Building Simulation

Seventh International IBPSA Conference
Rio de Janeiro, Brazil
August 13-15, 2001

ENERGYPLUS: NEW CAPABILITIES IN A WHOLE-BUILDING ENERGY SIMULATION PROGRAM

Drury B. Crawley
US Department of Energy
Washington, DC 20585 USA

Frederick C. Winkelmann
Lawrence Berkeley National Laboratory
Berkeley, California 94720

Linda K. Lawrie
US Army Construction Engineering
Research Laboratory
Champaign, Illinois 61821

Curtis O. Pedersen
University of Illinois
Urbana, Illinois 61801

ABSTRACT

A new building energy simulation program developed under support from the US government was released in April 2001. EnergyPlus is based on the most popular features and capabilities of BLAST and DOE-2 but is a completely new program written in Fortran 90. New features include variable time steps, user-configurable modular systems, an integrated heat and mass balance-based zone simulation, multizone airflow, air pollutant transport, moisture transfer in building components, solar photovoltaic simulation—and input and output data structures tailored to facilitate third party module and interface development. EnergyPlus is primarily a simulation engine without an user interface—although user interfaces are under development by the private sector This paper focuses on the general simulation methods and capabilities of EnergyPlus, contrasting it with those of DOE-2 and BLAST. Plans for future releases of EnergyPlus are also described.

INTRODUCTION

For more than twenty years, the U.S. government supported development of two building energy simulation programs, DOE-2 and BLAST. BLAST (Building System Laboratory 1999), sponsored by the U.S. Department of Defense (DOD), has its origins in the NBSLD program developed at the U.S. National Bureau of Standards (now NIST) in the early 1970s. DOE–2 (Winkelmann et al. 1993), sponsored by the U.S. Department of Energy (DOE), has its origins in the Post Office program written in the late 1960s for the U.S. Post Office. The main difference between the programs is load calculation method—DOE–2 uses a room weighting factor approach while BLAST uses a heat balance approach. Both programs are widely used throughout the world.

Each program comprises hundreds of subroutines working together to simulate heat and mass energy flows throughout a building. In some cases, subroutines in DOE–2 were more accurate. In other cases, subroutines in BLAST were more accurate. In both cases, simulation methodologies are often difficult to trace due to decades of development (and multiple authors). Often, this results in 'spaghetti code' with data and subroutines for a particular simulation capability spread throughout the program. To modify either program, a developer must have many years experience working within the code, knowledge of code unrelated to their task (because of the spaghetti), and (often for sponsors) an extraordinary investment of time and money.

Many people questioned why the U.S. government was supporting two separate (and comparable capability) programs. Discussions on merging the two programs began in earnest in 1994 with a DOD-sponsored workshop. Although nothing concrete resulted from that workshop, DOE eventually took the initiative and began developing a new program named EnergyPlus in 1996. The EnergyPlus team includes U. S. Army Construction Engineering Research Laboratories (CERL), University of Illinois (UI), Lawrence Berkeley National Laboratory (LBNL), Oklahoma State University (OSU), GARD Analytics, and DOE. In this paper, we present an overview of the organization and capabilities of EnergyPlus and explain the rationale and structure behind the overall program.

What is EnergyPlus?

When we began planning development of EnergyPlus, we thought that we could create a 'best of' program—combining modules from the two programs—without starting from scratch. After initial development work, we determined that EnergyPlus would cost less to develop, be released faster, and be easier to modify and extend if we wrote all new code.

Thus, EnergyPlus is an all-new program but one based on the most popular features and capabilities of BLAST and DOE-2. A major goal we set for developing EnergyPlus was to create a well-organized, modular structure to facilitate adding features and links to other programs. Despite the advantages of the structure and object-orientation of C/C++, we decided to select Fortran 90 as the programming language for EnergyPlus. Thus, EnergyPlus comprises completely new, modular, structured code written in Fortran 90.

We have focused on developing a simulation engine without an interface. Input and output are simple comma-separated, ASCII text files, much simpler input than either DOE–2 or BLAST. Both BLAST and DOE–2 have successfully attracted many third-party developers to create user interfaces and new modules. During EnergyPlus beta testing we began working with these same developers to ensure that third party user interfaces will be available soon after EnergyPlus was released.

ENERGYPLUS STRUCTURE

In the late 1990s, DOE sponsored two workshops on next generation energy tools. From these workshops, there was strong consensus that a more flexible and robust tool with additional capabilities is needed. Recurrent themes were issues and capabilities to handle design, environment, economics, and occupant comfort and safety. One of the highest priorities was an integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction.

In response to these findings, we decided that integrated simulation should be the underlying concept for EnergyPlus. Loads calculated (by a heat balance engine) at a user-specified time step (15-minute default) are passed to the building systems simulation module at the same time step. The building systems simulation module, with a variable time step (down to seconds if necessary), calculates heating and cooling system and plant and electrical system response. Feedback from the building systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures and humidity if necessary.

The integrated solution technique overcomes the most serious deficiency of BLAST and DOE–2 simulations: inaccurate space temperature predication due to lack of feedback from the HVAC module on meeting loads. Accurate prediction of space temperatures is crucial to energy efficient system engineering—system size, plant size, occupant comfort and occupant health are dependent on space temperatures. Integrated simulation also allows users to evaluate a number of processes that neither BLAST nor DOE–2 can simulate well. Some of the more important include realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone airflow.

Figure 1 shows the overall program structure. EnergyPlus has three basic components—a simulation manager, a heat and mass balance simulation module, and a building systems simulation module. The simulation manager controls the entire simulation process.

A new building systems simulation manager handles communication between the heat balance engine and various HVAC modules and loops, such as coils, boilers, chillers, pumps, fans, and other equipment/components. (In the first release, the building systems simulation manager only has HVAC systems and equipment/components. Future releases of EnergyPlus will include electrical systems simulation.) The building systems simulation manager also controls interaction and data exchange between EnergyPlus and SPARK (Buhl et al. 1993) and TRNSYS (Solar Energy Laboratory 2000) simulations. Gone are the hardwired 'template' systems (VAV, Constant Volume Reheat, etc.) of DOE–2 and BLAST—replaced by user-configurable heating and cooling equipment components formerly within the template. This gives users much more flexibility in matching their simulation to the actual system configurations. The building systems simulation module also manages data communication between the HVAC modules, input data, and output data structures.

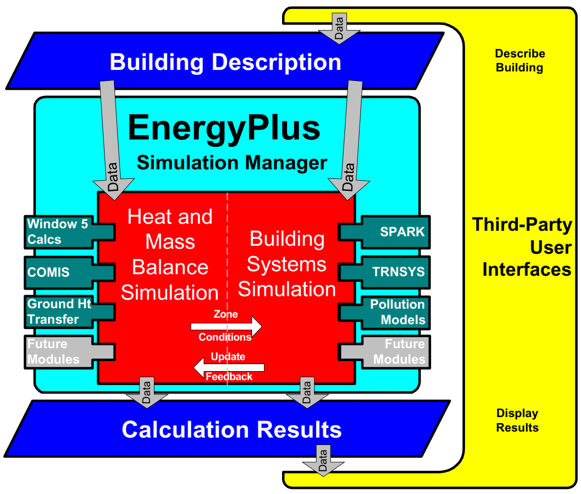

Figure 1. Overall EnergyPlus Structure

A comparison of major features and capabilities of EnergyPlus, BLAST, IBLAST, and DOE–2 is shown in Tables 1, 2, and 3. Table 1 shows general features, Table 2 load calculation features, and Table 3 HVAC features. The simulation manager, heat balance simulation manager, and building systems simulation manager are described briefly below.

Simulation Management

At the outermost program level, the Simulation Manager controls the interactions between all simulation loops from a sub-hour level up through the user selected time step and simulation period—whether day, month, season, year or several years. Actions of individual simulation modules are directed by the simulation manager, instructing simulation modules to take actions such as initialize, simulate, record keep, or report. We created the simulation manager to specifically address the legacy issues of spaghetti code and lack of structure in DOE-2 and BLAST. The simulation manager provides several critical benefits:

- major simulation loops are in a single module
- modules are self-contained and more object-based
- data access is controlled
- new modules are easily added

Heat and Mass Balance

As noted earlier, the underlying building thermal zone calculation method in EnergyPlus is a heat balance model. The fundamental assumption of heat balance models is that air in each thermal zone can be modeled as well stirred with uniform temperature throughout.

Although this does not reflect physical reality well, the only current alternative is Computational Fluid Dynamics (CFD)—a complex and computationally intensive simulation of fluid (in this case, air) movement. Currently, CFD is most useful in research applications. The modular structure of EnergyPlus allows these new models to be included in future releases once they are available. The other major assumption in heat balance models is that room surfaces (walls, windows, ceilings, and floors) have:

- uniform surface temperatures,
- uniform long- and short-wave irradiation,
- diffuse radiating surfaces, and
- one-dimensional heat conduction.

The EnergyPlus integrated solution manager manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager. The surface heat balance module simulates inside and outside surface heat balance; interconnections between heat balances and boundary conditions; and conduction, convection, radiation, and mass transfer (water vapor) effects. The air mass balance module deals with various mass streams such as ventilation air, exhaust air, and infiltration. It accounts for thermal mass of zone air and evaluates direct convective heat gains. Through this module we are connecting to COMIS (Huang et al. 1999) for improved multizone airflow, infiltration, indoor contaminant, and ventilation calculations. In addition to the basic heat and mass balance engine from IBLAST, we created three new modules based on capabilities within DOE–2: daylighting illumination (Winkelmann and Selkowitz 1985), WINDOW 5-based fenestration (Arestah et al. 1994), and anisotropic sky. The daylighting module calculates interior daylight illuminance, glare from windows, glare control, and electric lighting controls (on/off, stepped, continuous dimming), and calculates electric lighting reduction for the heat balance module. The fenestration module includes capabilities from the soon-to-be released WINDOW 5—accurate angular dependence of transmission and absorption for both solar and visible radiation, and temperature-dependent U-value. Users can enter a layer-by-layer window description or choose windows from the library (conventional, reflective, low-e, gas fill, electrochromic). For sun control, movable interior and exterior window shades

Table 1. Comparison of General Features and Capabilities

General Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Integrated, Simultaneous Solution • Integrated loads/systems/plant • Iterative solution • Tight coupling	No	No	**Yes**	**Yes**
Multiple Time Step Approach • User-defined time step for interaction between zones and environment (15-min default) • Variable time-step for interactions between zone air mass and HVAC system (≥ 1 min)	No	No	**Yes**	**Yes**
Input Functions • Users can modify code without recompiling	**Yes**	No	No	**Yes**
Reporting Mechanism				
• Standard reports	**Yes**	**Yes**	**Yes**	**Yes**
• User-definable reports	No	No	No	**Yes**
• Visual surface output	No	No	No	**Yes**

Table 2. Comparison of Loads Features and Capabilities

HVAC Systems and Equipment Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Fluid Loops • Connect primary equipment and coils • Hot water loops, chilled water and condenser loops, refrigerant loops	No	No	No	**Yes**
Air Loops • Connect fans, coils, mixing boxes, zones	No	No	No	**Yes**
User-configurable HVAC systems	No	No	No	**Yes**
High-Temperature Radiant Heating • Gas/electric heaters, wall radiators	No	**Yes**	**Yes**	**Yes**
Low-Temperature Radiant Heating/Cooling • Heated floor/ceiling • Cooled ceiling	No	No	**Yes**	**Yes**
Atmospheric Pollution Calculation • CO_2, SO_x, NO_x, CO, particulate matter and hydrocarbon production • On-site and at power plant • Calculate reductions in greenhouse gases	**Yes**	**Yes**	No	**Yes**
SPARK link	No	No	No	**Yes**
TRNSYS link	No	No	No	**Yes**

and electrochromic glazing can be simulated. Winkelmann (2001) provides more information on the EnergyPlus window calculations.

Several other modules have been reengineered for inclusion in EnergyPlus: solar shading from BLAST and conduction transfer function calculations from IBLAST. The major enhancements of the IBLAST (and EnergyPlus) heat balance engine over BLAST include mass transfer and radiant heating and cooling. The mass transfer capability within EnergyPlus allows fundamental, layer-by-layer solution for mass transfer through surfaces and a mass balance on zone air similar to the air heat balance. The radiant heating and cooling models are an expansion of the conduction transfer function and incorporate thermal comfort calculations. This provides a means for improved modeling and control capabilities for the new building systems simulation manager.

One last important feature of the EnergyPlus heat balance engine is that it is essentially identical in

Table 3. Comparison of HVAC Features and Capabilities

Loads Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Heat Balance Calculation • Simultaneous calculation of radiation and convection processes each time step	No	**Yes**	**Yes**	**Yes**
Interior Surface Convection • Dependent on temperature and air flow • Internal thermal mass	No **Yes**	**Yes** **Yes**	**Yes** **Yes**	**Yes** **Yes**
Moisture Absorption/Desorption • Combined heat and mass transfer in building envelopes	No	No	**Yes**	**Yes**
Thermal Comfort • Human comfort model based on activity, inside drybulb, humidity, and radiation	No	**Yes**	**Yes**	**Yes**
Anisotropic Sky Model • Sky radiance depends on sun position for better calculation of diffuse solar on tilted surfaces	**Yes**	No	No	**Yes**
Advanced Fenestration Calculations • Controllable window blinds • Electrochromic glazing	**Yes**	No	No	**Yes**
WINDOW 5 Calculations • More than 200 window types—conventional, reflective, low-E, gas-fill, electrochromic • Layer-by-layer input for custom glazing	**Yes** No	No No	No No	**Yes** **Yes**
Daylighting Illumination and Controls • Interior illuminance from windows and skylights • Step, dimming, on/off luminaire controls • Glare simulation and control • Effects of dimming on heating and cooling	**Yes**	No	No	**Yes**

functionality to the Loads Toolkit recently completed by UI under ASHRAE Research Project 987 (Pedersen et al. 2001). UI developed both the Loads Toolkit and the EnergyPlus heat and mass balance engine and used the programming standard developed in the EnergyPlus project to produce the Loads Toolkit. Both projects benefit: modularization efforts started by EnergyPlus will be useful in the Loads Toolkit and new component models developed for the Loads Toolkit will enhance EnergyPlus. Strand and Pedersen (2001) provide more information on the heat and mass balance incorporated in EnergyPlus in comparison with the Loads Toolkit.

Building Systems Simulation Manager

After the heat balance manager completes simulation for a time step, it calls the Building Systems Simulation Manager, which controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions. EnergyPlus does not use the sequential simulation method found in DOE–2 and BLAST (first building loads, then air distribution system, and then central plant) since this imposes rigid boundaries on program structures and limits input flexibility. Instead, we designed the building systems simulation manager to fully integrated simulation of loads, systems, and plant; and be modular and extensible.

To implement these concepts, we use loops throughout the building systems simulation manager—primarily HVAC air and water loops. Loops mimic the network of pipes and ducts found in real buildings. As mentioned earlier, EnergyPlus has no hardwired 'template' systems. Instead, we developed equivalent input file templates for major system types in BLAST and DOE–2. These templates provide an easy starting point for users to develop inputs for system configurations that differ from 'default' configurations. The air loop simulates: air transport, conditioning and mixing, and includes supply and return fans, central heating and cooling coils, heat recovery, and controls for supply air temperature and outside air economizer. The air loop connects to the zone through the zone equipment: diffusers, reheat/recool coils, supply air control (mixing dampers, fan-powered VAV box, induction unit, VAV dampers), local convection units (window air-conditioner, fan coil, water-to-air heat pump, air-to-air heat pump), high-temperature radiant/convective units (baseboard, radiators) and low-temperature radiant panels. Users must specify equipment in the order it will be used to meet zone heating and cooling demand.

For the air loop, the solution method is iterative, not 'single-pass' as in DOE–2 and BLAST. In order to specify equipment connections to a loop, nodes are defined at key locations around the loop with each node assigned a unique numeric identifier.

There are two loops for HVAC plant equipment—a primary loop (for supply equipment such as boilers, chillers, thermal storage, and heat pumps) and a secondary loop (for heat rejection equipment such as cooling towers and condensers). Equipment is specified by type (gas-fired boiler, open drive centrifugal chiller) and operating characteristics. In the first release of EnergyPlus, we implemented performance-based equipment models (such as in BLAST and DOE–2). But because of the modular code, it will be easy for developers to add other types of models. As in the air loop, the primary and secondary plant loops use explicit nodes to connect equipment to each loop. Connections between the air loop and zone equipment and the primary and secondary loops are made through the node data structure and must be explicitly defined in the input file. Fisher et al. (1999) provide additional information about the modular, loop-based approach to building systems simulation in EnergyPlus. A similar loop approach is planned for an electrical loop for simulating electrical systems—supply (utility, photovoltaic modules, and fuel cells) and demand (plug loads, lighting, and other electrical loads).

In the near term, EnergyPlus users will have more systems and equipment options through a link to SPARK (Buhl et al. 1993), an equation-based simulation tool for solving complex problems. A library of HVAC components based on the ASHRAE primary and secondary toolkits (LeBrun et al. 1999, Brandemuehl et al. 1993) is already available. EnergyPlus will continue to have system types (in input file templates) but developers and advanced users will be able to easily build complex new HVAC models with SPARK. A similar link is under development to the TRNSYS simulation model (Solar Energy Laboratory 2000), providing users with photovoltaic, solar thermal, and additional system and plant models.

INPUT, OUTPUT, AND WEATHER DATA

Both DOE–2 and BLAST use highly structured but user readable input files. Rather than focusing on user readability, we designed the EnergyPlus input files for easy maintenance and expansion. We chose to keep the input file simple in order to accept simulation input data from other sources such as CAD systems and pre-processors similar to those written for BLAST and DOE–2. EnergyPlus input files, while readable, are definitely not user-friendly. We expect most users will use EnergyPlus through one of the third-party interfaces under development. To make it easy for current DOE–2 and BLAST users to move to EnergyPlus, the team has written utilities that convert BLAST and DOE–2 **loads** input to the new EnergyPlus input structure.

The International Alliance for Interoperability has been developing an object-oriented data protocol for building information exchange. Several building CAD programs began incorporating this protocol, known as

Industry Foundation Classes (IFC), in 2001. The IFC may become another means of sharing information among building programs—including EnergyPlus (Bazjanac and Crawley 1999).

EnergyPlus uses a free format input file that contains a complete object-based description of the building and its systems. The basic syntax is:

object, data, data, data, . . ., data;

'Object' is a pre-defined word denoting a building component, such as SURFACE, MATERIAL, LIGHTING, SYSTEM, HEATING COIL, and BOILER. This word is followed by a list of data values and terminates with a semicolon. These data describe performance characteristics and intended use for that object in the simulation.

Unlike BLAST and DOE–2, the input file must explicitly provide all information—there are very few default assumptions. Users may include comments throughout their input data file. The input file syntax is not hardwired within EnergyPlus; instead EnergyPlus reads an input data dictionary at runtime to determine the syntax of the input data file. The general syntax of the input data dictionary is:

Object, A1 [an alpha], N1 [a number],...;

For example, for the EnergyPlus Location command, the data dictionary line is:

Location, A1 [Location Name], N1 [Latitude], N2 [Longitude], N3 [Time Zone], N4 [Elevation];

This tells EnergyPlus that, for the Location command, to expect one text field (A1) with the location name, and four numeric inputs (N1, N2, N3, and N4)–latitude, longitude, time zone and elevation, respectively. Words in brackets [ ] describe the variable and its units (meters, liters/second, etc.).

During a simulation, EnergyPlus saves results for each time step in an output data structure so that these results can be reported at each time step or aggregated to longer time intervals. This structure and subsequent output uses a similar philosophy to the input—simple text files with a syntax of object, time stamp, data, data, data, . . ., data; . The output data is simple yet contains much of the simulation results so that users and interface developers can easily access specific results without modifying the calculation engine.

Several report types are available—standard output (user specified variables at specified time intervals), one time output (such as input echo, input verification and interim calculations), and visual surface output (including DXF outputs). The data structure is simple and comma-separated, allowing output post-processors to easily read the data and create more elaborate reports. One drawback of our simple file format is that the output files can become very large.

The other major data is weather. Rather than using a binary weather file created by a separate weather processor, again we use a simple text-based format, similar to the input data and output data files. The weather data includes basic location information in the first eight lines: location (name, state/province/region, country), data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings period, typical and extreme periods, two lines for comments, and period covered by the data. The time-step data are also comma-separated are an extension of the TMY2 format (National Renewable Energy Laboratory 1995). EnergyPlus does not require a full year (8760 or 8784 hours) of data for its weather files. In fact, EnergyPlus allows and reads subsets of years and even sub-hourly data (the weather format includes a 'minutes' field). EnergyPlus comes with a utility that reads standard weather service file types such as TD1440 and DATSAV2 and newer 'typical year' weather files such as TMY2, IWEC, and WYEC2. Crawley, Hand and Lawrie (1999) provide more information on the weather data format.

In summary, all the data files associated with EnergyPlus, input, output, and weather, have simple self-contained formats that can be easily read and interpreted by other programs—spreadsheets, databases, or custom interface programs.

ADDING A NEW MODULE

One of the main goals for EnergyPlus is to make it easy for developers to add new features and modules. The process is conceptually simple:

- Define model parameters, equations, specialized coefficients and needed data.
- Determine the "plug-in" point—where EnergyPlus will call your module.
- Write specs for inputs necessary to "execute" the model.
- Using the EnergyPlus Programming Standard, and other developer documents, write the code – possibly breaking simulation tasks into modules, add call from higher level manager.
- Write and add input syntax to the Input Data Dictionary and produce the proper "GetInput" routine in the new module to obtain the data.
- Debug simulation routine; resolve snags associated with interactions with other loops

- Implement report variables; use to recheck results, repair model.

TESTING

A critical part of EnergyPlus version 1.0 development has been testing of the various beta releases using several simultaneous paths. The primary emphasis to date has been on comparative and analytical testing. Comparative testing of basic loads algorithms has been completed using the ASHRAE Standard 140-2001 (ASHRAE 2001) series of tests, which consist of a basic shoebox with windows and shading for both low mass and high mass construction. Figure 2 shows sample EnergyPlus results compared against reference data for a number of other simulation programs provided with Standard 140-2001. Analytical tests in progress include the BEPAC conduction tests (Bland 1993), which provide analytical solutions for conduction through a range of thickness for a variety of materials from aluminum to concrete. The conduction is driven by step, sine and ramp exterior temperature functions. Comparative version testing of EnergyPlus against itself has been extremely useful in detecting and resolving problems introduced during development. The testing to date demonstrates that EnergyPlus provides results in good agreement with other simulation programs for simple cases. Testing will continue throughout the development of EnergyPlus and the results and methodologies will be made available to users as part of the EnergyPlus documentation. For more information on the testing and validation of EnergyPlus, see Witte et al. (2001).

SUMMARY

In summary, EnergyPlus is a new building energy simulation program that combines the best features of the BLAST and DOE–2 programs along with many new capabilities. Connectivity and extensibility were overriding objectives in the design and development process to facilitate third party interface and module development. EnergyPlus not only combines the best features of the BLAST and DOE–2 programs, but also represents a significant step forward in terms of computational techniques and program structures.

We released EnergyPlus Version 1.0 in April 2001 and plan to release updates to EnergyPlus on a regular schedule. In mid-2001, we began planning new features to include in the second release of EnergyPlus based on suggestions by users, developers, and the team. Working with a coordinating group of users and developers, we have selected the features and capabilities for that release. New features already under development are electrical system simulation, fuel cells, advanced fenestration and daylighting, and other building technologies. These and other features will be included in the second major release (1.1) currently planned for 2003.

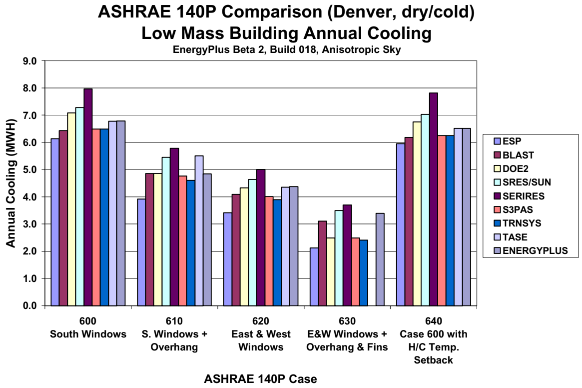

Figure 2. Sample EnergyPlus Comparative Testing Results

WEB RESOURCES

Up to date information on EnergyPlus including availability of updates, documentation, licensing, weather data, programming standards, and other documentation is available on the EnergyPlus web site:

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

Web-based directory of more than 200 building-related software tools from around the world:

http://www.eren.doe.gov/buildings/tools_directory/

REFERENCES

ASHRAE. 2001. *ANSI/ASHRAE Standard 140-2001, Standard Method of Test of the Evaluation of Building Energy Analysis Computer Programs*. Atlanta, Georgia: ASHRAE.

Arasteh, D. K., E. U. Finlayson, and C. Huizenga. 1994. *Window 4.1: Program Description*, Lawrence Berkeley National Laboratory, report no LBL-35298. Berkeley, California: Lawrence Berkeley Laboratory.

Bazjanac, Vladimir, and Drury Crawley. 1999. “Industry Foundation Classes and Interoperable Commercial Software in Support of Design of Energy-Efficient Buildings,” in *Proceedings of Building Simulation ’99*, Volume II, pp. 661-668, September 1999, Kyoto, Japan, IBPSA.

Bland, B. H.. 1993. "Conduction tests for the validation of dynamic thermal models of buildings," *BEPAC Technical Note 93/1*, August 1993. BEPAC.

Brandemuehl, Michael J., Shauna Gabel, and Inger Andresen. 1993. *HVAC2 Toolkit: Algorithms and Subroutines for Secondary HVAC System Energy Calculations*, Atlanta, Georgia: American Society of Heating, Refrigerating and Air-conditioning Engineers.

Building Systems Laboratory. 1999. *BLAST 3.0 Users Manual*. Urbana-Champaign, Illinois: Building Systems Laboratory, Department of Mechanical and Industrial Engineering, University of Illinois.

Buhl, W. F., A.E. Erdem, F. C. Winkelmann and E. F. Sowell. 1993. "Recent Improvements in SPARK: Strong-Component Decomposition, Multivalued Objects and Graphical Editors," in *Proceedings of Building Simulation '93*, pp. 283-289, August 1993, Adelaide, South Australia, Australia, IBPSA.

Crawley, Drury B., Jon W. Hand, and Linda K. Lawrie. 1999. "Improving the Weather Information Available to Simulation Programs," in *Proceedings of Building Simulation '99*, Volume II, pp. 529-536, September 1999, Kyoto, Japan, IBPSA.

Crawley, D. B., L. K. Lawrie, F. C. Winkelmann, W. F. Buhl, A. E. Erdem, C. O. Pedersen, R. J. Liesen, and D. E. Fisher. 1997. "The Next-Generation in Building Energy Simulation—A Glimpse of the Future," in *Proceedings of Building Simulation '97*, Volume II, pp. 395-402, September 1997, Prague, Czech Republic, IBPSA.

Fisher, Daniel E, Russell D Taylor, Fred Buhl, Richard J Liesen, and Richard K Strand. 1999. "A Modular, Loop-Based Approach to HVAC Energy Simulation And Its Implementation in EnergyPlus," in *Proceedings of Building Simulation '99*, Kyoto, Japan, September 1999. IBPSA.

Huang, Joe, Fred Winkelmann, Fred Buhl, Curtis Pedersen, Daniel Fisher, Richard Liesen, Russell Taylor, Richard Strand, Drury Crawley, and Linda Lawrie. 1999. "Linking the COMIS Multi-Zone Airflow Model With the EnergyPlus Building Energy Simulation Program," in *Proceedings of Building Simulation '99*, Volume II, pp.1065-1070, Kyoto, Japan, September 1999. IBPSA.

LeBrun, Jean, Jean-Pascal Bourdouxhe, and Marc Grodent. 1999. *HVAC1 Toolkit: A Toolkit for Primary HVAC System Energy Calculation*, Atlanta, Georgia: American Society of Heating, Refrigerating, and Air-conditioning Engineers.

National Renewable Energy Laboratory. 1995. *User's Manual for TMY2s (Typical Meteorological Years)*, NREL/SP-463-7668, and TMY2s, Typical Meteorological Years Derived from the 1961-1990 National Solar Radiation Data Base, June 1995, CD-ROM. Golden, Colorado: NREL.

Pedersen, Curtis O., Richard K. Strand, Richard J. Liesen, and Daniel E. Fisher. 2001. *Loads Toolkit 987-RP*. Atlanta: ASHRAE.

Solar Energy Laboratory. 2000. *TRNSYS Version 15 User Manual and Documentation*, February 2000. Madison, Wisconsin: Solar Energy Laboratory, Mechanical Engineering Department, University of Wisconsin.

Strand, Richard K. and Curtis O. Pedersen. 2001. "Modularization and Simulation Techniques for Heat Balance Based Energy and Load Calculation Programs: The Experience of the ASHRAE Loads Toolkit And EnergyPlus," in *Proceedings of Building Simulation 2001*, August 2001, Rio de Janiero, Brazil, IBPSA.

Winkelmann, Frederick C. 2001. "Modeling Windows in EnergyPlus," in *Proceedings of Building Simulation 2001*, August 2001, Rio de Janiero, Brazil, IBPSA.

Winkelmann, F. C., B. E. Birdsall, W. F. Buhl, K. L. Ellington, A. E. Erdem, J. J. Hirsch, and S. Gates. 1993. *DOE–2 Supplement, Version 2.1E*, LBL-34947, November 1993, Lawrence Berkeley National Laboratory. Springfield, Virginia: National Technical Information Service.

Winkelmann F. C. and S. E. Selkowitz. 1985. "Daylighting Simulation in the DOE–2 Building Energy Analysis Program," in *Energy and Buildings*, 8, pp. 271-286.

Witte, Michael J., Robert J. Henninger, Jason Glazer, and Drury B. Crawley. 2001. "Testing and Validation of a New Building Energy Simulation Program," in *Proceedings of Building Simulation 2001*, August 2001, Rio de Janiero, Brazil, IBPSA.