. The following tables show the same results including a column for each program indicating a yes or no if DOE-2 (DeST or EnergyPlus) was within the range. From the comparisons, we can conclude that the simulation results of the three programs mostly fell within the ranges, but EnergyPlus had smaller heating loads for cases 910, 920, 930, 940, 300 and 310.

Note:

In Table 5.7, 'Min.' and 'Max.' are the minimum and the maximum results of all the programs being tested, except DOE2.1E-RevWindow, DeST and EnergyPlus. The label of y in black means the result of the program was within the range of [Min., Max.]. The label of y in yellow means the result of the program was not in the range of [Min., Max.], but within the 5% relaxed range [Min./1.05, Max.*1.05]. The label of n in red means the result was not within the 5% relaxed range [Min./1.05, Max.*1.05].

Table 5.7 Comparisons of Annual Heating Loads

ANNUAL HEATING LOADS (MWH)									
Case	Description	Min.	Max.	DOE-2.1E		DeST		EnergyPlus	
600	Base Case	4.296	5.709	4.994	y	5.007	y	4.364	y
610	South Shading	4.355	5.786	5.042	y	5.042	y	4.398	y
620	East/West Window Orientation	4.613	5.944	5.144	y	5.292	y	4.512	y
630	East/West Shading	5.050	6.469	5.508	y	5.570	y	4.813	y
640	Thermostat Setback	2.751	3.803	2.995	y	3.127	y	2.667	y
650	Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y
900	High Mass Base Case	1.170	2.041	1.301	y	1.894	y	1.163	y
910	High Mass South Shading	1.512	2.282	1.559	y	2.266	y	1.427	n
920	High Mass East/West Window Orientation	3.261	4.300	3.312	y	4.025	y	3.087	n
930	High Mass East/West Shading	4.143	5.335	4.249	y	4.485	y	3.785	n
940	High Mass Thermostat Setback	0.793	1.411	0.838	y	1.270	y	0.727	n
950	High Mass Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y
960	Sunspace	2.144	3.373	2.216	y	2.835	y	2.322	y
220	In-Depth Base Case	6.944	8.787			8.022	y	7.096	y
230	Infiltration	10.376	12.243			11.550	y	10.884	y
240	Internal Gains	5.649	7.448			6.759	y	5.848	y
250	Exterior Shortwave Absorptance	4.751	7.024	5.738	y	6.173	y	5.097	y
270	South Solar Gains	4.510	5.920			5.160	y	4.473	y
280	Cavity Albedo	4.675	6.148			5.570	y	4.670	y
290	South Shading	4.577	5.942			5.295	y	4.502	y
300	East/West Window	4.761	5.964			5.333	y	4.512	n
310	East/West Shading	5.221	6.165			5.633	y	4.776	n
320	Thermostat	3.859	5.141			4.403	y	3.767	y
395	Solid Conduction Test	4.799	5.835	5.472	y	5.238	y	5.038	y
400	Opaque Windows with	6.900	8.770	7.659	y	7.902	y	7.006	y

	Dead Band								
410	Infiltration	8.596	10.506	9.380	y	9.660	y	8.893	y
420	Internal Gains	7.298	9.151	8.074	y	8.385	y	7.628	y
430	Ext. Shortwave Absorptance	5.429	7.827	6.309	y	6.910	y	5.857	y
440	Cavity Albedo	4.449	5.811			5.146	y	4.546	y
800	High Mass without Solar Gains	4.868	7.228	5.353	y	6.444	y	5.195	y
810	High Mass Cavity Albedo	1.839	3.004			2.560	y	1.875	y

Table 5.8 Comparison of Annual Cooling Loads

ANNUAL COOLING LOADS (MWH)									
Case	**Description**	**Min.**	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600	Base Case	6.137	8.448	8.054	y	5.924	y	7.006	y
610	South Shading	3.915	6.139	5.874	y	4.873	y	4.976	y
620	East/West Window Orientation	3.417	5.482	5.256	y	3.847	y	4.384	y
630	East/West Shading	2.129	3.701	3.235	y	2.879	y	2.952	y
640	Thermostat Setback	5.952	8.097	7.713	y	5.759	y	6.710	y
650	Night Ventilation	4.816	7.064	6.678	y	4.625	y	5.538	y
900	High Mass Base Case	2.132	3.669	3.390	y	2.296	y	2.683	y
910	High Mass South Shading	0.821	1.883	1.738	y	1.202	y	1.350	y
920	High Mass East/West Window Orientation	1.840	3.313	3.169	y	2.401	y	2.683	y
930	High Mass East/West Shading	1.039	2.238	1.823	y	1.696	y	1.745	y
940	High Mass Thermostat Setback	2.079	3.546	3.272	y	2.262	y	2.606	y
950	High Mass Night Ventilation	0.387	0.921	0.749	y	0.455	y	0.571	y
960	Sunspace	0.411	0.895	0.855	y	0.537	y	0.732	y
220	In-Depth Base Case	0.186	0.835			0.561	y	0.396	y
230	Infiltration	0.454	1.139			0.857	y	0.685	y
240	Internal Gains	0.415	1.246			0.879	y	0.690	y
250	Exterior Shortwave Absorptance	2.177	4.284			2.311	y	3.671	y
270	South Solar Gains	7.528	10.350			7.859	y	8.523	y
280	Cavity Albedo	4.873	7.114			4.876	y	5.534	y
290	South Shading	5.204	8.089			6.049	y	6.415	y
300	East/West Window	4.302	7.100			5.342	y	5.478	y
310	East/West Shading	2.732	5.471			3.813	y	3.743	y
320	Thermostat	5.061	7.304			5.129	y	5.853	y
395	Solid Conduction Test	0.000	0.016	0.001	y	0.002	y	0.000	y

400	Opaque Windows with Dead Band	0.000	0.061	0.016	y	0.014	y	0.005	y
410	Infiltration	0.000	0.084	0.035	y	0.029	y	0.014	y
420	Internal Gains	0.011	0.189	0.105	y	0.094	y	0.064	y
430	Ext. Shortwave Absorptance	0.422	1.106	1.106	y	0.465	y	0.783	y
440	Cavity Albedo	3.967	5.204			4.193	y	4.497	y
800	High Mass without Solar Gains	0.055	0.325	0.323	y	0.137	y	0.301	y
810	High Mass Cavity Albedo	1.052	1.711			1.323	y	1.318	y

Table 5.9 Comparison of Peak Heating Loads

PEAK HEATING LOADS (kW)									
Case	**Description**	**Min.**	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600	Base Case	3.437	4.354	3.767	y	3.986	y	3.732	y
610	South Shading	3.437	4.354	3.755	y	3.954	y	3.720	y
620	East/West Window Orientation	3.591	4.379	3.785	y	3.962	y	3.726	y
630	East/West Shading	3.592	4.280	3.762	y	3.963	y	3.703	y
640	Thermostat Setback	5.232	6.954	5.656	y	5.991	y	6.265	y
650	Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y
900	High Mass Base Case	2.850	3.797	3.248	y	3.600	y	3.140	y
910	High Mass South Shading	2.858	3.801	3.256	y	3.612	y	3.139	y
920	High Mass East/West Window Orientation	3.308	4.061	3.508	y	3.776	y	3.453	y
930	High Mass East/West Shading	3.355	4.064	3.536	y	3.801	y	3.475	y
940	High Mass Thermostat Setback	3.980	6.428	5.322	y	5.723	y	4.785	y
950	High Mass Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y
960	Sunspace	2.410	2.863	2.603	y	2.601	y	2.691	y
220	In-Depth Base Case	2.867	3.695			3.485	y	3.211	y
230	Infiltration	4.386	5.279			5.058	y	5.031	y
240	Internal Gains	2.685	3.495			3.304	y	3.027	y
250	Exterior Shortwave Absorptance	2.866	3.695			3.406	y	3.211	y
270	South Solar Gains	2.863	3.661			3.366	y	3.006	y
280	Cavity Albedo	2.864	3.685			3.394	y	3.007	y
290	South Shading	2.863	3.661			3.366	y	2.994	y
300	East/West Window	3.014	3.681			3.358	y	3.000	y
310	East/West Shading	3.015	3.669			3.359	y	2.976	y
320	Thermostat	2.861	3.651			3.348	y	3.005	y

395	Solid Conduction Test	2.062	2.385	2.301	y	2.291	y	2.246	y
400	Opaque Windows with Dead Band	2.867	3.695	3.255	y	3.485	y	3.211	y
410	Infiltration	3.625	4.487	4.002	y	4.271	y	4.121	y
420	Internal Gains	3.443	4.287	3.819	y	4.091	y	3.937	y
430	Ext. Shortwave Absorptance	3.442	4.287	3.819	y	4.020	y	3.937	y
440	Cavity Albedo	3.439	4.376			3.957	y	3.733	y
800	High Mass without Solar Gains	3.227	4.138	3.634	y	3.878	y	3.794	y
810	High Mass Cavity Albedo	2.979	3.963			3.646	y	3.290	y

Table 5.10 Comparison of Peak Cooling Loads

PEAK COOLING LOADS (kW)									
Case	**Description**	**Min.**	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600	Base Case	5.965	7.188	6.965	y	6.151	y	6.678	y
610	South Shading	5.669	6.673	6.482	y	5.964	y	6.274	y
620	East/West Window Orientation	3.634	5.096	4.679	y	3.819	y	4.005	y
630	East/West Shading	3.072	4.116	3.834	y	3.270	y	3.446	y
640	Thermostat Setback	5.884	7.126	6.903	y	6.116	y	6.614	y
650	Night Ventilation	5.831	7.068	6.843	y	5.973	y	6.479	y
900	High Mass Base Case	2.888	3.932	3.778	y	3.469	y	3.320	y
910	High Mass South Shading	1.896	3.277	2.703	y	2.844	y	2.640	y
920	High Mass East/West Window Orientation	2.385	3.505	3.342	y	2.844	y	2.835	y
930	High Mass East/West Shading	1.873	3.080	2.638	y	2.527	y	2.332	y
940	High Mass Thermostat Setback	2.888	3.932	3.778	y	3.497	y	3.320	y
950	High Mass Night Ventilation	2.033	3.170	2.917	y	2.586	y	2.451	y
960	Sunspace	0.953	1.422	1.048	y	1.085	y	1.213	y
220	In-Depth Base Case	0.560	1.340			1.060	y	0.900	y
230	Infiltration	1.059	1.875			1.576	y	1.397	y
240	Internal Gains	0.739	1.540			1.241	y	1.083	y
250	Exterior Shortwave Absorptance	2.258	4.912			2.169	y	3.073	y
270	South Solar Gains	6.356	7.234			6.396	y	6.856	y
280	Cavity Albedo	4.444	5.220			4.311	y	4.734	y
290	South Shading	6.203	6.976			6.293	y	6.737	y
300	East/West Window	3.404	4.657			3.858	y	3.894	y
310	East/West Shading	2.848	4.164			3.241	y	3.246	y

320	Thermostat	5.701	6.553			5.752	y	6.184	y
395	Solid Conduction Test	0.000	0.394	0.175		0.174	y	0.049	y
400	Opaque Windows with Dead Band	0.000	0.666	0.407		0.420	y	0.235	y
410	Infiltration	0.035	0.814	0.559		0.573	y	0.378	y
420	Internal Gains	0.258	1.047	0.792		0.786	y	0.621	y
430	Ext. Shortwave Absorptance	1.427	2.578	2.113		1.486	y	1.845	y
440	Cavity Albedo	4.424	5.278			4.854	y	4.827	y
800	High Mass without Solar Gains	0.685	1.358	1.267		0.937	y	1.125	y
810	High Mass Cavity Albedo	1.852	2.991			2.497	y	2.175	y

Table 5.11 Comparison of Hourly Zone Temperature

MAXIMUM ANNUAL HOURLY ZONE TEMPERATURE (°C)									
		Min.	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600FF	Base Case	64.90	75.10	73.40	y	65.49	y	66.03	y
650FF	Night Ventilation	41.81	46.40	45.50	y	42.39	y	43.65	y
900FF	High Mass Base Case	63.24	73.50	71.70	y	63.67	y	64.31	y
950FF	High Mass Base Case	35.54	38.50	37.10	y	35.67	y	36.90	y
960FF	Sunspace	48.88	55.34	51.60	y	55.54	y	52.93	y
MINIMUM ANNUAL HOURLY ZONE TEMPERATURE (°C)									
		Min.	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600FF	Base Case	-18.80	-15.57	-17.70	y	-18.60	y	-17.51	y
650FF	Night Ventilation	-6.38	-1.65	-2.00	y	-4.50	y	-2.39	y
900FF	High Mass Base Case	-23.00	-21.10	-21.00	y	-22.91	y	-23.08	y
950FF	High Mass Base Case	-20.20	-17.80	-17.80	y	-19.97	y	-20.34	y
960FF	Sunspace	-2.82	5.80	6.00	y	0.48	y	2.44	y
AVERAGE ANNUAL HOURLY ZONE TEMPERATURE (°C)									
		Min.	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600FF	Base Case	24.22	27.40			24.43	y	26.19	y
650FF	Night Ventilation	24.45	27.50			24.45	y	26.40	y
900FF	High Mass Base Case	17.99	20.80			17.81	y	18.87	y
950FF	High Mass Base Case	14.00	15.30			13.88	y	14.62	y
960FF	Sunspace	26.43	30.50			29.92	y	29.51	y

As some results of the ASHRAE Standard 140-2007 test cases for DOE2.1E-RevWindow were not supplied, the sensitivities were analyzed only for case 600 series (low-mass cases) and case 900 series (high-mass cases). These results were summarized in Table 5.12 and Table 5.13, and also showed in a set of charts presented in the Appendix. In the following tables, MIN and MAX mean the minimum and the maximum results of all the programs being tested, except DOE2.1E-RevWindow, DeST and EnergyPlus. The label of 'y' means the result of the program was within the range of the minimum and maximum, and the label of 'n' means the opposite. The sensitivities illustrate that the results of all three programs change in the same direction when an influencing factor was added, for example, south shading, window orientation, thermostat setback and ventilation. But the sensitivities of some cases in EnergyPlus and DeST were not within the range of spread of results from other programs.

Table 5.12 the Sensitivities of Low-mass Basic Cases

ANNUAL HEATING (MWH)								
CASES	**Min.**	**Max.**	**DOE2.1E**		**ENERGYPLUS**		**DEST**	
610-600	0.021	0.098	0.048	y	0.034	y	0.035	y
620-600	0.138	0.682	0.150	y	0.148	y	0.284	y
630-620	0.267	0.551	0.364	y	0.302	y	0.278	y
640-600	-2.166	-1.545	-1.999	y	-1.697	y	-1.880	y
ANNUAL COOLING (MWH)								
CASES	**Min.**	**Max.**	**DOE2.1E**		**ENERGYPLUS**		**DEST**	
610-600	-2.309	-1.272	-2.180	y	-2.030	y	-1.051	n
620-600	-2.966	-2.341	-2.798	y	-2.623	y	-2.077	n
630-620	-2.138	-0.983	-2.021	y	-1.431	y	-0.968	n
640-600	-0.351	-0.153	-0.341	y	-0.296	y	-0.164	y
650-600	-1.419	-1.244	-1.376	y	-1.468	n	-1.299	y
PEAK HEATING (kW)								
CASES	**Min.**	**Max.**	**DOE2.1E**		**ENERGYPLUS**		**DEST**	
610-600	-0.014	0.001	-0.012	y	-0.012	y	-0.031	n
620-600	-0.008	0.240	0.018	y	-0.006	y	-0.023	n
630-620	-0.026	0.003	-0.023	y	-0.024	y	0.001	y
640-600	1.546	2.600	1.889	y	2.533	y	2.006	y
PEAK COOLING (kW)								
CASES	**MIN**	**Min.**	**Max.**		**ENERGYPLUS**		**DEST**	
610-600	-0.811	-0.116	-0.483	y	-0.404	y	-0.187	y
620-600	-2.560	-1.716	-2.286	y	-2.673	n	-2.332	y
630-620	-0.878	-0.371	-0.845	y	-0.559	y	-0.548	y
640-600	-0.083	-0.033	-0.062	y	-0.065	y	-0.035	y
650-600	-0.163	-0.085	-0.122	y	-0.199	n	-0.178	n

Table 5.13 the Sensitivities of High-mass Basic Cases

ANNUAL HEATING (MWH)								
CASES	Min.	Max.	DOE2.1E		ENERGYPLUS		DEST	
900-600	-3.837	-3.126	-3.693	y	-3.200	y	-3.113	n
910-900	0.179	0.442	0.258	y	0.263	y	0.372	y
920-900	1.998	2.505	2.011	y	1.924	n	2.131	y
930-920	0.595	1.080	0.937	y	0.697	y	0.460	n
940-900	-0.718	-0.377	-0.463	y	-0.436	y	-0.624	y
960-900	0.775	1.718	0.915	y	1.159	y	0.941	y
ANNUAL COOLING (MWH)								
CASES	Min.	Max.	DOE2.1E		ENERGYPLUS		DEST	
900-600	-4.779	-3.832	-4.664	y	-4.323	y	-3.628	n
910-900	-1.786	-0.832	-1.652	y	-1.333	y	-1.094	y
920-900	-0.356	0.018	-0.221	y	0.000	y	0.106	n
930-920	-1.425	-0.682	-1.346	y	-0.938	y	-0.705	y
940-900	-0.174	-0.053	-0.118	y	-0.077	y	-0.033	n
950-900	-2.826	-1.745	-2.641	y	-2.111	y	-1.841	y
960-900	-2.774	-1.644	-2.535	y	-1.951	y	-1.759	y
PEAK HEATING (kW)								
CASES	Min.	Max.	DOE2.1E		ENERGYPLUS		DEST	
900-600	-0.587	-0.414	-0.519	y	-0.592	n	-0.385	n
910-900	-0.587	0.019	0.008	y	-0.001	y	0.012	y
920-900	0.003	0.458	0.260	y	0.313	y	0.176	y
930-920	0.026	0.047	0.028	y	0.021	n	0.025	n
940-900	0.026	2.631	2.074	y	1.645	y	2.123	y
960-900	-1.018	-0.440	-0.645	y	-0.449	y	-0.999	y
PEAK COOLING (kW)								
CASES	Min.	Max.	DOE2.1E		ENERGYPLUS		DEST	
900-600	-3.355	-2.810	-3.187	y	-3.358	n	-2.682	n
910-900	-1.122	-0.310	-1.075	y	-0.680	y	-0.626	y
920-900	-0.517	0.048	-0.436	y	-0.485	y	-0.626	n
930-920	-0.736	-0.387	-0.704	y	-0.503	y	-0.316	n
950-900	-0.890	-0.534	-0.861	y	-0.869	y	-0.883	y
960-900	-2.510	-1.935	-2.730	n	-2.107	y	-2.385	y

6 In-depth analysis between EnergyPlus and DeST

6.1 Introduction

The results of the ASHRAE Standard 140-2007 tests showed that EnergyPlus had lower heating loads and higher cooling loads compared with DeST, even though both fell within the range of results of other programs. Figure 6.1 gives the annual heating and cooling results of two cases from the ASHRAE Standard 140-2007 tests, where EnergyPlus had 11% lower annual heating loads and 5% higher annual cooling loads compared with DeST, for case 195. Case 195 was the simplest test case as it has no windows, no internal gain and no infiltration. In case 600, the differences between EnergyPlus and DeST were much larger, 13% annual heating and 18% annual cooling.

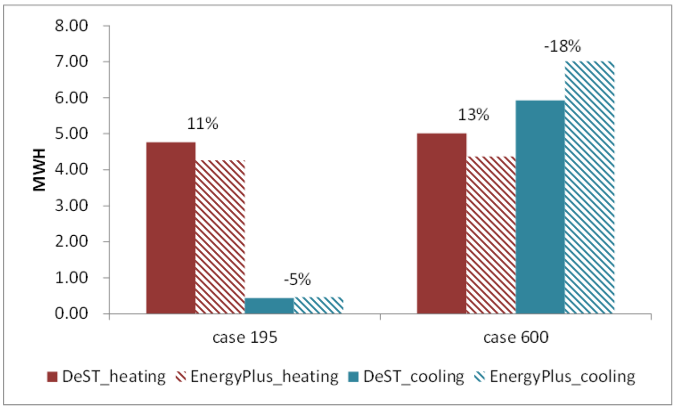

Figure 6.1 Load Comparisons between DeST and EnergyPlus

The ASHRAE Standard 140-2007 tests were not enough for an in-depth comparison between EnergyPlus and DeST. Although the standard included a large number of test cases (the sensitivities of which were analyzed and discussed) some key influencing factors resulting in the discrepancies of results were not identified. This part was carried out to help identify and understand the differences of load calculating algorithms and their effects on load results between EnergyPlus and DeST. The following tests modified some inputs, mainly default values or algorithms by the program, based on the ASHRAE Standard 140-2007.

6.2 Test suite

A series of cases were designed as shown in Table 5.12. According to the ASHRAE Standard 140-2007 section 5.2.1.9, the algorithms for surface convection coefficients can be provided by the program itself if the program being tested calculates exterior surface radiation and convection automatically. For ASHRAE Standard 140-2007 tests, the inside surface convection algorithm was set to “TARP” and the outside convection algorithm was set to “DOE-2” in EnergyPlus. The hourly values had a large discrepancy compared with the DeST default values as shown in Figure 3.1 and Figure 3.2. In this condition, inputs to the energy model of EnergyPlus and DeST were not equivalent. In order to estimate the effect of surface convection coefficients on load simulations, in case C1 to C9, exterior and interior surface convection coefficients in EnergyPlus were specified as the same values as the DeST defaults. In case C10 they were provided by each program automatically.

A brief description of case C1 to C10 is listed in Table 6.1. Case C3 was exactly the same as Case 195 in ASHRAE Standard 140-2007 tests, except for in EnergyPlus where the surface convection coefficients were set to the same default values as DeST. Based on case C3, other cases were designed by adding influencing factors one-by-one. Case C2 was exactly the same as case C3 except for the single-room building model was suspended in the outdoor air (the boundary of the floor is the air, not the ground), and the solar/visible absorptance and infrared emissivity of the exterior and interior surfaces were specified as zero, i.e. only convective heat transfer was considered. Case C1 was the simplest test. It was the same as Case 195 but the outdoor air temperature was kept at 10°C. As the thermal boundary conditions were constant, the heating or cooling loads for Case C1 could be calculated analytically. Case C4 changed the solar/visible absorptance of the exterior and interior surfaces to 0.6. Otherwise it was the same as Case C3. Case C5 changed the infrared emissivity of the exterior and interior surfaces to 0.9. Case C6 was based on Case C5 except internal heat gains were added (200 W continuous, 100% sensible, 60% radiative, 40% convective). Case C7 added infiltration (0.5 air changes per hour). Case C8 modified the thermostat control strategy (heating set-point remained at 20°C, the cooling set-point was changed to 27°C). Case C9 added south windows (the same as case 600). Contrasting case C9 with case 600 in the ASHRAE Standard 140-2007 tests, we could find that they were the same except for surface convection coefficients in EnergyPlus were set to the DeST default values. Case C10 was exactly same as case 600.

Table 6.1 Test Cases for In-depth Analysis

Case	**Description**
C1	case 195 + suspended in the outdoor air + solar/visible absorptance and infrared emissivity equal zero + the outdoor air temperature always was 10°C
C2	C1+the outdoor air temperature was exactly same as case 195
C3	Case 195 (Surface convection coefficients in EnergyPlus were set as DeST defaults)
C4	C3 + solar absorptance equals 0.6
C5	C4 + infrared emissivity equals 0.9
C6	C5 + internal heat gains
C7	C6 + infiltration
C8	C7 + the thermostat control strategy same as Case 600
C9	C8 + South window (Case 600, Surface convection coefficients in EnergyPlus were set as DeST defaults)
C10	case 600 exactly same as ASHRAE Standard 140-2007

6.3 Results and discussion

As it was in a steady thermal state, the hourly load for Case C1 could be calculated analytically. Table 6.2 gives the results for the UA calculations. All envelopes had a thermal conductance of 49.48 W/K. The indoor-outdoor air temperature difference was 10 °C, so the hourly heating load was always 0.495 kW. The simulation results of DeST and EnergyPlus are very close, shown in Figure 6.2, showing that there was no difference between DeST and EnergyPlus in this condition.

Table 6.2 the UA Calculation of Case C1

	h_out W/(m²·K)	R (m²·K) /W	h_in W/(m²·K)	A m²	U W/(m²·K)	UA W/ K
Light wall	23.3	1.789	3.5	75.6	0.47	35.70
Light floor	0	25.254	4	48	0.04	1.88
Light roof	23.3	2.993	1	48	0.25	11.89
Total						49.48

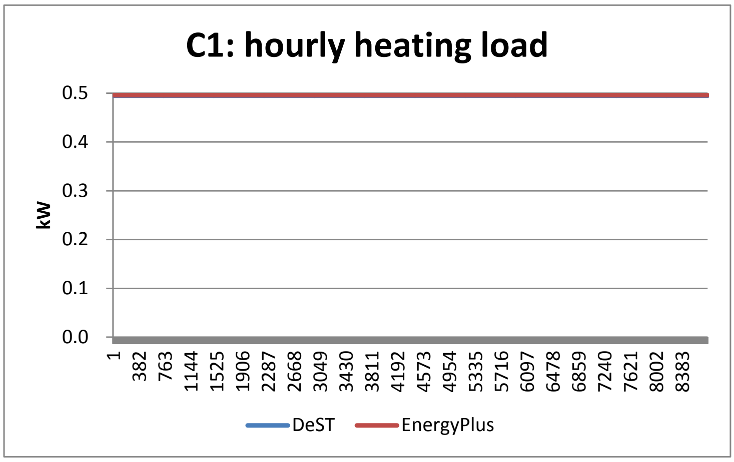

Figure 6.2 Hourly Heating Load of C1

C2 introduced changing hourly outdoor air temperatures. The simulation results are shown in Figure 5.8, which indicates almost no difference between DeST and EnergyPlus.

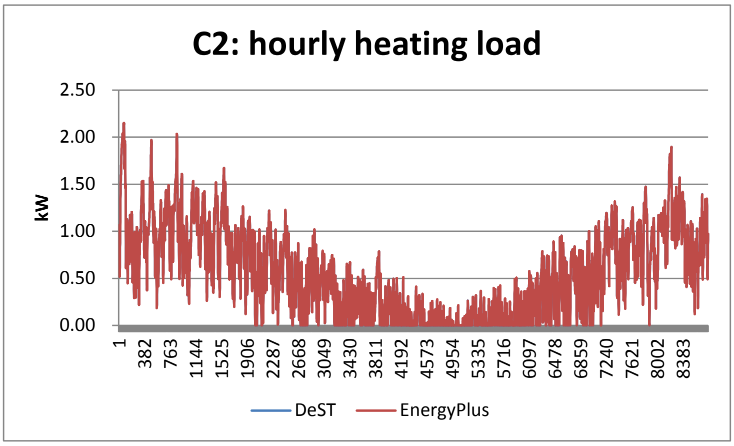

Figure 6.3 Hourly Heating Load of C2

Table 6.3 illustrates the summary of annual heating and cooling loads for the ten cases. Figure 6.4 compares the annual heating load difference between EnergyPlus and DeST. The results from Case C1 to Case C9 were almost the same, but a large discrepancy occurs in case C10. Comparing the simulation results from C1 to C9 (Figure 6.5), we see that a big discrepancy in the annual cooling loads happens after south windows were added to the simulations. Incident angle-dependent optical properties for the double-pane window in ASHRAE Standard 140-2007 were discussed in 3.2.7. In EnergyPlus and DeST the transmittance at different angles of incidence is automatically calculated. There was no big discrepancy in the window models themselves. However, we can see that the annual solar radiation on the south wall in DeST is about 5.1% smaller than in EnergyPlus, and the annual window transmitted solar radiation was

7.0% smaller (shown in Figure 6.6). The main reason for the difference in solar radiation was the time-point used for the solar position calculation and sky diffuse solar radiation model. DeST uses the beginning of the hour while EnergyPlus uses the end of every time step, which was 15 minutes by default.

Comparing the results of Case C9 and Case C10, we can see that another main influencing factor were the surface convection coefficients. For Case C10 in EnergyPlus, the Inside Surface Convection Algorithm was set to TARP and the Outside Convection Algorithm was set to DOE-2. DeST used constant values for both. As both exterior and interior surface convection coefficients were smaller in EnergyPlus than the DeST default values, EnergyPlus resulted in lower annual heating loads and higher annual cooling loads.

Table 6.3 Annual Heating and Cooling Loads

Case	**Annual heating MWh**		**Annual cooling MWh**	
	DeST	**EnergyPlus**	**DeST**	**EnergyPlus**
C1	4.333	4.341	0.000	0.000
C2	4.844	4.853	0.383	0.385
C3	4.758	4.756	0.434	0.437
C4	4.126	4.095	1.042	1.038
C5	4.689	4.641	0.866	0.821
C6	3.544	3.493	1.355	1.309
C7	5.248	5.327	1.442	1.394
C8	5.025	5.089	0.276	0.227
C9	5.007	4.989	5.924	6.351
C10	5.007	4.364	5.924	7.006

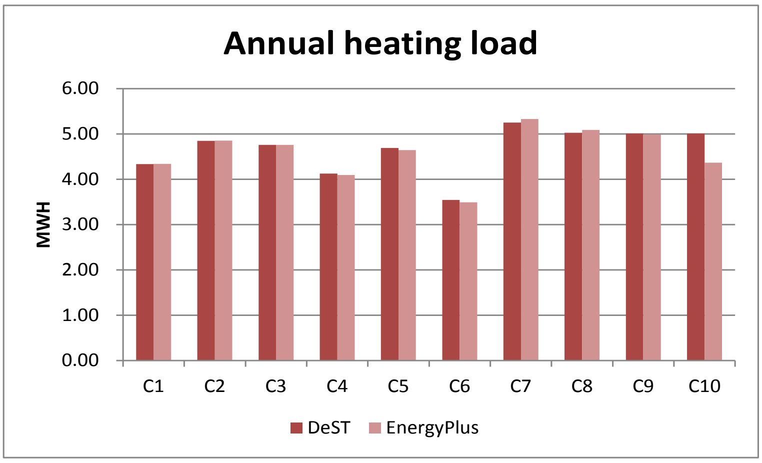

Figure 6.4 Comparisons of Annual Heating Loads between DeST and EnergyPlus

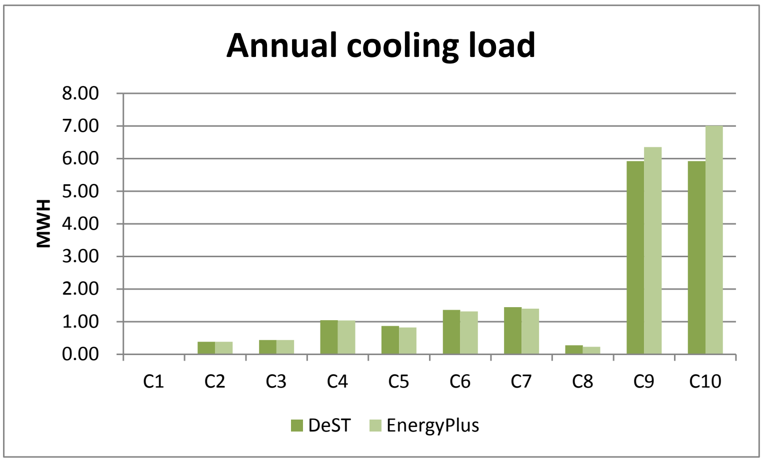

Figure 6.5 Comparisons of Annual Cooling Loads between DeST and EnergyPlus

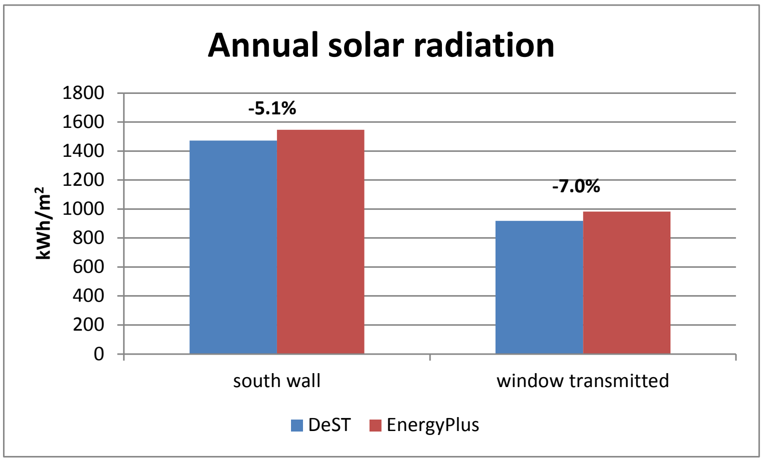

Figure 6.6 Comparisons of Annual Solar Radiation between DeST and EnergyPlus

7 Special tests

7.1 Introduction

In Section 5, the basic capabilities of the three BEMPs to perform load simulations were tested using a series of cases from ASHRAE Standard 140-2007. The results of DOE-2.1E, DeST and EnergyPlus were mostly within the range of other benchmarked programs. This demonstrated that the three BEMPs were good enough for basic load calculations. However, these test cases were too simple to account for other important factors that influence the results of building thermal load simulations, such as adjacent zone heat transfer, variable occupancy, variable thermostat control strategy, etc. On the other hand, DOE-2.1E has no strict heat balance model compared with DeST and EnergyPlus. This may lead to inaccuracies in some special cases. Thus, special tests were designed to identify these limitations and their effect on simulation results.

The special tests included two parts. The first part was used to test the zone heat balance calculations under two extreme cases. In the second part, double-room cases were tested. This was to see how the heat flux of common interior walls between adjacent spaces was accounted for, and how the results were affected by daytime (office schedule case) and nighttime (bedroom schedule case) occupancies, and part-time operation of the air-conditioning.

Table 7.1 Special Test Cases

	Case	Description
Part 1	EC1	Heat balance test for single-room case
	EC2	Heat balance test for double-room case
Part 2	SC1	Basic test
	SC2	One room using an office occupancy profile, the other room is empty and unconditioned
	SC3	One room using a bedroom occupancy profile, the other room is empty and unconditioned

7.2 Part 1: Extreme cases

7.2.1 EC1: heat balance test for single room

The purpose of this case was to test the ability of the three BEMPs to perform a single-zone heat balance with part-time air-conditioning. Inputs to the energy model for the three BEMPs were specified to be as equivalent as possible.

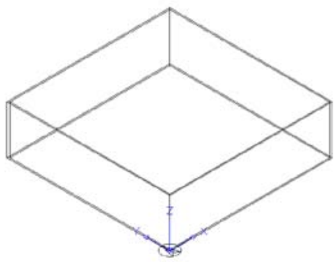

Figure 7.1 the Geometry of Case EC1

The building was a rectangular zone with dimensions 10 m wide × 10 m long × 3 m high, as show in Figure 7.1. The construction of the exterior walls, roof and floor, and the weather data were the same as Case 600 in ASHRAE Standard 140-2007. As the three programs have different was of calculating solar radiation (see section 3.2.3), all solar/visible absorptance coefficients were specified as zero, thus eliminating solar radiation from the load calculations. The thermal emissivity of both the exterior and interior surfaces was specified to be 0.9. Surface convection coefficients for both the exterior and interior surfaces were specified to use the default values or algorithms in DOE-2.1E and DeST. EnergyPlus used the same values as the DeST defaults. The room had no internal gains or infiltration.

Figure 7.2 shows the room being conditioned every other hour, that is, the first hour was conditioned, the second hour was unconditioned, the third hour was conditioned, etc. When the room was conditioned, the room temperature was kept at 20°C. The three BEMPs were used to calculate the hourly room temperature.

Figure 7.3 shows the room being conditioned only during the night (8:00 p.m. to 8:00 a.m.) and unconditioned during the day. When the room was conditioned, the room temperature was also kept at 20°C.

Both Figure 7.2 and Figure 7.3 show a good match in room temperature results and the difference among the three programs for calculated annual heating loads (no cooling loads) was less than 7%. Thus, it can be concluded that all three programs perform a single zone heat balance very well.

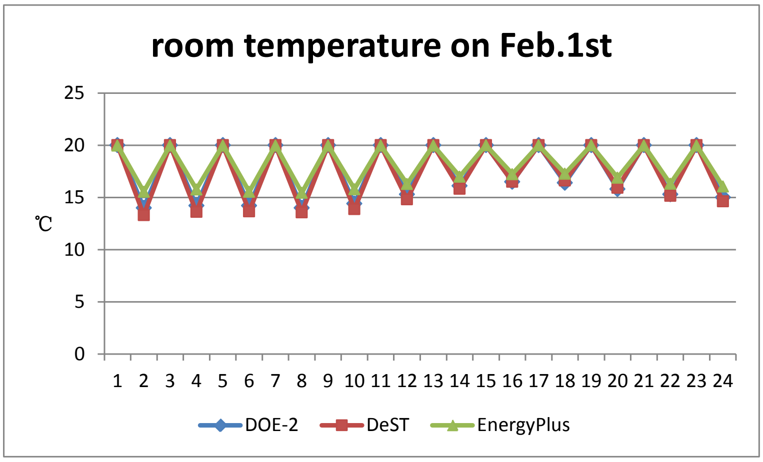

Figure 7.2 the Simulated Room Temperature Conditioned Every Other Hour

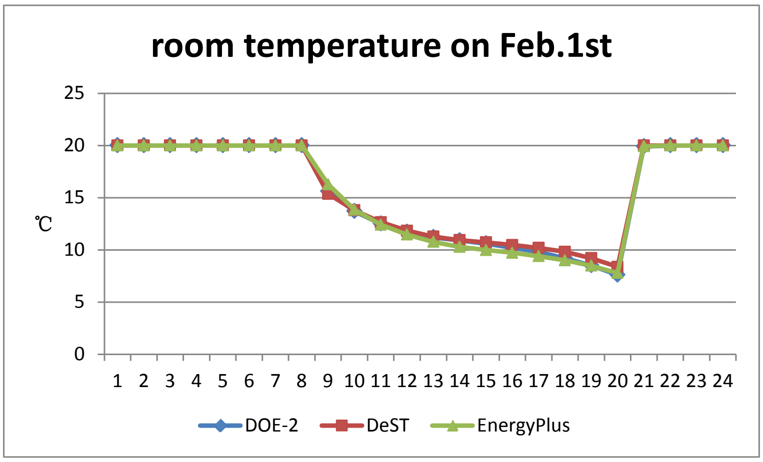

Figure 7.3 the Simulated Room Temperature Conditioned only at Night

7.2.2 EC2: heat balance test for double room

The purpose of this case was to test the limitations of the three programs in performing the heat balance of multiple zones. Inputs to the energy models for the three BEMPs were specified to be as equivalent as possible.

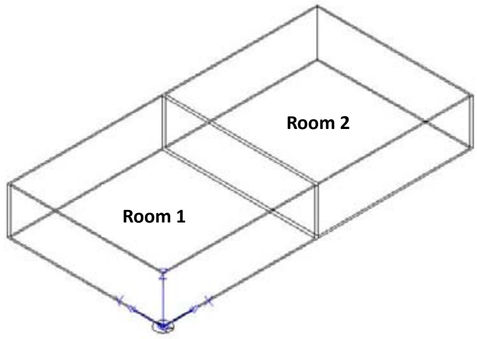

Figure 7.4 Geometry of Case EC2

The building was a rectangle split into two zones, both with dimensions 10 m wide × 10 m long × 3 m high (Figure 7.4). The construction of the exterior walls, roofs and floors were the same as in Case 600. The interior wall was the same as Case 960 in ASHRAE Standard 140-2007. All solar/visible absorptance and thermal emissivity coefficients were set equal to zero, so only convective heat transfer between the outdoor air and the two rooms was considered. Surface convection coefficients of both the exterior and the interior were specified to be the same values as the DeST defaults.

The outdoor air temperature and ground temperature were always set to 10°C. Each room had no internal gain or infiltration. The air temperature of Room 1 varied periodically (switching between 29.8°C and 16.2°C every hour) for the whole year (Figure 7.5). Room 2 was not air-conditioned and its temperature was simulated based on heat transfer between the two rooms (Figure 7.6). The results indicate that the room temperature from DeST and EnergyPlus was always constant. For DOE-2.1E the room temperature fluctuated between 13.8°C and 14.4°C. The reason was that DOE-2.1E used the air temperature from the previous time step to calculate the heat flux between Room 1 and Room 2. This is a limitation of DOE-2.1E in accounting for accurate heat transfer of multiple zones.

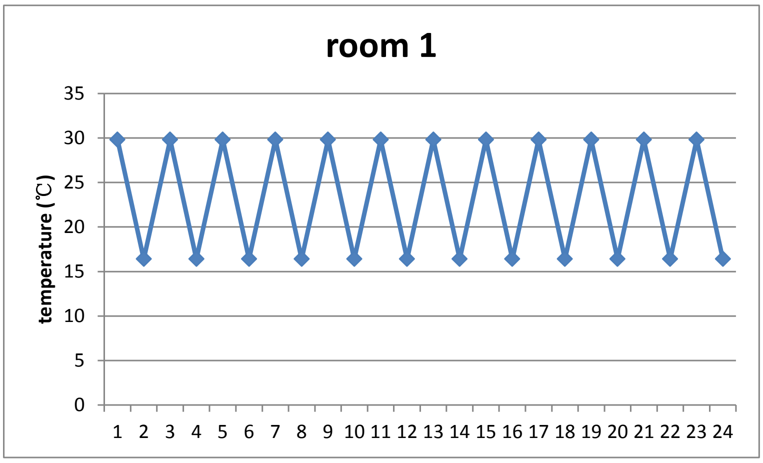

Figure 7.5 The Temperature Setting of Room 1

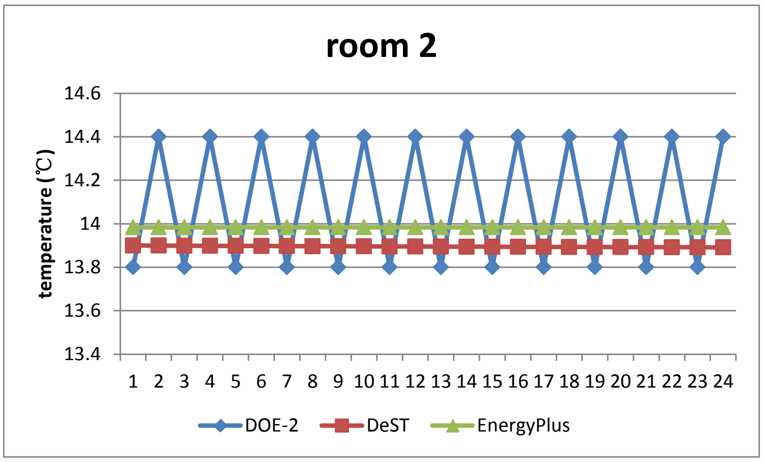

Figure 7.6 The Simulated Temperature Results of Room 2

7.3 Part 2: double-room cases under practical engineering conditions

The two extreme cases indicated that DOE-2.1E had limitations in accurately calculating the heat balance of multiple zones. Cases when adjacent zones have very different conditions, or a zone is air-conditioned part-time, or when an adjacent zone is not air-conditioned are very common in China, especially true in residential buildings. As extreme conditions mentioned in the section 7.2 rarely happens in the real world, this part was carried out to test and compare the ability of the three BEMPs in simulating building loads under practical engineering condition. Three cases were designed. The first is a basic test (SC1) where both rooms were conditioned at the same temperature. For the second (SC2) Room 1 was conditioned part-time using an office occupancy schedule and Room 2 was always unconditioned. For the third (SC3) Room 1 was conditioned part-time using a bedroom (night time) occupancy schedule and Room 2 was always unconditioned.

7.3.1 SC1-basic test

SC1 was a rectangle split into two zones, each with dimensions 10 m wide × 10 m long × 3 m high, with a window area of 12 m^2 on the south facade.

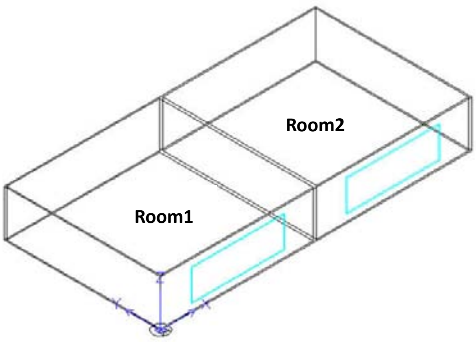

Figure 7.7 the Geometry of SC1

- Weather data

The same as the building thermal envelope and fabric tests in ASHRAE Standard 140-2007.

- Construction

The construction of the exterior walls, roofs and floors was the same as Case 600 and the interior wall was the same as Case 960 in ASHRAE Standard 140-2007.

- Window properties

The properties of the double-pane window are the same as in Case 600 in ASHRAE Standard 140-2007.

- Infiltration

The infiltration rate is always 0.5 ACH in DeST and EnergyPlus, but in DOE-2.1E the default method for infiltration calculation is related with the infiltration rate given by the user and the outdoor wind speed.

- Internal gains

The inputs for "people heat level" were equivalent for the three programs though their values were not the same. The value of people/lighting/equipment schedule was always one.

Table 7.2 Internal heat Gains

	DOE-2.1E	DeST	EnergyPlus
People	0.1 People/m^2 Sensible heat: 66 W Latent heat: 71W Default weighting factor	0.1 People/m^2 Sensible heat: 66 W Latent heat: 0.102kg/h Default distribution	0.1 People/m^2 Active level: 137 W Sensible heat fraction: 0.48 Same as DeST
Lighting	10 W/m^2 Default lighting type	10 W/m^2 Default distribution	10 W/m^2 Same as DeST
equipment	5 W/m^2 Default weighting factor	5 W/m^2 Default distribution	5 W/m^2 Same as DeST

- Mechanical systems

DeST and EnergyPlus use an ideal air conditioning (AC) system. DOE-2.1E uses a "two pipe fan coil" AC system. The AC system was always on and the heating and cooling set-points were both 21.1°C. The AC system in DOE-2.1E was a 100% convective air system, 100% efficient with no duct losses and adequate capacity. This was very close to an ideal AC system.

- Other

Solar/visible absorptance was 0.6, thermal emissivity was 0.9 and ground reflectance was 0.2 in the three programs. Surface convection coefficients, solar distribution and time steps per hour were set to the default values or algorithms in each program.

7.3.2 SC2 - Room 1 office schedule

SC2 was exactly the same as SC1, except for Room 1 used office schedules and Room 2 was empty and unconditioned (no internal heat gains).

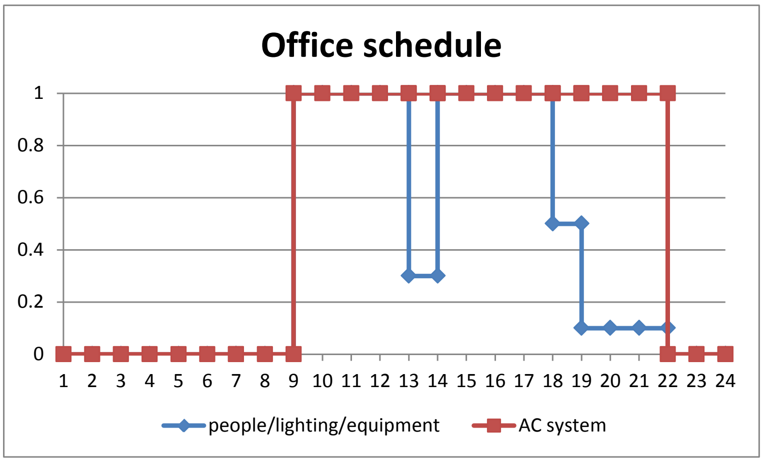

Figure 7.8 Office Schedule Used in SC2

7.3.3 SC3 – Room 1 bedroom schedule

SC3 was exactly the same as SC2 except for Room 1 used bedroom schedules.

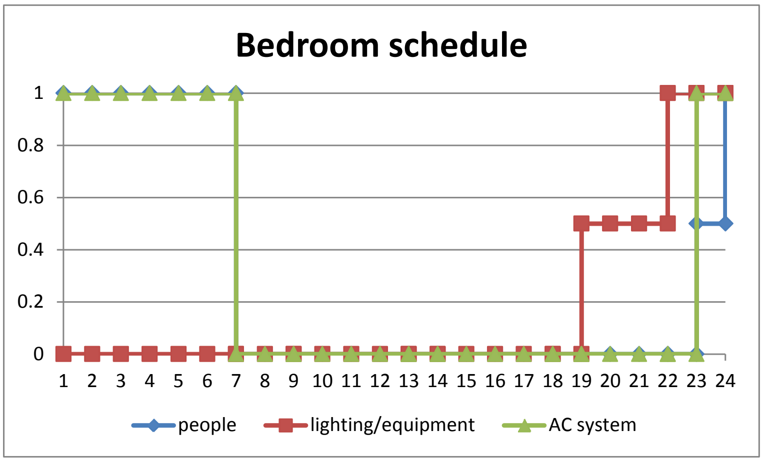

Figure 7.9 Bedroom Schedule Used in SC2

7.3.4 Comparison of results from the building load and system calculation in DOE-2.1E

As mentioned in section 3.1, the hourly heating or cooling loads were calculated by both the LOADS and SYSTEMS subprograms in DOE-2.1E. Their outputs had large discrepancies under most conditions. In VisualDOE 4.0, the building loads were calculated by the LOADS subprogram assuming that each space was maintained at 70℉ (21.1°C). The results of SC1 from LOADS and SYSTEMS were the same as shown in Figure 7.10 and Figure 7.11. This also indicated that the load results from SYSTEMS in this case can be considered as “ideal”.

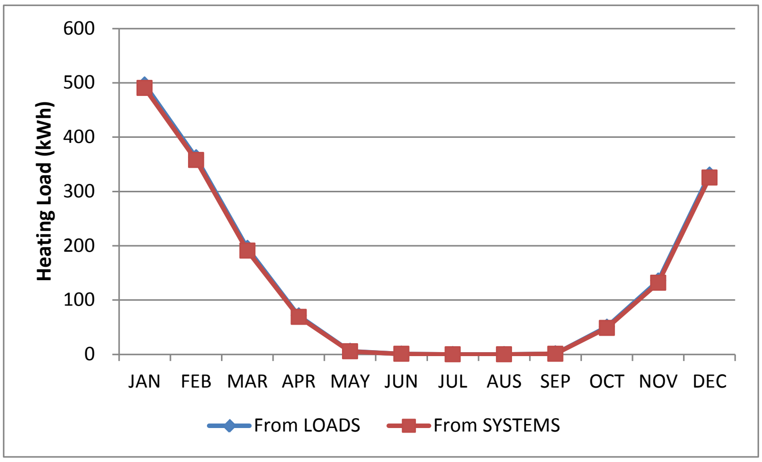

Figure 7.10 Comparison of LOADS and SYSTMES Heating Results of SC1

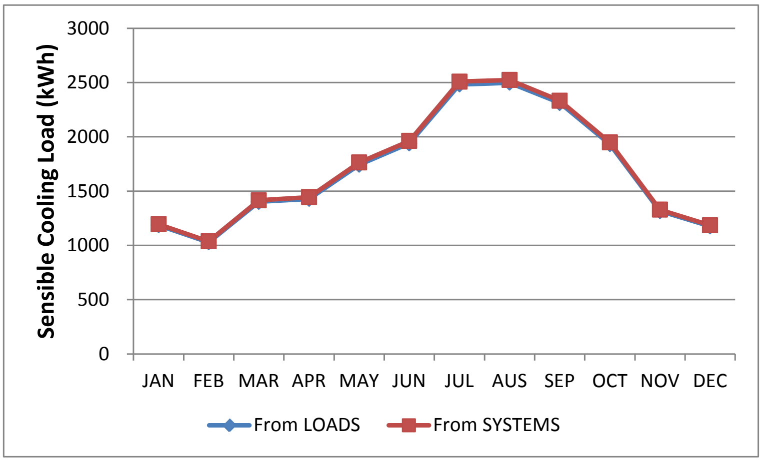

Figure 7.11 Comparison of LOADS and SYSTMES cooling results of SC1

In case SC2 and SC3, Room 1 used an office schedule and a bedroom schedule respectively. The AC system was operating part-time, which was different from the assumptions of continuous conditioning in the LOADS subprogram of DOE-2.1E. As a result, the heating or cooling load from DOE-2.1E's LOADS output was much larger than from SYSTEMS. So, when the AC system was operating part-time or the set-points of the zone temperature were not constant, the results from LOADS would not be realistic.

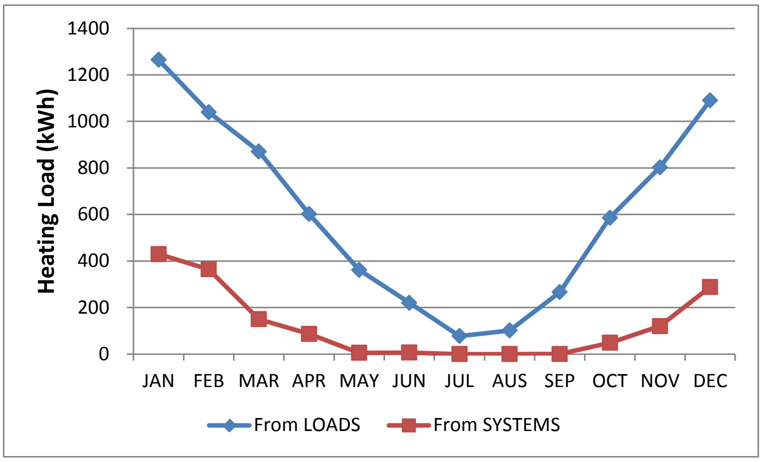

Figure 7.12 Comparison of DOE-2.1E LOADS and SYSTEMS Heating Results for SC2

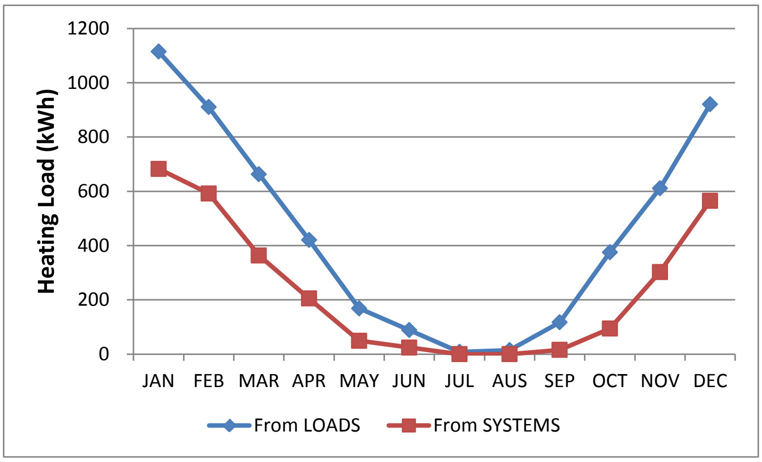

Figure 7.13 Comparison of DOE-2.1E LOADS and SYSTEMS Cooling Results for SC2

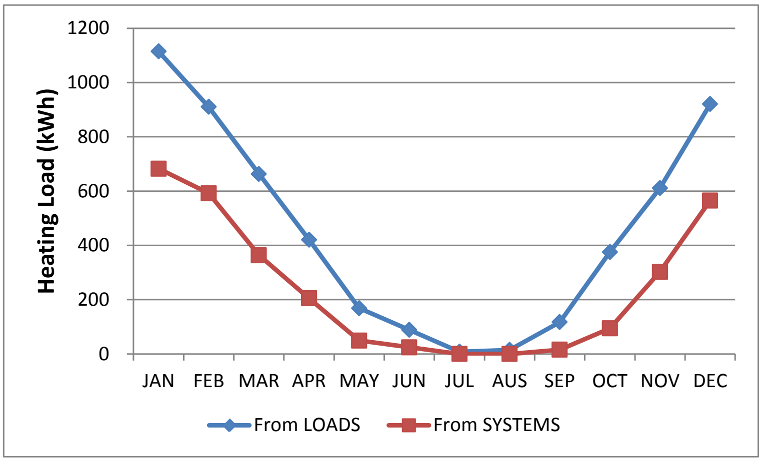

Figure 7.14 Comparison of DOE-2.1E LOADS and SYSTEMS Heating Results for SC3

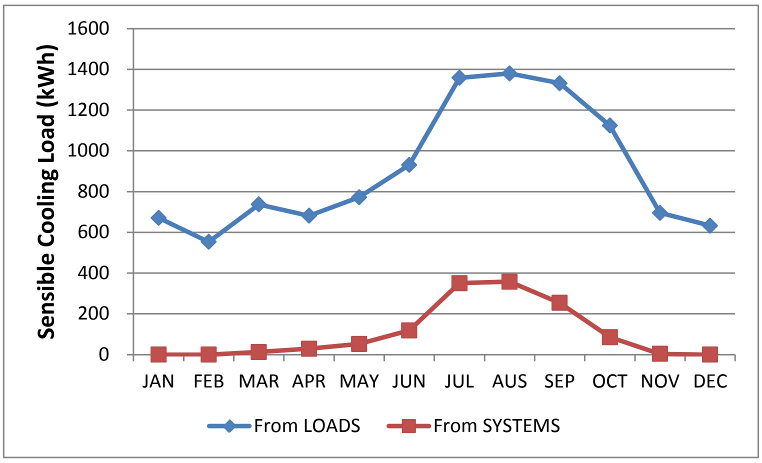

Figure 7.15 Comparison of DOE-2.1E LOADS and SYSTEMS Cooling Results for SC3

7.3.5 Comparison of results from SC1, SC2 and SC3

The monthly cooling loads for SC1 from the three BEMPs were very close (Figure 7.16), even though some default values or algorithms used by the BEMPs were not equivalent (e.g. the surface convection coefficients mentioned in 7.3.1). In SC1 there was no heat flux between the adjacent zones due to the two rooms being at the same temperature, so the results could be used as the benchmark. From the results of SC2 and SC3, we could see that the monthly cooling loads from EnergyPlus and DeST were always similar but the cooling loads from DOE-2.1E deviated from EnergyPlus and DeST. In case SC2, the annual cooling load calculated by DOE-2.1E was 35% higher than DeST, and 18% higher than EnergyPlus. In case SC3, the annual cooling load from DOE-2.1E was 101% higher than DeST, and 69% higher than EnergyPlus. These results show that DOE-2.1E has limitations calculating accurately the heat balance of multiple zones with part-time operation of the AC system. This results in an over-estimation of the cooling loads, especially under the nighttime air-conditioning condition.

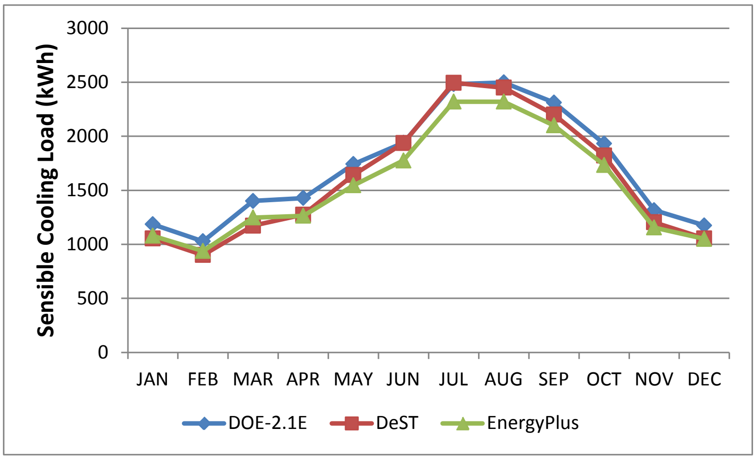

Figure 7.16 Monthly Cooling Load of SC1

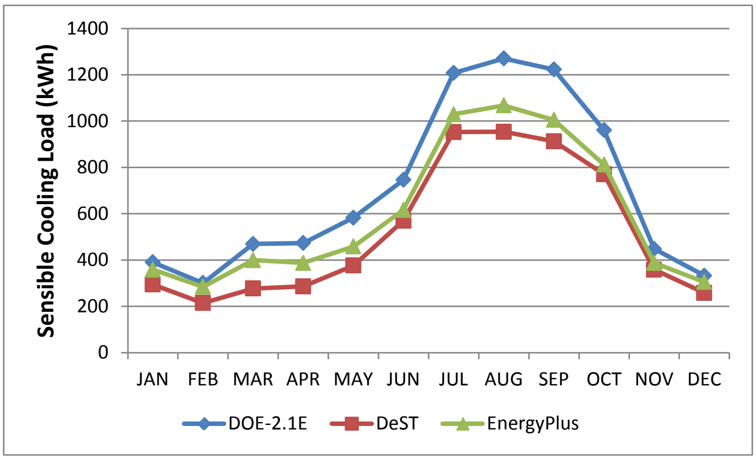

Figure 7.17 Monthly Cooling Load of SC2

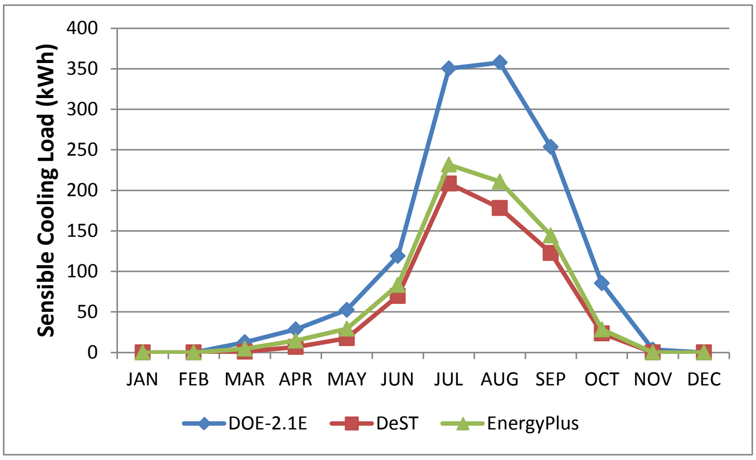

Figure 7.18 Monthly Cooling Load of SC3

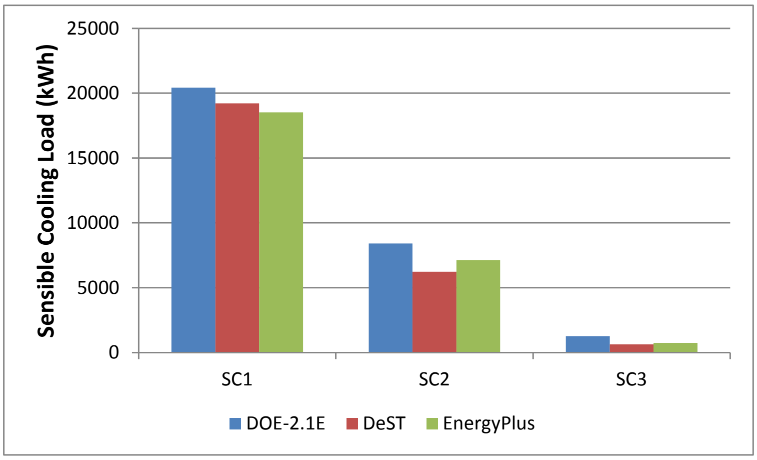

Figure 7.19 Annual Cooling Loads

From the monthly heating results (Figures 7.20 to 7.22) from the three BEMPs, DeST and EnergyPlus always had close simulation results of all three test cases. However, the results from DOE-2.1E were always smaller mainly due to the differences in default values and algorithms used for the infiltration rate and surface convection coefficients (see Section 7.3.1). For the three test cases, the annual heating loads from DOE-2.1E were about 20% lower than those from EnergyPlus or DeST, according to Figure 7.23.

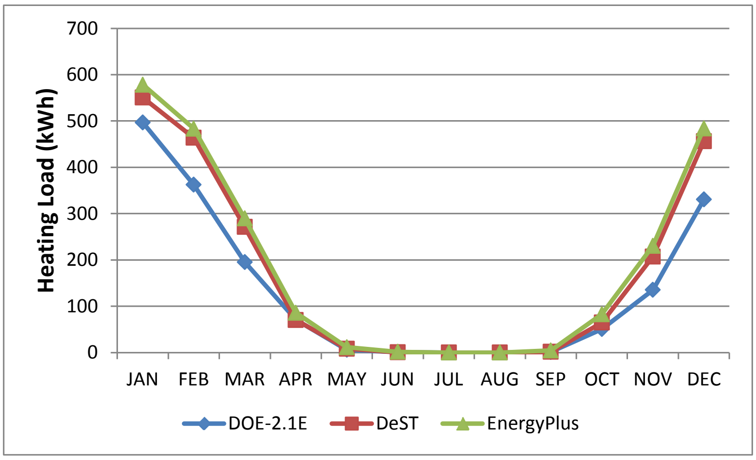

Figure 7.20 Monthly Heating Load of SC1

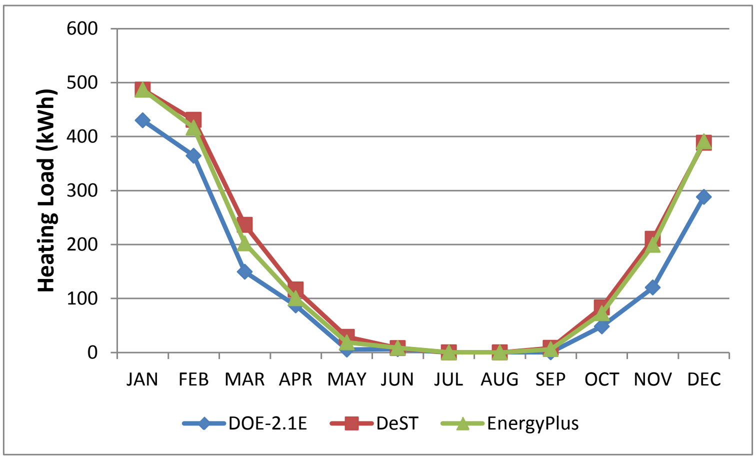

Figure 7.21 Monthly Heating Load of SC2

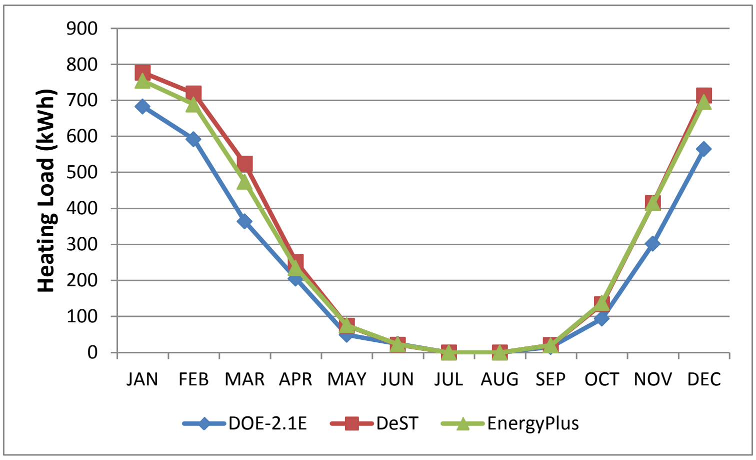

Figure 7.22 Monthly Heating Load of SC3

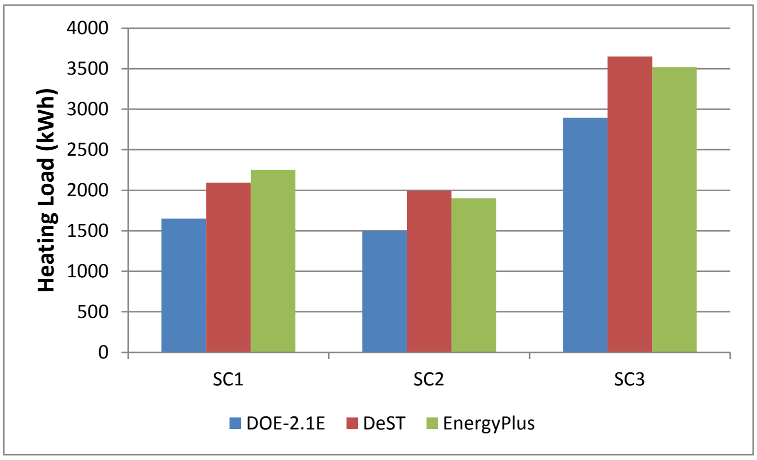

Figure 7.23 Annual Heating Load

8 Conclusion

In this study, the differences of algorithms and model inputs between the three BEMPs for load calculations have been summarized. This was the base for comparing the difference of simulation results and analyzing their influencing factors. It was concluded that DeST and EnergyPlus can perform an accurate zone heat balance while DOE-2 cannot. This may lead to inaccurate simulation results from DOE-2 for some applications, especially under extreme modeling conditions. For modeling assumptions and simplifications, EnergyPlus mostly allows users to specify certain values or algorithms, while DOE-2 and DeST mostly use constant values (usually assigned default values by the program itself). The differences between the three BEMPs mainly exist in the calculation methods for surface convection coefficients, long-wave radiation exchange, time-point for solar position calculation, sky diffuse solar radiation, solar distribution, and window models. User inputs and default inputs (or algorithms) were summarized in order to analyze their influence on load calculations.

Weather variables used in each program were summarized and compared, as weather data is an important factor when trying to achieve equivalent inputs for different BEMPs. The conversion of weather data between different programs can be achieved by the weather processor programs.

But on some special conditions discussed in section 4.2.1, the direct conversion by the weather processor programs may lead to nonequivalent inputs, which causes large discrepancies of simulation results. Some weather variables, especially solar data, require reformulation.

The building thermal envelope and fabric tests from ASHRAE Standard 140-2007 were adopted to test the basic capabilities of the three BEMPs to perform load simulations. This included solution algorithms, modeling assumptions and simplifications. The results of the three programs mostly fell within the range of spread of results of other programs, demonstrating that the three programs all had the basic capability to perform load simulations. The modeling assumptions in each program were reasonable. The sensitivity analysis illustrated that the results of the three programs changed in the same direction when an influencing factor was added. It was concluded from an in-depth analysis that load simulation results from DeST and EnergyPlus had little difference if the surface convection coefficients in EnergyPlus were specified as the same as in DeST. Other main influencing factors were the surface convection coefficients, the solar position calculation, and the sky diffuse solar models.

The special tests were carried out to identify the limitations of the three BEMPs. The simulation results proved that DOE-2 had limitations in accurately performing the heat balance of multiple zones with part-time operation of the AC system. This was due to its lack of a zone heat balance method in the load calculations. Double-room test cases considering the heat transfer between adjacent zones, realistic occupancy schedules and the part-time operation of air-conditioning were carried out to estimate the influences of these factors on the simulation results. The results showed that DeST and EnergyPlus had close monthly heating/cooling loads, while DOE-2 had much higher monthly cooling loads, especially in the night-time cooling cases.

In conclusion, all the three BEMPs have the basic capability for performing load simulations. Discrepancies in their results for simple cases such as the ASHRAE Standard 140-2007 tests are very small if the inputs to the different building energy models are equivalent. The annual heating/cooling load differences between EnergyPlus and DeST are less than 7.5% if the inputs for surface convection coefficients were the same. Compared with EnergyPlus and DeST, DOE-2.1E had limitations in accurately accounting for heat transfer of multiple zones and part-time operation of AC systems.

Acknowledgment

This work was supported by the U.S.-China Clean Energy Research Center for Building Energy Efficiency. It was co-sponsored by the Energy Foundation under the China Sustainable Energy Program. Thanks Joel Neymark of J. Neymark & Associates and Robert Henninger of Gard Analytics for the review.

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25. EnergyPro (2011). EnergyPro User's Manual, Version 5, July, 2011. EnergySoft, LLC, USA.
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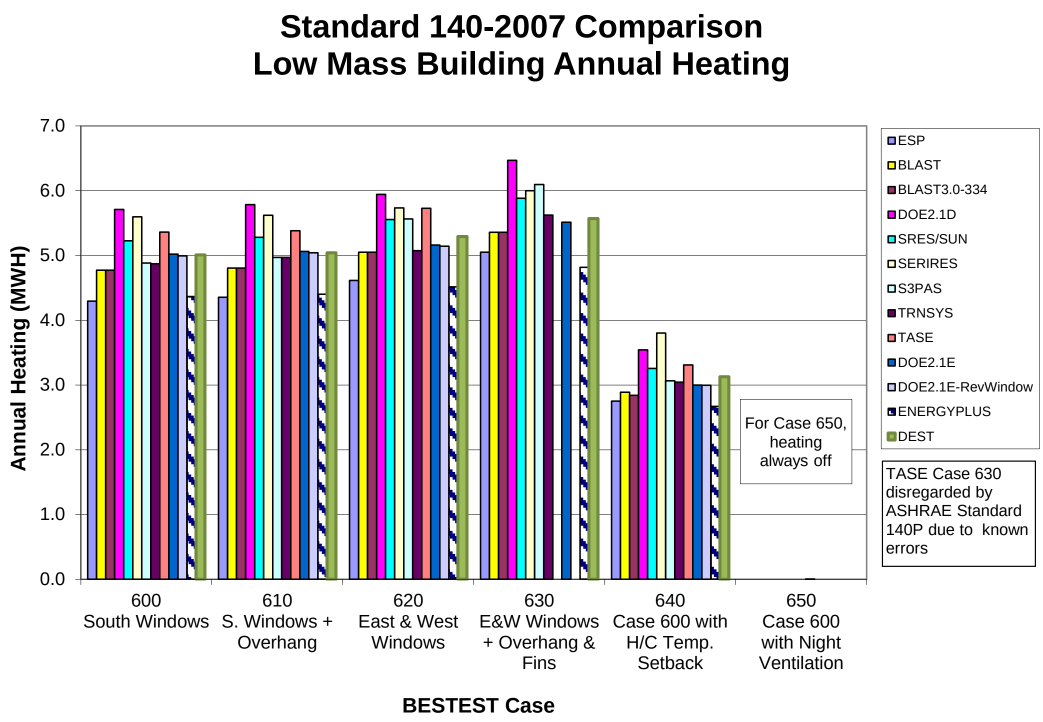
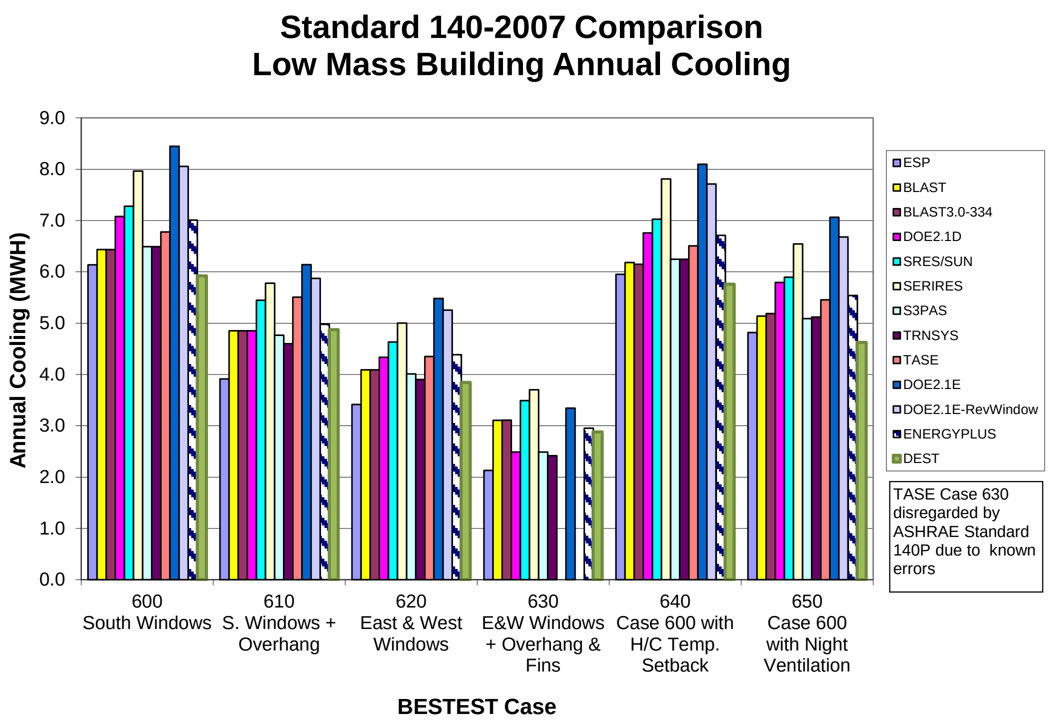
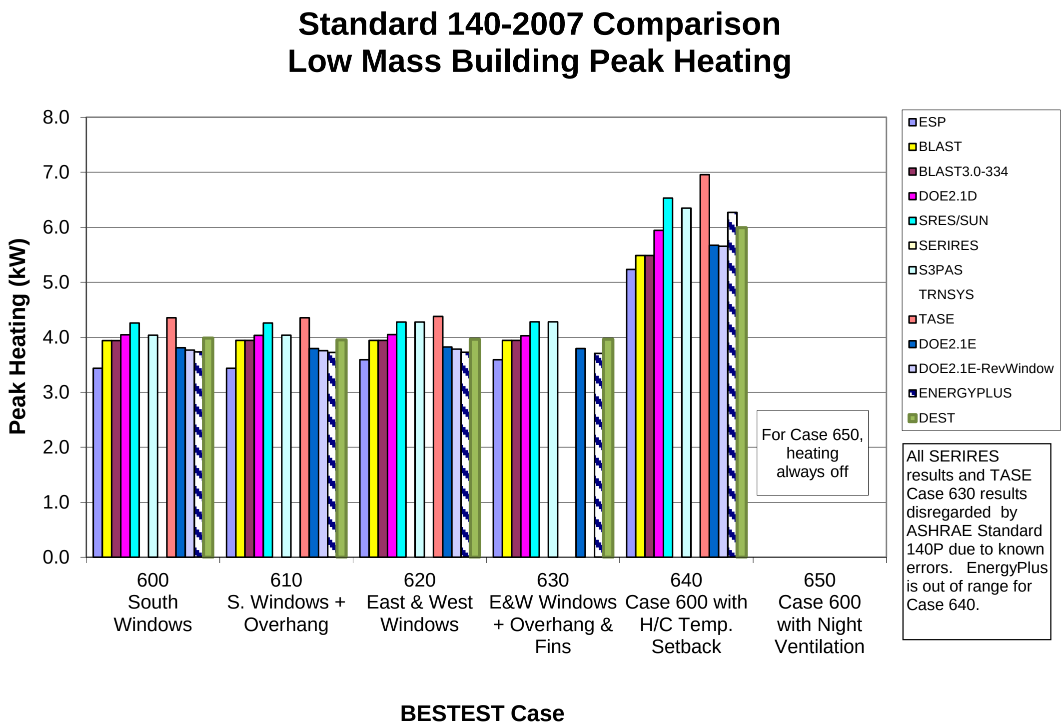
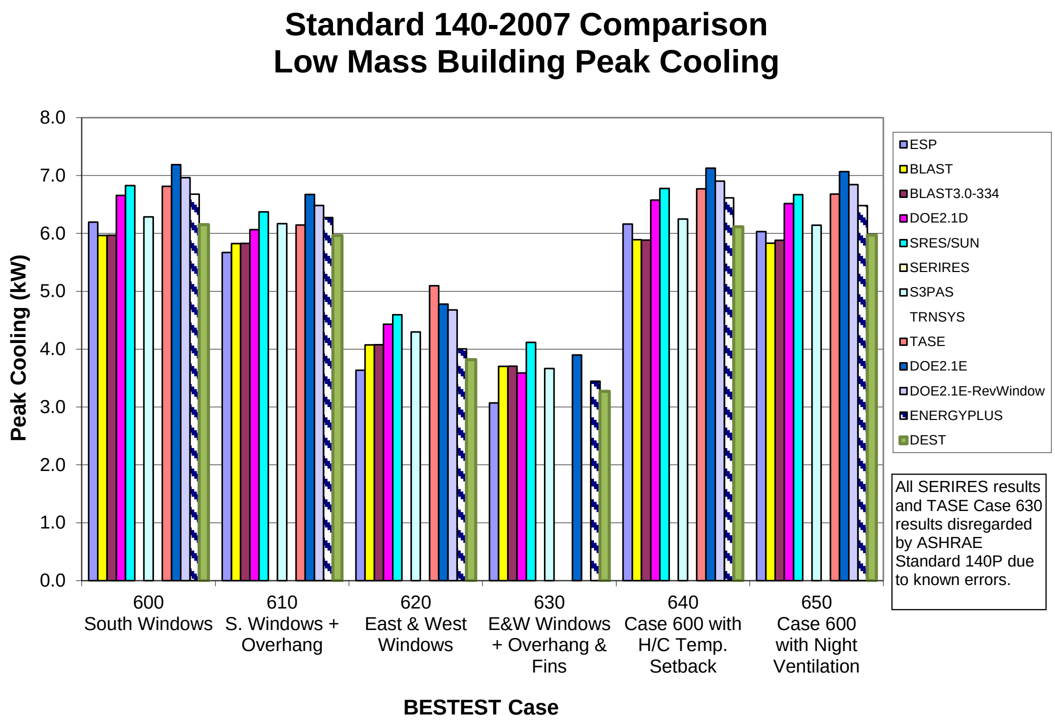
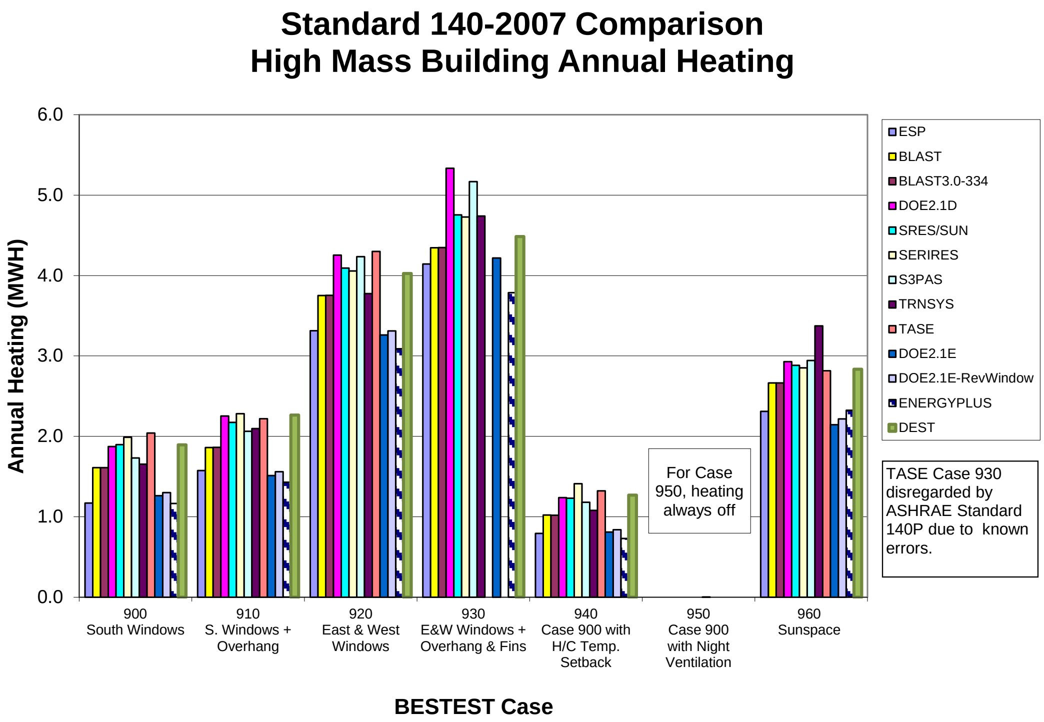
Appendix: ASHRAE 140-2007 test results



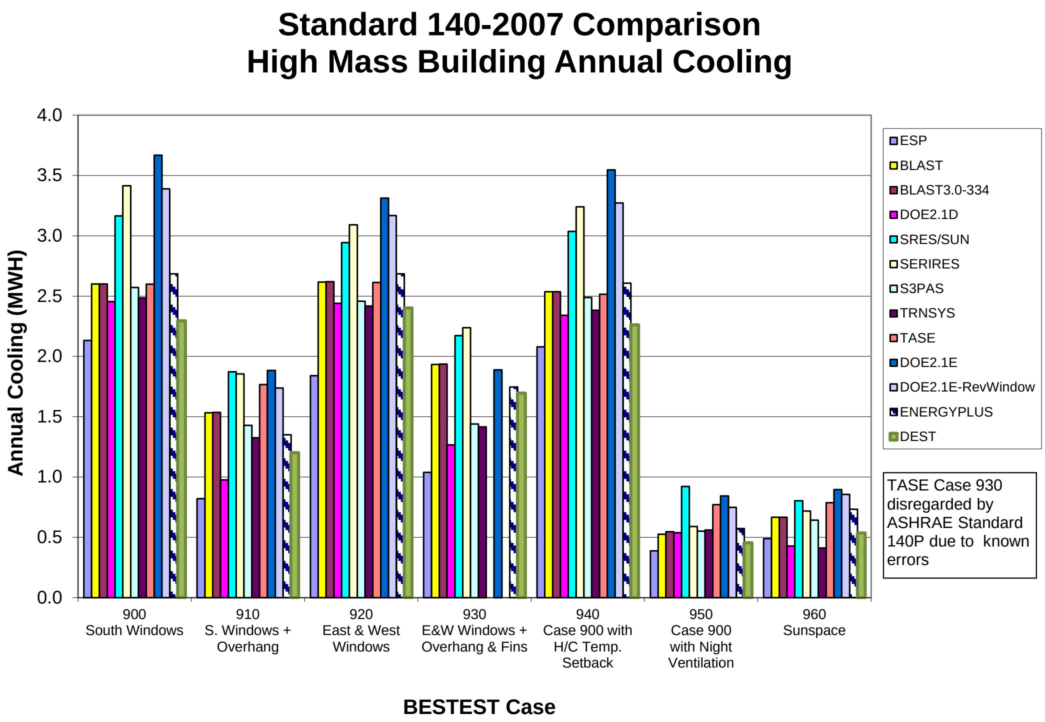



Standard 140-2007 Comparison
Low Mass Building Peak Heating
Peak Heating (kW)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
600 South Windows
610 S. Windows + Overhang
620 East & West Windows
630 E&W Windows + Overhang & Fins
640 Case 600 with H/C Temp. Setback
650 Case 600 with Night Ventilation
BESTEST Case
For Case 650, heating always off
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
All SERIRES results and TASE Case 630 results disregarded by ASHRAE Standard 140P due to known errors. EnergyPlus is out of range for Case 640.

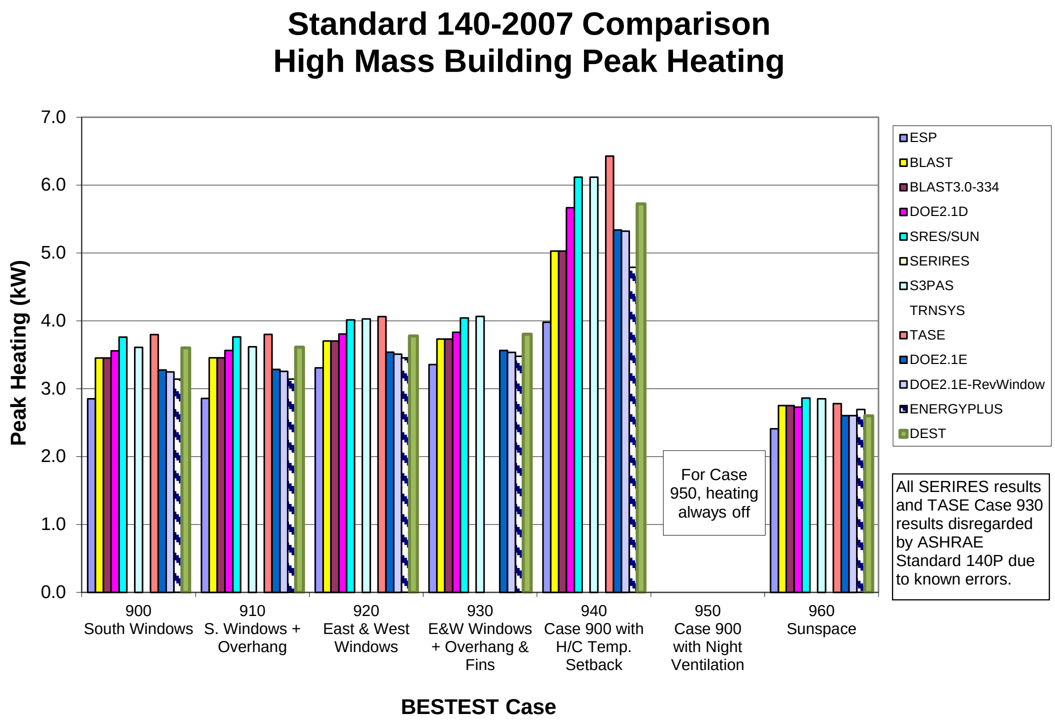

Standard 140-2007 Comparison
Low Mass Building Peak Cooling
Peak Cooling (kW)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
600 South Windows
610 S. Windows + Overhang
620 East & West Windows
630 E&W Windows + Overhang & Fins
640 Case 600 with H/C Temp. Setback
650 Case 600 with Night Ventilation
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
All SERIRES results and TASE Case 630 results disregarded by ASHRAE Standard 140P due to known errors.

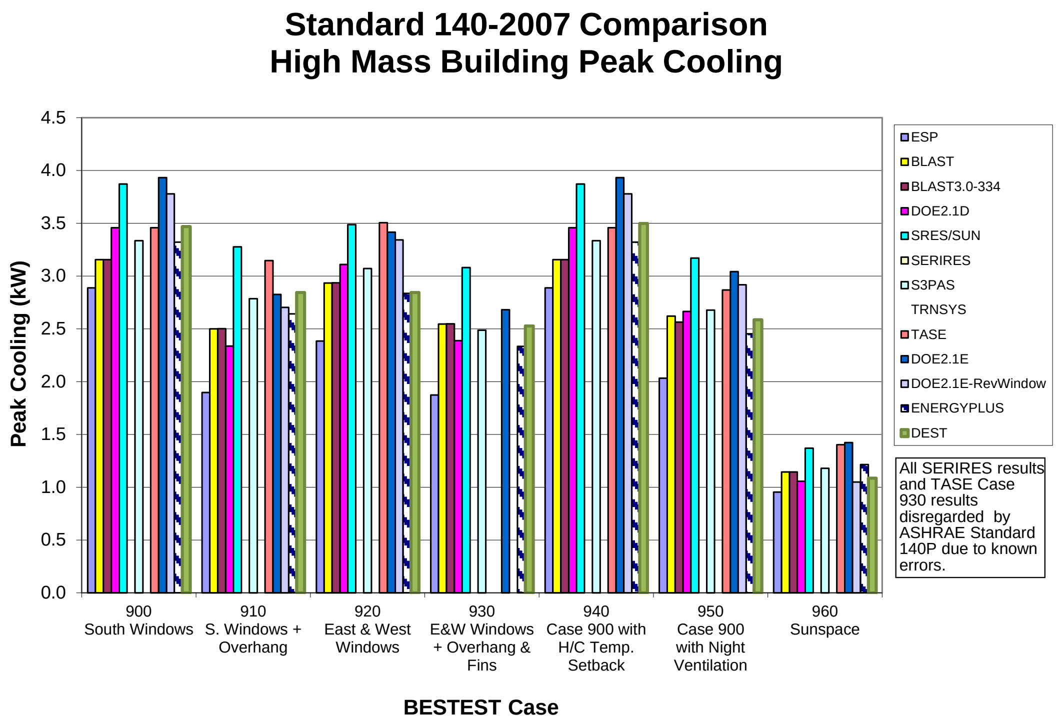


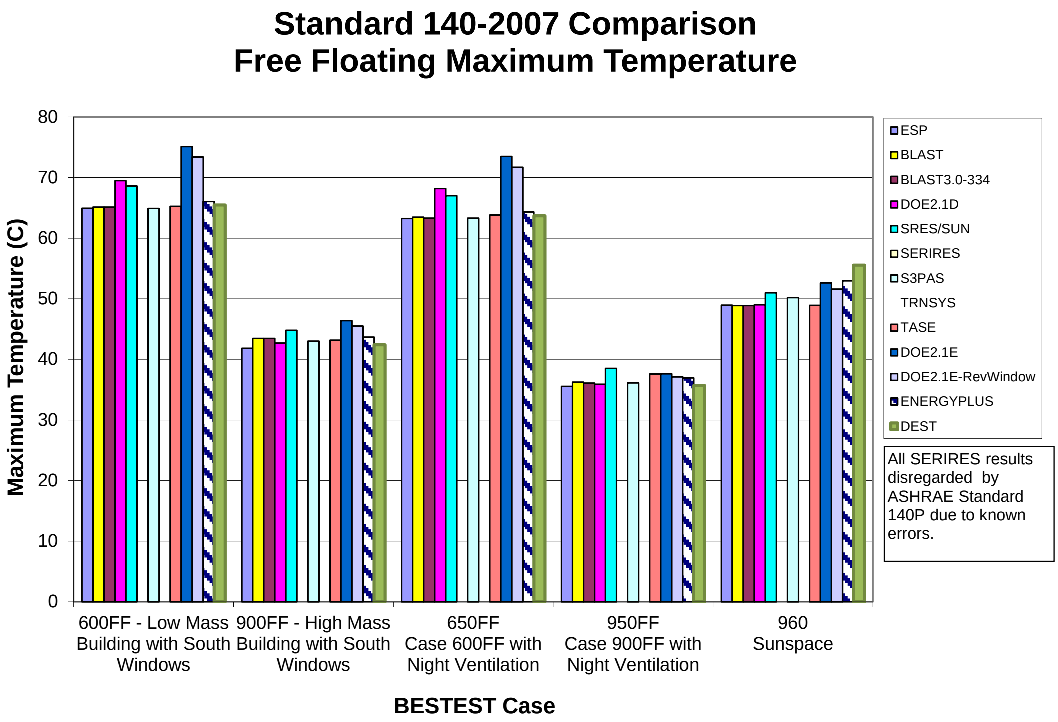
Standard 140-2007 Comparison
High Mass Building Annual Heating
Annual Heating (MWH)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
For Case 950, heating always off
TASE Case 930 disregarded by ASHRAE Standard 140P due to known errors.
900 South Windows
910 S. Windows + Overhang
920 East & West Windows
930 E&W Windows + Overhang & Fins
940 Case 900 with H/C Temp. Setback
950 Case 900 with Night Ventilation
960 Sunspace
BESTEST Case

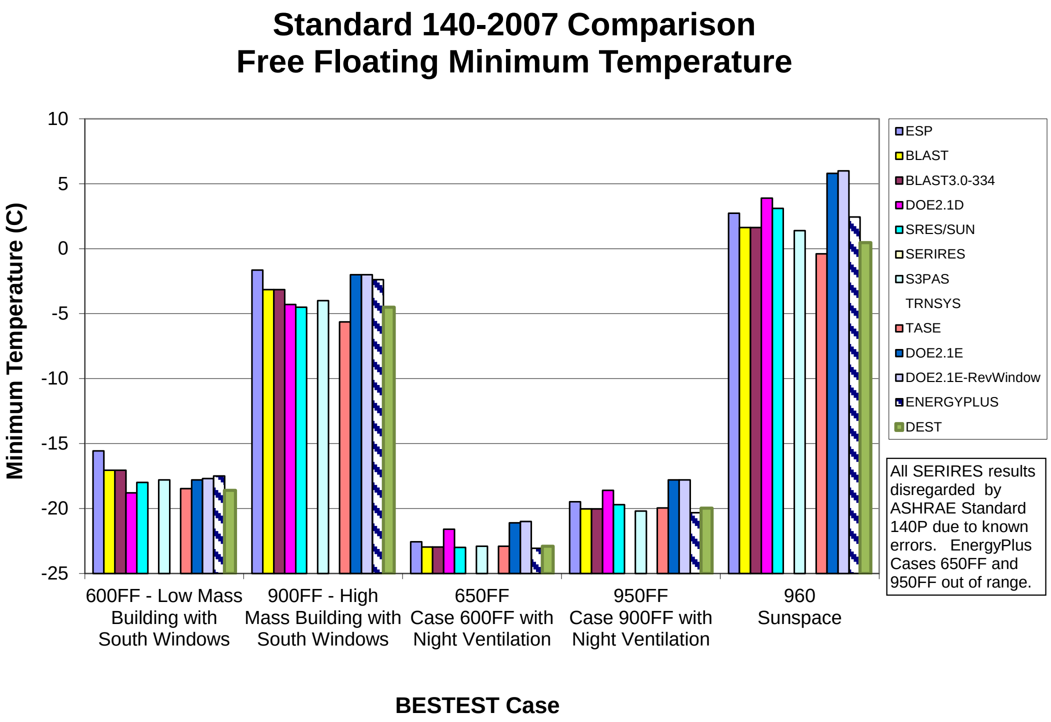


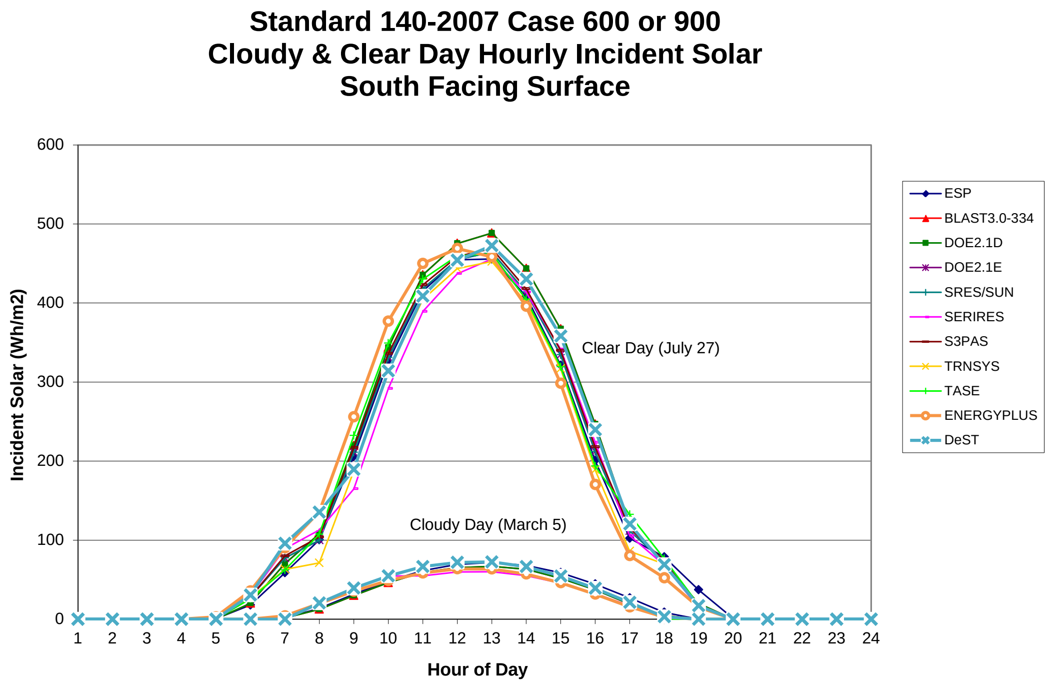
Standard 140-2007 Comparison
High Mass Building Annual Cooling
Annual Cooling (MWH)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
TASE Case 930 disregarded by ASHRAE Standard 140P due to known errors
900 South Windows
910 S. Windows + Overhang
920 East & West Windows
930 E&W Windows + Overhang & Fins
940 Case 900 with H/C Temp. Setback
950 Case 900 with Night Ventilation
960 Sunspace
BESTEST Case

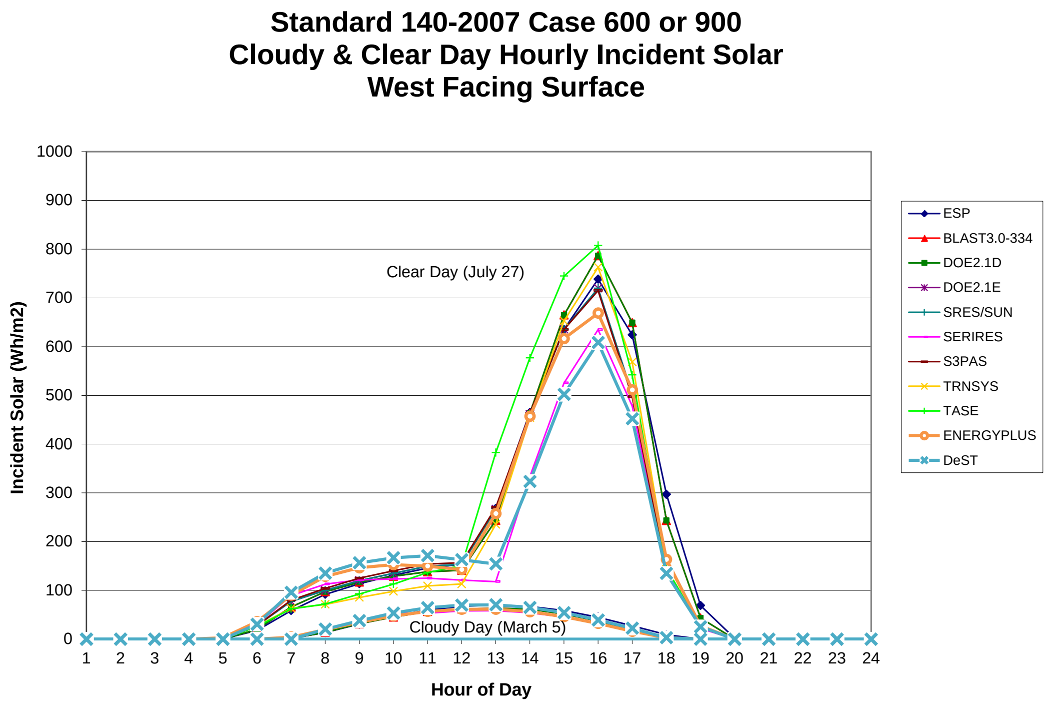

Standard 140-2007 Comparison
High Mass Building Peak Heating
Peak Heating (kW)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
For Case 950, heating always off
900 South Windows
910 S. Windows + Overhang
920 East & West Windows
930 E&W Windows + Overhang & Fins
940 Case 900 with H/C Temp. Setback
950 Case 900 with Night Ventilation
960 Sunspace
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
All SERIRES results and TASE Case 930 results disregarded by ASHRAE Standard 140P due to known errors.

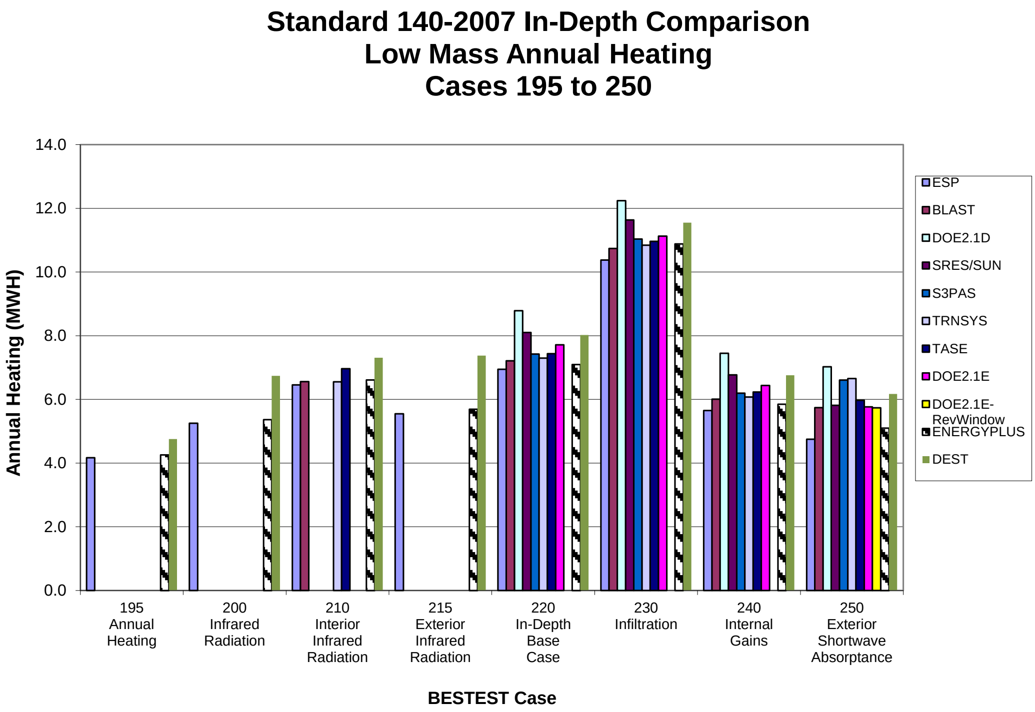

Standard 140-2007 Comparison
High Mass Building Peak Cooling
Peak Cooling (kW)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
900 South Windows
910 S. Windows + Overhang
920 East & West Windows
930 E&W Windows + Overhang & Fins
940 Case 900 with H/C Temp. Setback
950 Case 900 with Night Ventilation
960 Sunspace
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
All SERIRES results and TASE Case 930 results disregarded by ASHRAE Standard 140P due to known errors.


Standard 140-2007 Comparison
Free Floating Maximum Temperature
Maximum Temperature (C)
80
70
60
50
40
30
20
10
0
600FF - Low Mass Building with South Windows
900FF - High Mass Building with South Windows
650FF Case 600FF with Night Ventilation
950FF Case 900FF with Night Ventilation
960 Sunspace
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
All SERIRES results disregarded by ASHRAE Standard 140P due to known errors.

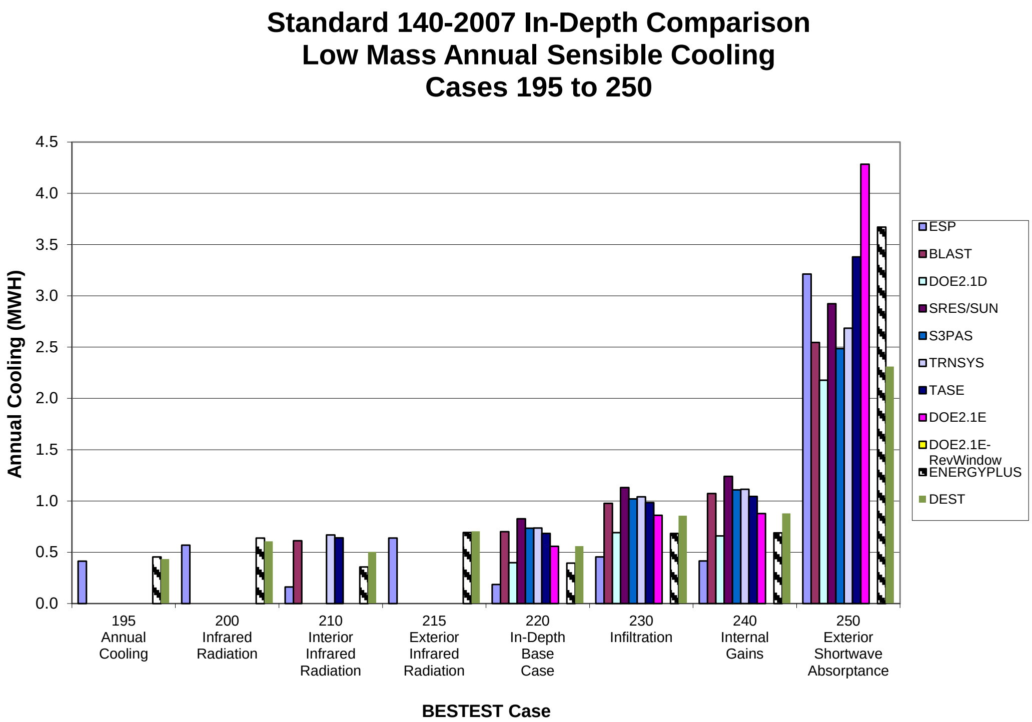

Standard 140-2007 Comparison
Free Floating Minimum Temperature
Minimum Temperature (C)
10
5
0
-5
-10
-15
-20
-25
600FF - Low Mass Building with South Windows
900FF - High Mass Building with South Windows
650FF Case 600FF with Night Ventilation
950FF Case 900FF with Night Ventilation
960 Sunspace
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST
All SERIRES results disregarded by ASHRAE Standard 140P due to known errors. EnergyPlus Cases 650FF and 950FF out of range.


Standard 140-2007 Case 600 or 900
Cloudy & Clear Day Hourly Incident Solar
South Facing Surface
Incident Solar (Wh/m2)
Hour of Day
Clear Day (July 27)
Cloudy Day (March 5)
ESP
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
ENERGYPLUS
DeST

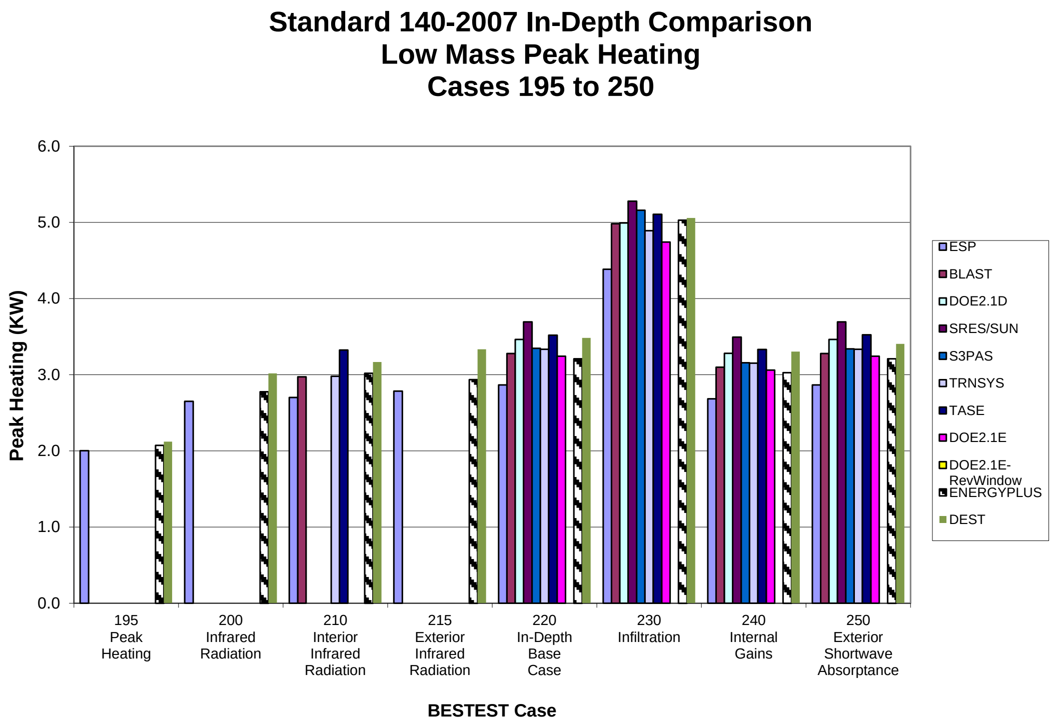

Standard 140-2007 Case 600 or 900
Cloudy & Clear Day Hourly Incident Solar
West Facing Surface
Incident Solar (Wh/m2)
Hour of Day
Clear Day (July 27)
Cloudy Day (March 5)
ESP
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
ENERGYPLUS
DeST



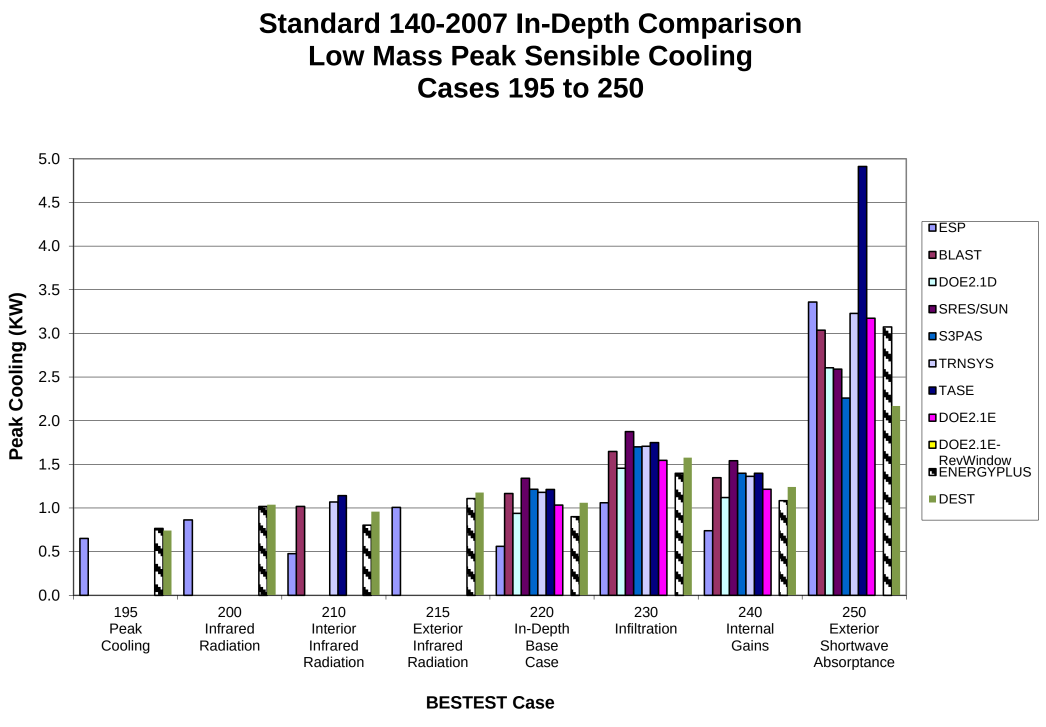
Standard 140-2007 In-Depth Comparison
Low Mass Annual Heating
Cases 195 to 250
Annual Heating (MWH)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
195 Annual Heating
200 Infrared Radiation
210 Interior Infrared Radiation
215 Exterior Infrared Radiation
220 In-Depth Base Case
230 Infiltration
240 Internal Gains
250 Exterior Shortwave Absorptance
BESTEST Case
ESP
BLAST
DOE2.1D
SRES/SUN
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST



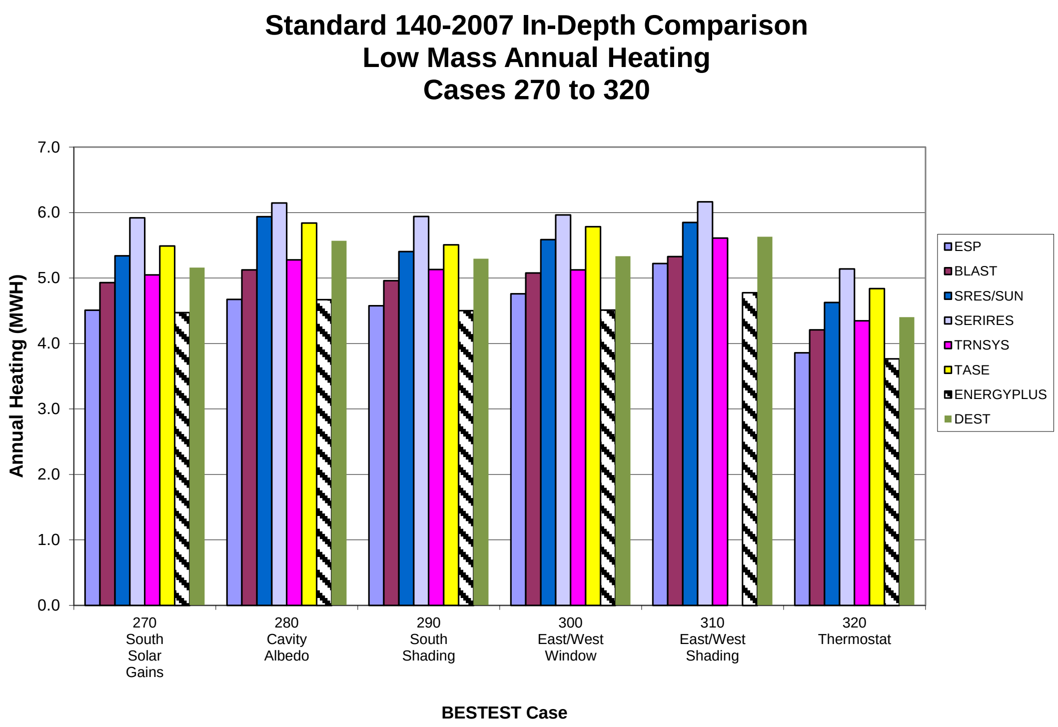
Standard 140-2007 In-Depth Comparison
Low Mass Annual Sensible Cooling
Cases 195 to 250
Annual Cooling (MWH)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
195 Annual Cooling
200 Infrared Radiation
210 Interior Infrared Radiation
215 Exterior Infrared Radiation
220 In-Depth Base Case
230 Infiltration
240 Internal Gains
250 Exterior Shortwave Absorptance
BESTEST Case
ESP
BLAST
DOE2.1D
SRES/SUN
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST

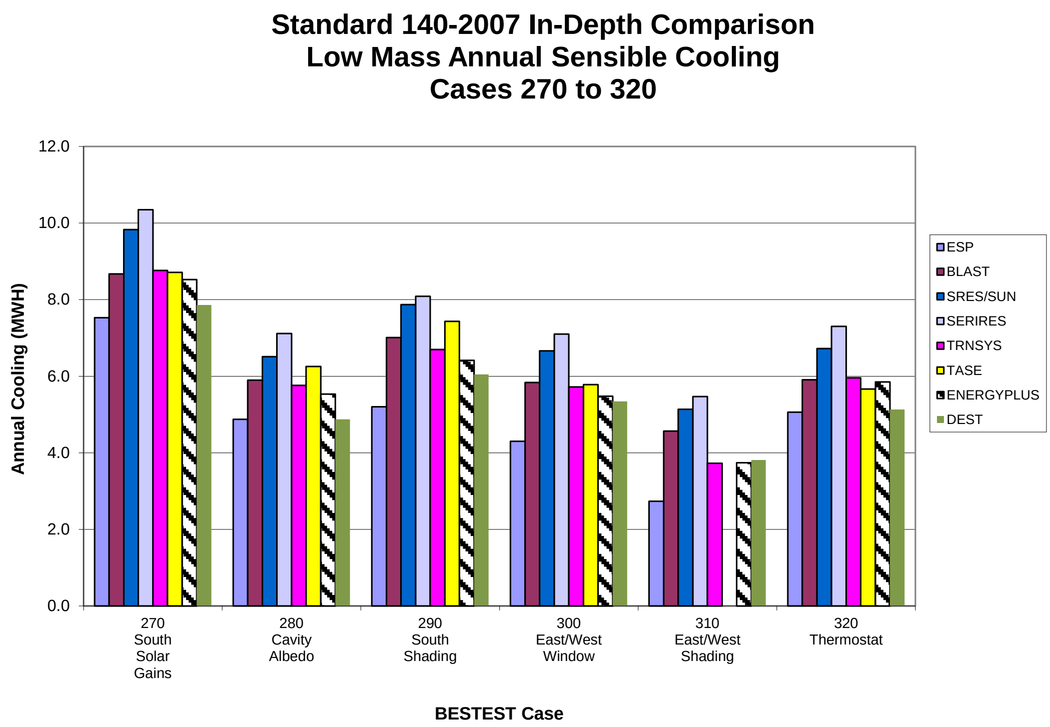


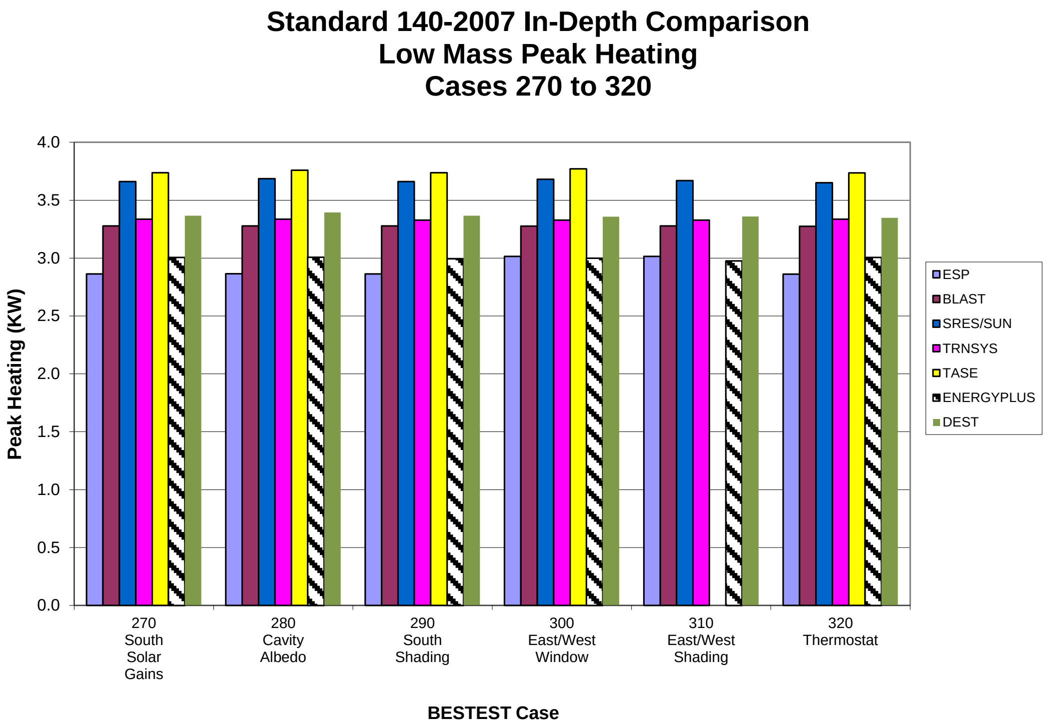
Standard 140-2007 In-Depth Comparison
Low Mass Peak Heating
Cases 195 to 250
Peak Heating (KW)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
195 Peak Heating
200 Infrared Radiation
210 Interior Infrared Radiation
215 Exterior Infrared Radiation
220 In-Depth Base Case
230 Infiltration
240 Internal Gains
250 Exterior Shortwave Absorptance
BESTEST Case
ESP
BLAST
DOE2.1D
SRES/SUN
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST

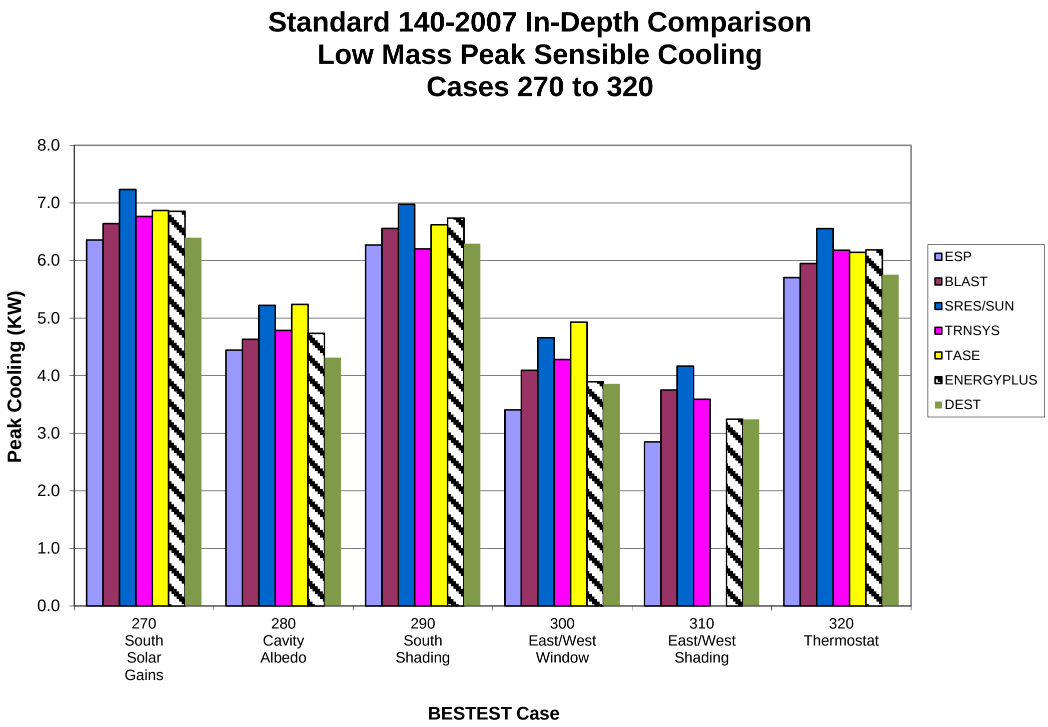


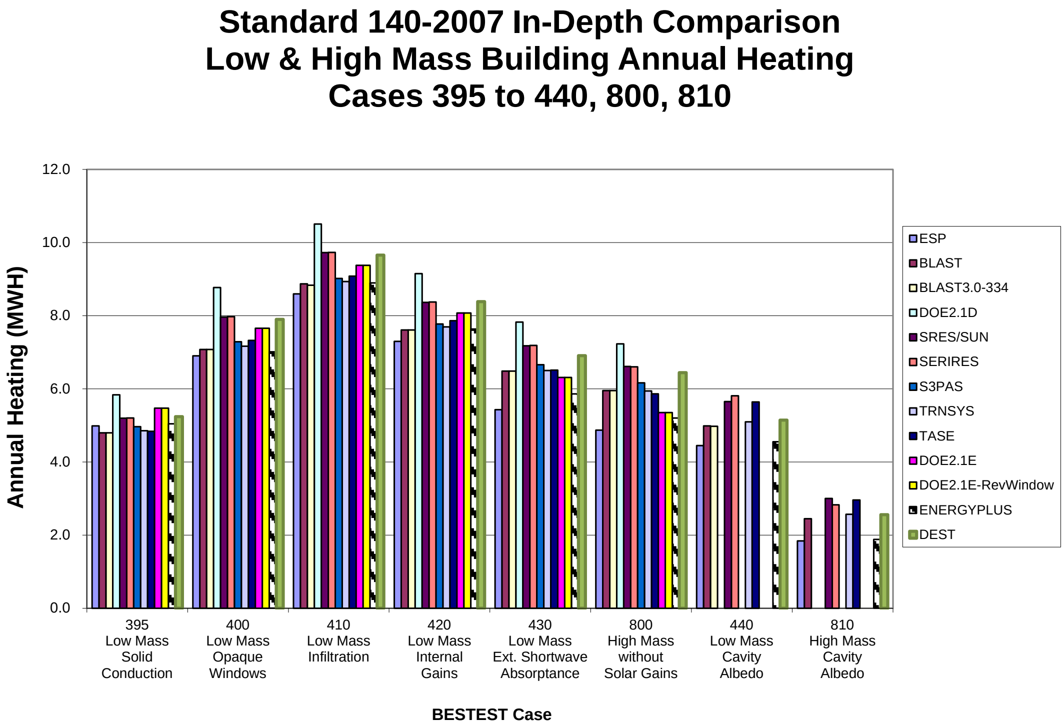
Standard 140-2007 In-Depth Comparison
Low Mass Peak Sensible Cooling
Cases 195 to 250
Peak Cooling (KW)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
195 Peak Cooling
200 Infrared Radiation
210 Interior Infrared Radiation
215 Exterior Infrared Radiation
220 In-Depth Base Case
230 Infiltration
240 Internal Gains
250 Exterior Shortwave Absorptance
BESTEST Case
ESP
BLAST
DOE2.1D
SRES/SUN
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST


Standard 140-2007 In-Depth Comparison
Low Mass Annual Heating
Cases 270 to 320
Annual Heating (MWH)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
270 South Solar Gains
280 Cavity Albedo
290 South Shading
300 East/West Window
310 East/West Shading
320 Thermostat
BESTEST Case
ESP
BLAST
SRES/SUN
SERIRES
TRNSYS
TASE
ENERGYPLUS
DEST

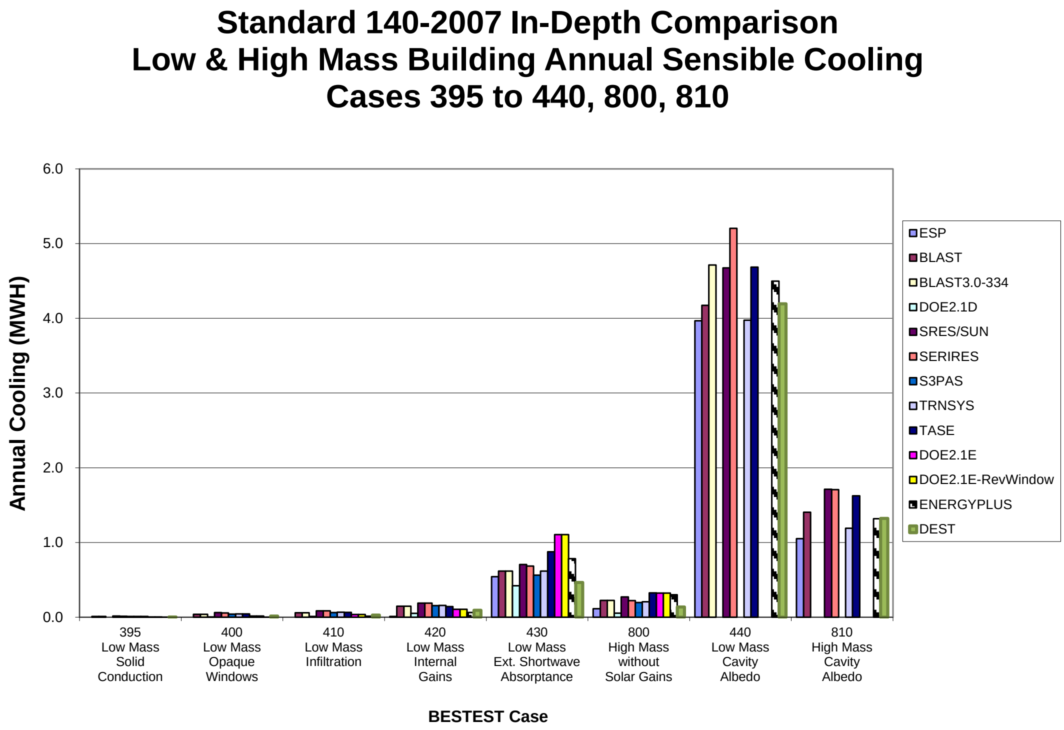

Standard 140-2007 In-Depth Comparison
Low Mass Annual Sensible Cooling
Cases 270 to 320
Annual Cooling (MWH)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
270 South Solar Gains
280 Cavity Albedo
290 South Shading
300 East/West Window
310 East/West Shading
320 Thermostat
BESTEST Case
ESP
BLAST
SRES/SUN
SERIRES
TRNSYS
TASE
ENERGYPLUS
DEST


Standard 140-2007 In-Depth Comparison
Low Mass Peak Heating
Cases 270 to 320
Peak Heating (KW)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
270 South Solar Gains
280 Cavity Albedo
290 South Shading
300 East/West Window
310 East/West Shading
320 Thermostat
BESTEST Case
ESP
BLAST
SRES/SUN
TRNSYS
TASE
ENERGYPLUS
DEST

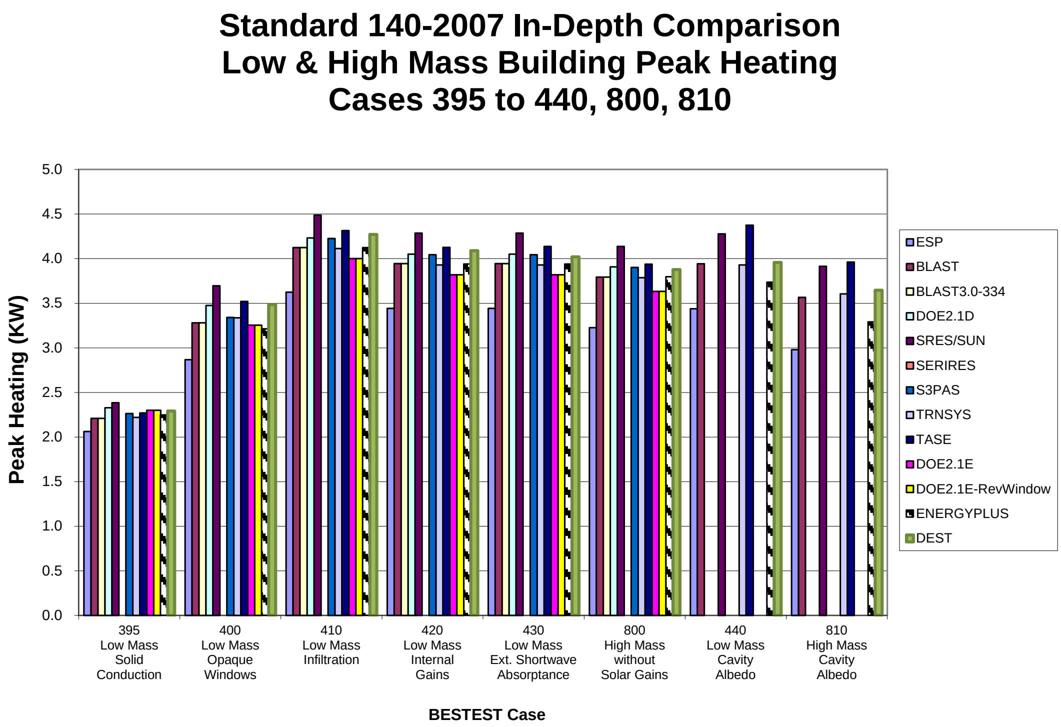

Standard 140-2007 In-Depth Comparison
Low Mass Peak Sensible Cooling
Cases 270 to 320
Peak Cooling (KW)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
270 South Solar Gains
280 Cavity Albedo
290 South Shading
300 East/West Window
310 East/West Shading
320 Thermostat
BESTEST Case
ESP
BLAST
SRES/SUN
TRNSYS
TASE
ENERGYPLUS
DEST



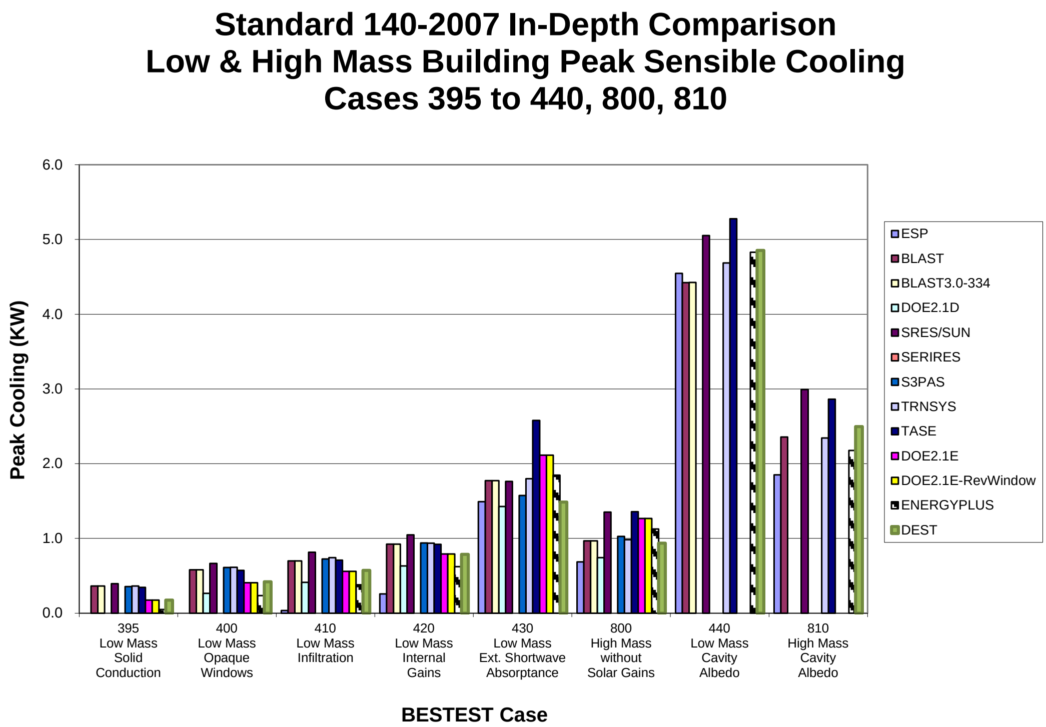
Standard 140-2007 In-Depth Comparison
Low & High Mass Building Annual Heating
Cases 395 to 440, 800, 810
Annual Heating (MWH)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
395 Low Mass Solid Conduction
400 Low Mass Opaque Windows
410 Low Mass Infiltration
420 Low Mass Internal Gains
430 Low Mass Ext. Shortwave Absorptance
800 High Mass without Solar Gains
440 Low Mass Cavity Albedo
810 High Mass Cavity Albedo
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST



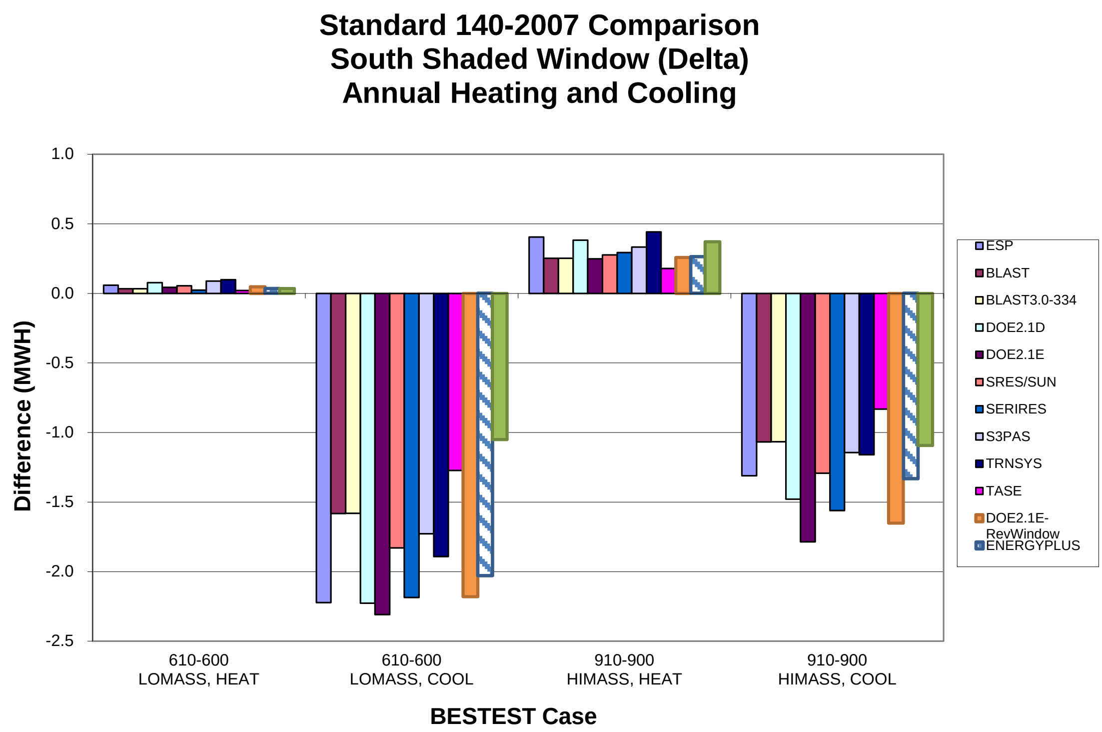
Standard 140-2007 In-Depth Comparison
Low & High Mass Building Annual Sensible Cooling
Cases 395 to 440, 800, 810
Annual Cooling (MWH)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
395 Low Mass Solid Conduction
400 Low Mass Opaque Windows
410 Low Mass Infiltration
420 Low Mass Internal Gains
430 Low Mass Ext. Shortwave Absorptance
800 High Mass without Solar Gains
440 Low Mass Cavity Albedo
810 High Mass Cavity Albedo
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST

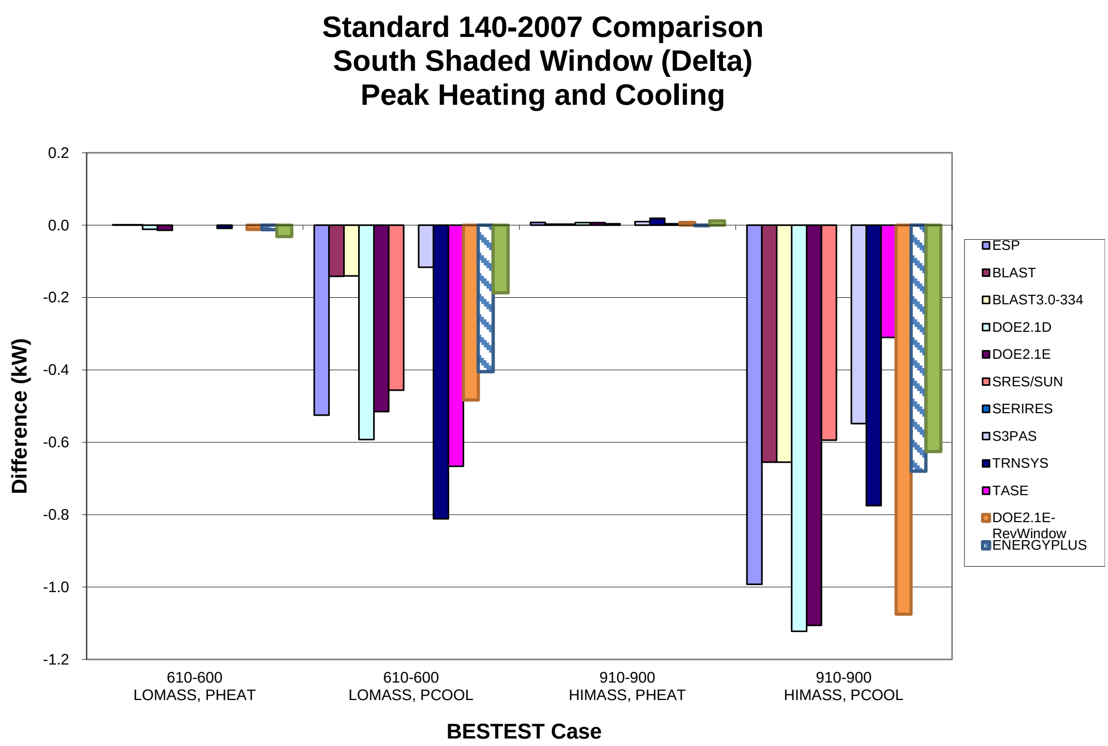


Standard 140-2007 In-Depth Comparison
Low & High Mass Building Peak Heating
Cases 395 to 440, 800, 810
Peak Heating (KW)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
395 Low Mass Solid Conduction
400 Low Mass Opaque Windows
410 Low Mass Infiltration
420 Low Mass Internal Gains
430 Low Mass Ext. Shortwave Absorptance
800 High Mass without Solar Gains
440 Low Mass Cavity Albedo
810 High Mass Cavity Albedo
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST

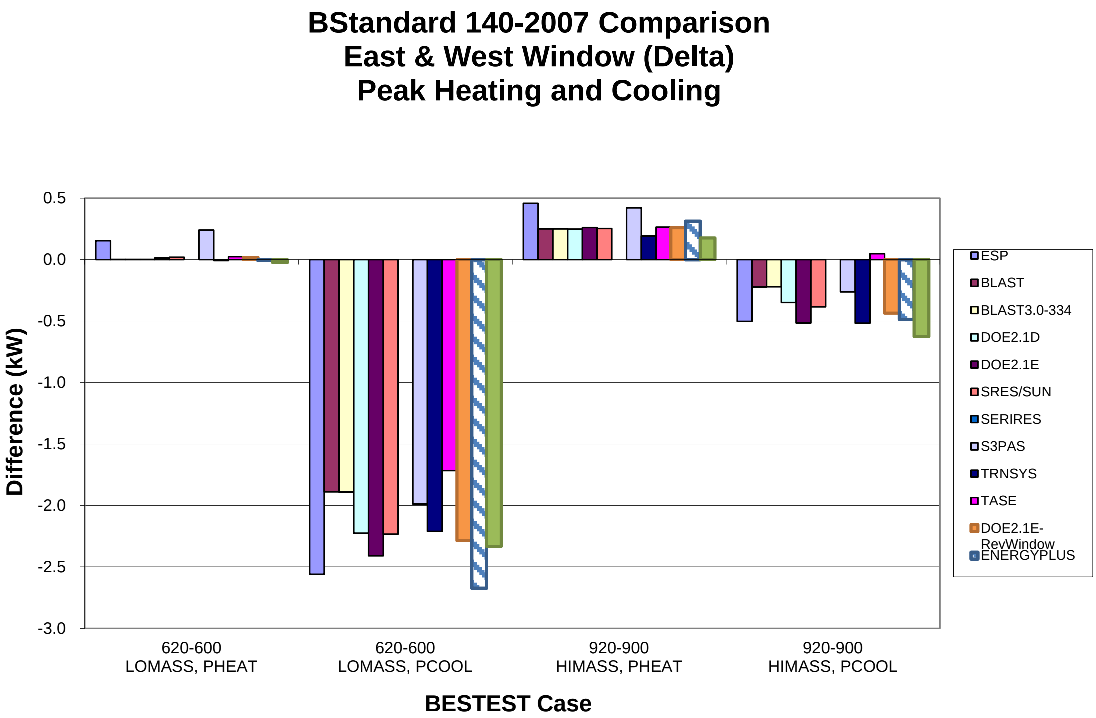


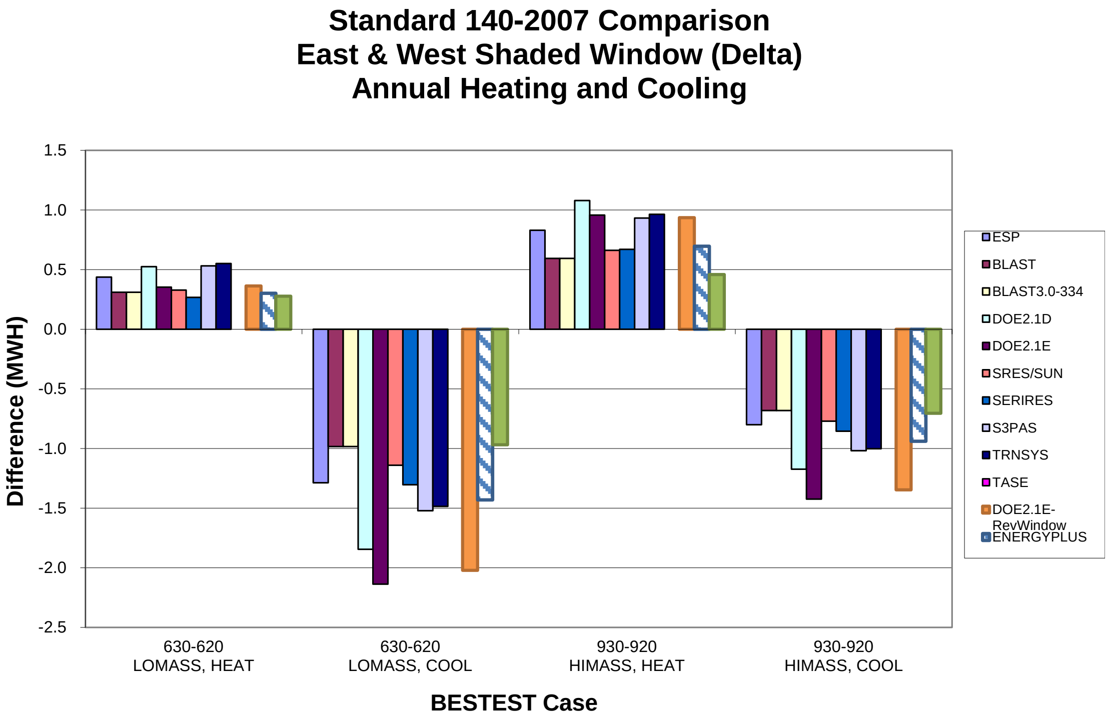
Standard 140-2007 In-Depth Comparison
Low & High Mass Building Peak Sensible Cooling
Cases 395 to 440, 800, 810
Peak Cooling (KW)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
395 Low Mass Solid Conduction
400 Low Mass Opaque Windows
410 Low Mass Infiltration
420 Low Mass Internal Gains
430 Low Mass Ext. Shortwave Absorptance
800 High Mass without Solar Gains
440 Low Mass Cavity Albedo
810 High Mass Cavity Albedo
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E
DOE2.1E-RevWindow
ENERGYPLUS
DEST

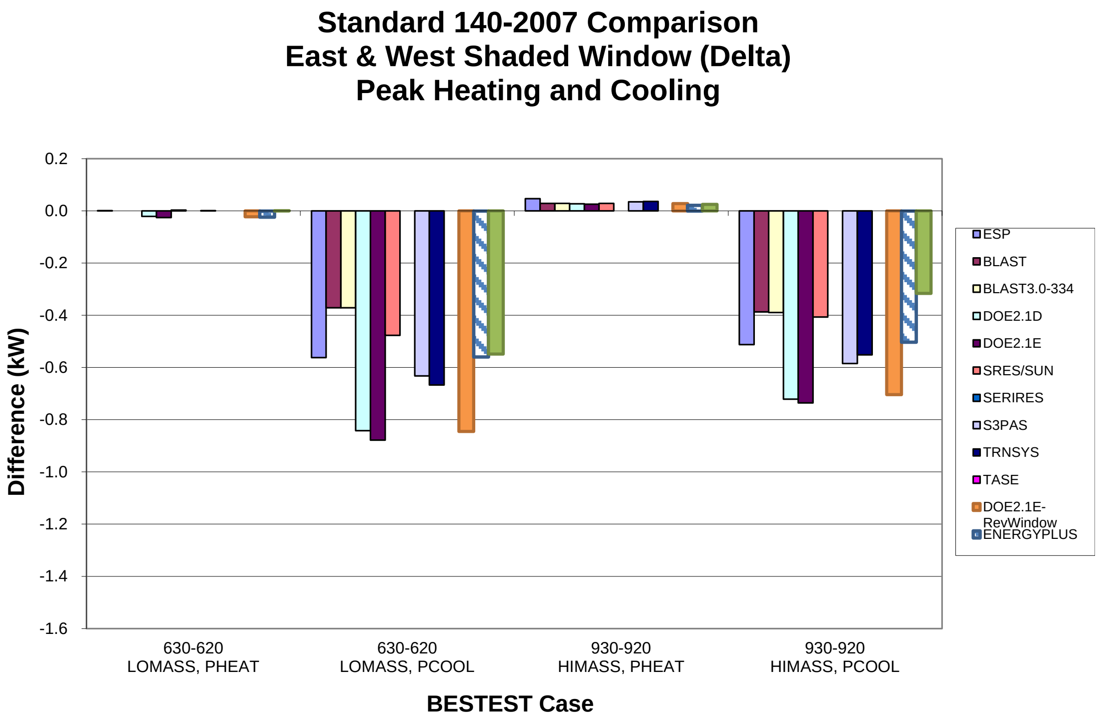

Standard 140-2007 Comparison
South Shaded Window (Delta)
Annual Heating and Cooling
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Difference (MWH)
610-600
LOMASS, HEAT
610-600
LOMASS, COOL
910-900
HIMASS, HEAT
910-900
HIMASS, COOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS

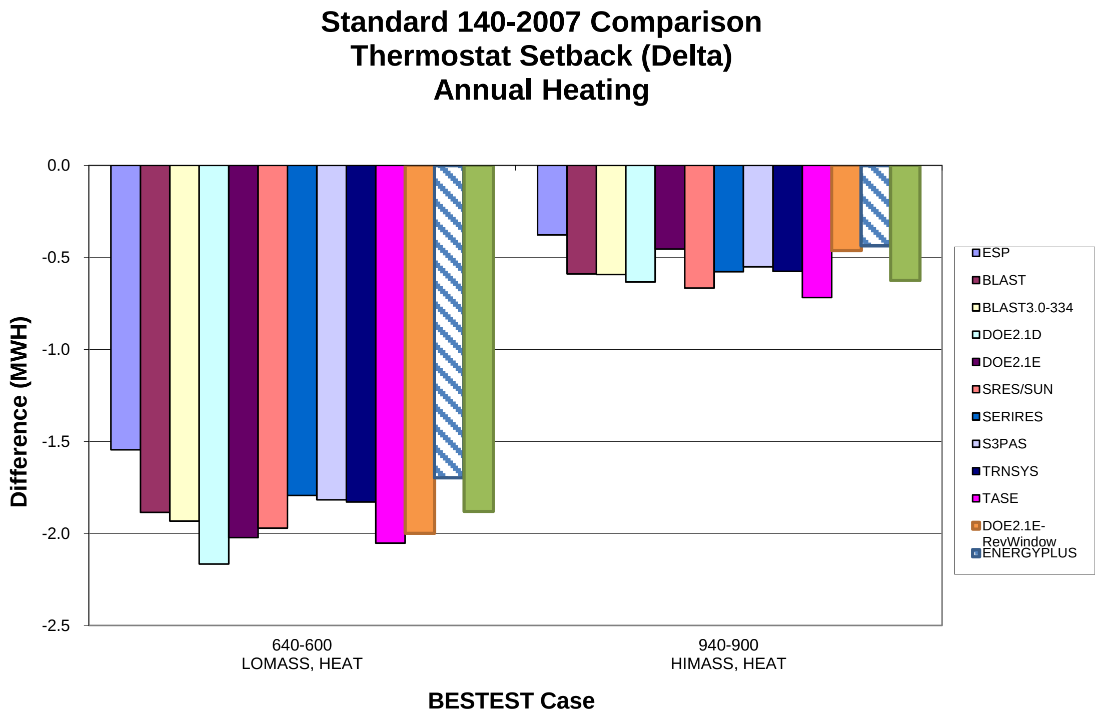

Standard 140-2007 Comparison
South Shaded Window (Delta)
Peak Heating and Cooling
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
Difference (kW)
610-600
LOMASS, PHEAT
610-600
LOMASS, PCOOL
910-900
HIMASS, PHEAT
910-900
HIMASS, PCOOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS


Standard 140-2007 Comparison
East & West Window (Delta)
Annual Heating and Cooling
Difference (MWH)
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
620-600
LOMASS,HEAT
620-600
LOMASS, COOL
920-900
HIMASS, HEAT
920-900
HIMASS, COOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS
DEST

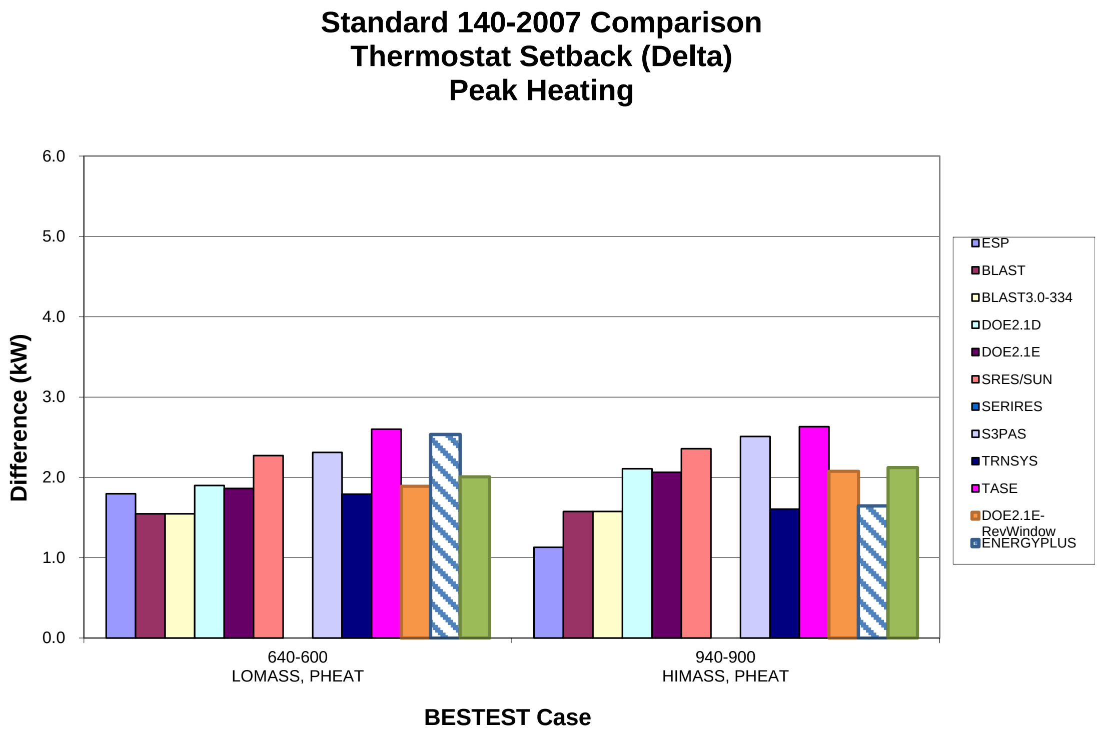

BStandard 140-2007 Comparison
East & West Window (Delta)
Peak Heating and Cooling
Difference (kW)
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
620-600
LOMASS, PHEAT
620-600
LOMASS, PCOOL
920-900
HIMASS, PHEAT
920-900
HIMASS, PCOOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS


Standard 140-2007 Comparison
East & West Shaded Window (Delta)
Annual Heating and Cooling
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Difference (MWH)
630-620 LOMASS, HEAT
630-620 LOMASS, COOL
930-920 HIMASS, HEAT
930-920 HIMASS, COOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS

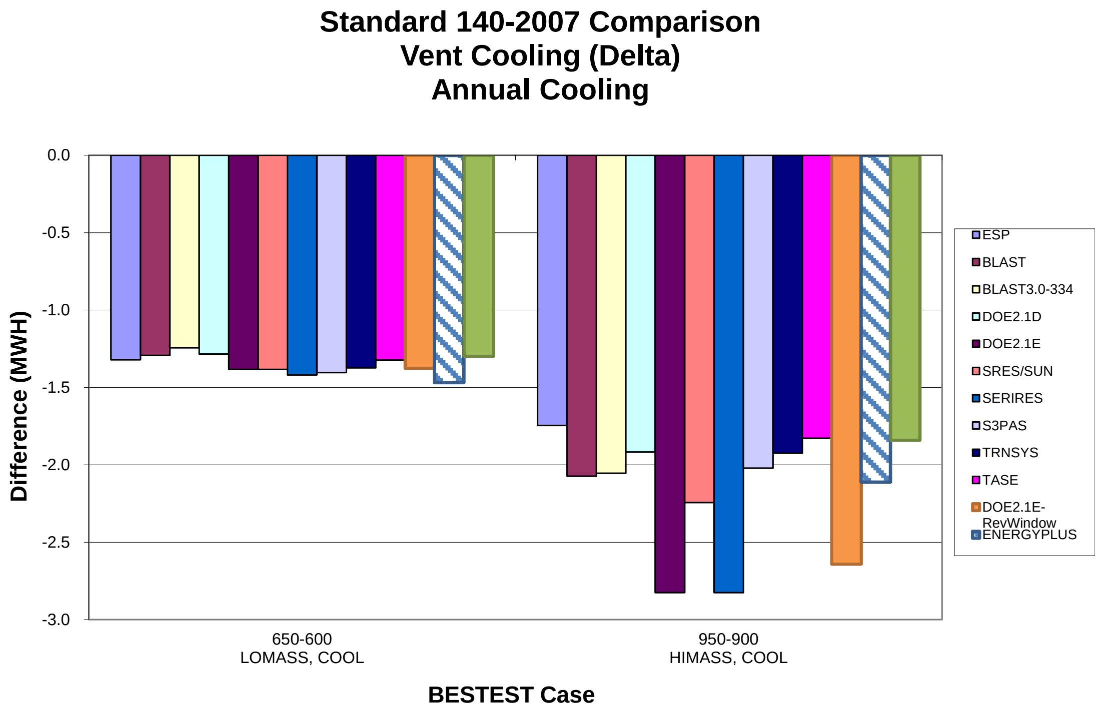

Standard 140-2007 Comparison
East & West Shaded Window (Delta)
Peak Heating and Cooling
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
Difference (kW)
630-620 LOMASS, PHEAT
630-620 LOMASS, PCOOL
930-920 HIMASS, PHEAT
930-920 HIMASS, PCOOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS

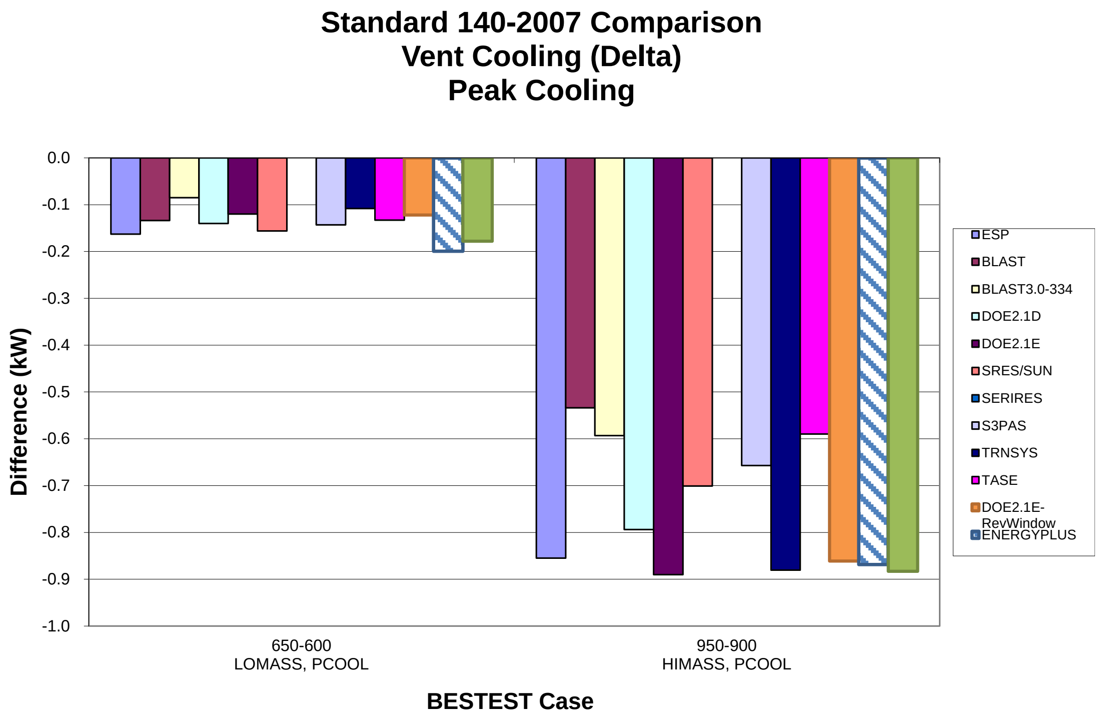


Standard 140-2007 Comparison
Thermostat Setback (Delta)
Annual Heating
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Difference (MWH)
640-600
LOMASS, HEAT
940-900
HIMASS, HEAT
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS

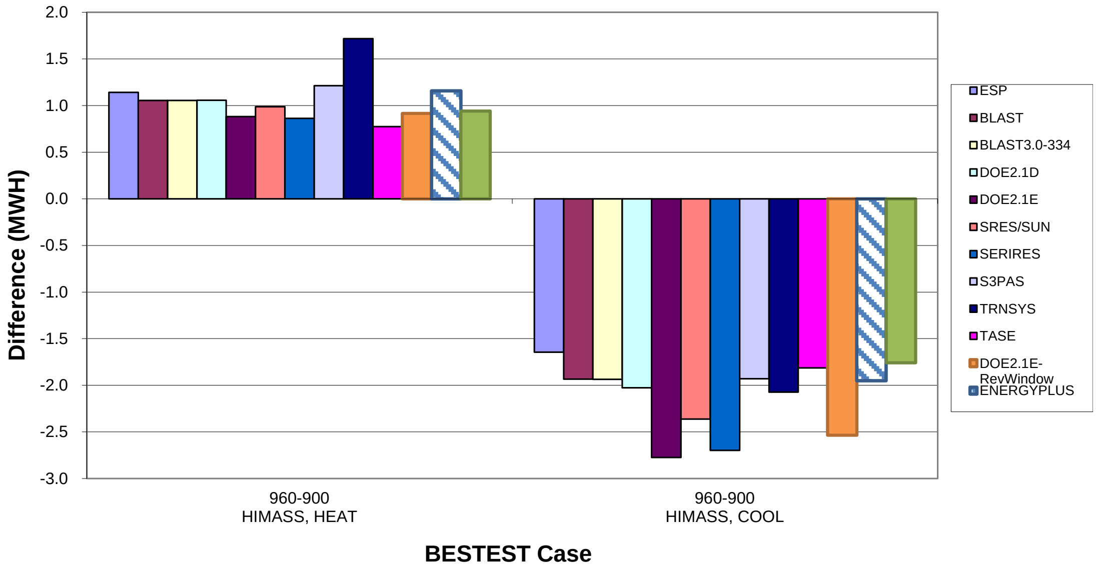


Standard 140-2007 Comparison
Thermostat Setback (Delta)
Peak Heating
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Difference (kW)
640-600
LOMASS, PHEAT
940-900
HIMASS, PHEAT
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS


Standard 140-2007 Comparison
Vent Cooling (Delta)
Annual Cooling
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Difference (MWH)
650-600
LOMASS, COOL
950-900
HIMASS, COOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS


Standard 140-2007 Comparison
Vent Cooling (Delta)
Peak Cooling
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
Difference (kW)
650-600
LOMASS, PCOOL
950-900
HIMASS, PCOOL
BESTEST Case
ESP
BLAST
BLAST3.0-334
DOE2.1D
DOE2.1E
SRES/SUN
SERIRES
S3PAS
TRNSYS
TASE
DOE2.1E-RevWindow
ENERGYPLUS

Standard 140-2007 Comparison
Sunspace (Delta)
Annual Heating and Cooling



Standard 140-2007 Comparison
Sunspace (Delta)
Peak Heating and Cooling
EnergyPlus Version 6.0.0.023