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ENERGYPLUS, A NEW-GENERATION BUILDING ENERGY SIMULATION PROGRAM

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ABSTRACT

Many of the popular building energy simulation programs around the world are reaching maturity—some use simulation methods (and even code) that originated in the 1960s. For more than two decades, the U. S. government supported development of two hourly building energy simulation programs, BLAST and DOE-2. Designed in the days of mainframe computers, expanding their capabilities further has become difficult, time-consuming, and expensive. Because of these problems, a U.S. federal agency began developing a new building energy simulation tool, EnergyPlus, building on the capabilities and features of BLAST and DOE-2. This paper focuses on the structure, features, and capabilities of EnergyPlus.

INTRODUCTION

In 1995, the U.S. Department of Energy (DOE) began planning for a new generation of simulation tools through a three-step process:

- Create an inventory of existing DOE-sponsored tools
- Sponsor workshops to get recommendations from users and developers about needs in energy simulation, and
- Define new generation tools based on the recommendations from the workshops and experience in developing BLAST (BLAST Support Office 1992) and DOE-2 (Winkelmann et al. 1993).

The inventory of DOE-sponsored tools first became a printed Building Energy Tools Directory (Crawley 1996) and later evolved into a web-based directory. Two workshops sponsored by DOE and the U.S. Department of Defense (DOD) in 1995 and 1996 provided significant input to planning efforts for a new simulation program, EnergyPlus. The tools directory and workshop results are described in Crawley et al. (1997). DOE chose three

organizations to form its initial development team: Lawrence Berkeley National Laboratory (LBNL)—developers of DOE's DOE-2 program (Winkelmann et al. 1993)—and U.S. Army Construction Engineering Research Laboratory (CERL) and the University of Illinois (UI)—developers of DOD's BLAST program (BLAST Support Office 1992)]. This paper describes the structure, features, and capabilities of EnergyPlus.

WHAT IS ENERGYPLUS?

EnergyPlus is a new building performance simulation program that combines the best capabilities and features from BLAST and DOE-2 along with new capabilities. EnergyPlus comprises completely new code written in Fortran 90. It is primarily a simulation engine—there is no formal user interface. Both BLAST and DOE-2 have many user interfaces developed by independent third-party developers. We have invited these same developers to work on graphical user interfaces for EnergyPlus.

MODULAR CODE

One of the main goals for EnergyPlus is to create a well-organized, modular structure that facilitates adding features and links to other programs. We decided to select Fortran 90 as the programming language for EnergyPlus because Fortran 90:

- is a modern, modular language with good compilers on many platforms
- allows C-like data structures and mixed language modules
- provides structure that begins to be object-based
- allows long variable names (up to 32 characters)
- provides backward compatibility during the development process

We began working on EnergyPlus by modularizing (restructuring) code from the heat balance engine in IBLAST, a research version of BLAST with integrated loads and HVAC calculation (Taylor et al. 1990, 1991). Normally such restructuring would result in major rewrites involving a long development period, and very extensive testing to ensure the new code performs as intended. To avoid this problem we devised a process we call ‘Evolutionary Reengineering (ER)’ that incrementally moves the program from old unstructured legacy code to new modular code by incorporating new code with old. Throughout the process, existing code still works with user input data, and is extended to generate parameters needed by the new code modules. In this way the new modules can be verified without having to completely replace the entire functional capability of the old program with new code before it can be tested. As the process proceeds, old routines are replaced by new routines and data structures. This makes the transition evolutionary and permits a smooth transition with a greater capability for verification testing. By the time we had achieved an alpha version, all the old code had been replaced with new, modular, Fortran 90 code.

ENERGYPLUS STRUCTURE

In the DOE/DOD workshops (Crawley et al. 1997) there was strong consensus that a more flexible and robust tool with additional capabilities is needed. Recurrent themes for simulation needs throughout the workshops were design, environment, economics, and occupant comfort and safety. Designers need tools that provide answers to very specific questions during design. They want tools that provide the highest level of simulation accuracy and detail reasonably possible but that don’t get in the user’s way. One of the highest priorities was an integrated (simultaneous) 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), 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 if necessary.

By using an integrated solution technique in EnergyPlus, the most serious deficiency of the BLAST and DOE-2 sequential simulations can be solved—inaccurate space temperature prediction due

to no feedback from the HVAC module to the loads calculations. Accurate prediction of space temperatures is crucial to energy efficient system engineering—system size, plant size, occupant comfort and occupant health all depend on accurate 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
- Interzone air flow

As shown in Figure 1, there are three basic components to EnergyPlus—a Simulation Manager, a Heat and Mass Balance Simulation module (based on IBLAST), and a new Building Systems Simulation module. The Simulation Manager controls the entire simulation process.

The Building Systems Simulation Manager handles communication between the heat balance engine and the HVAC water and air loops and their attached components (coils, boilers, chillers, pumps, fans, etc.) We replaced the hardwired ‘template’ systems (VAV, Constant Volume Reheat, etc.) of DOE-2 and BLAST with user-configurable heating and cooling equipment components. This gives users much more flexibility in matching their simulation to the actual system configurations. The Building Systems Simulation Manager also manages data communication between the HVAC modules, input data, and output data structures.

A comparison of major features and capabilities of EnergyPlus, BLAST, IBLAST, and DOE-2 are shown in Tables 1-3.

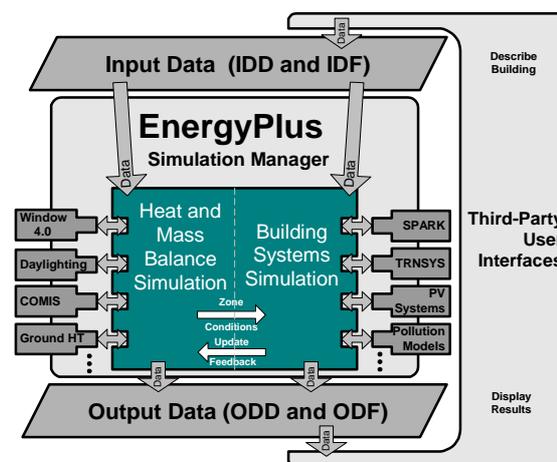


Figure 1 Overall EnergyPlus Structure

Table 1 Comparison of General Features and Capabilities

Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Integrated, Simultaneous Solution <ul style="list-style-type: none"> • Integrated loads/systems/plant • Iterative solution • Tight coupling 			X	X
Multiple Time Step Approach <ul style="list-style-type: none"> • 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 minute) 			X	X
Input Functions <ul style="list-style-type: none"> • Users can modify code without recompiling 	X			X
New Reporting Mechanism <ul style="list-style-type: none"> • Standard reports • User-definable reports with graphics 				X

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—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 contained 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

The underlying building thermal zone calculation method in EnergyPlus is a heat balance model in which room air is modeled as well stirred with

uniform temperature throughout. (The modular structure of EnergyPlus allows more detailed room air convection calculations—such as CFD or zonal methods—to be added later.) It is also assumed that room surfaces (walls, windows, ceilings, and floors) have:

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

Figure 2 shows the structure of the EnergyPlus integrated solution manager that 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, 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 EnergyPlus links to COMIS (Fuestel 1990) for improved multizone airflow, infiltration, indoor contaminant, and ventilation calculations.

In addition to the basic heat balance engine from IBLAST, we have created three new modules based on capabilities from DOE-2: daylighting simulation (Winkelmann and Selkowitz 1985), WINDOW 4-based window calculations (Arasteh et al. 1994), and anisotropic sky. The Daylighting Module calculates hourly interior daylight illuminance, glare from windows, glare control, electric lighting controls, and calculates electric lighting reduction for the heat balance module. The Window Module incorporates capabilities from WINDOW 4—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). Sun control can be modeled with pull-down shades, blinds or electrochromic glazing. The sky model includes non-isotropic radiance and luminance

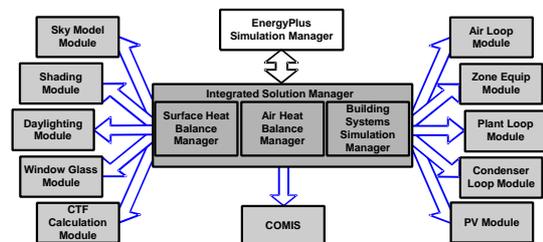


Figure 2 Integrated Simulation Manager

Table 2 Comparison of Loads Features and Capabilities

Loads Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Heat Balance Calculation <ul style="list-style-type: none"> Simultaneous calculation of radiation and convection processes each time step 		X	X	X
Interior Surface Convection <ul style="list-style-type: none"> Dependent on temperature and air flow Internal thermal mass 	X	X	X	X
Moisture Absorption/Desorption <ul style="list-style-type: none"> Combined heat and mass transfer in building envelopes 			X	X
Thermal Comfort <ul style="list-style-type: none"> Human comfort model based on activity, inside dry bulb, humidity, and radiation 		X	X	X
Anisotropic Sky Model	X			X
Advanced Fenestration <ul style="list-style-type: none"> Controllable window blinds Electrochromic glazing 	X			X
WINDOW 4 Library <ul style="list-style-type: none"> More than 200 window types—conventional, reflective, low-E, gas-fill, electrochromic User defined using WINDOW 4 	X	X	X	X
Daylighting Illumination and Controls <ul style="list-style-type: none"> Interior illuminance from windows and skylights Step, dimming, on/off luminaire controls Glare simulation/control Effects of dimming on heating and cooling 	X			X

distribution of the sky based on the empirical model by Perez (1990, 1991) as a function of sun position and cloud cover. This non-uniform radiance distribution improves calculation of diffuse solar on tilted surfaces (walls and sloped roofs).

Several other modules have been reengineered for inclusion in EnergyPlus: solar shading from BLAST and conduction transfer function calculations from

Table 3 Comparison of HVAC Features and Capabilities

HVAC Systems and Equipment Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Fluid Loops <ul style="list-style-type: none"> Connect primary equipment and coils Hot water loops, chilled water and condenser loops, refrigerant loops 	X			X
Air Loops <ul style="list-style-type: none"> Connect fans, coils, mixing boxes, zones 				X
User-configurable HVAC systems				X
Hardwired HVAC systems descriptions (templates)	X	X	X	
High-Temperature Radiant Heating <ul style="list-style-type: none"> Gas/electric heaters, wall radiators 		X		X
Low-Temperature Radiant Heating/Cooling <ul style="list-style-type: none"> Heated floor/ceiling Cooled ceiling 			X	X
Atmospheric Pollution Calculation <ul style="list-style-type: none"> CO₂, SO_x, NO_x, CO, particulate matter and hydrocarbon production On-site and at power plant Calculate reductions in greenhouse gases 	X	X		X
SPARK Connection				X
TRNSYS Connection				X

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. With the support of the Gas Research Institute and Florida Solar Energy Center, we plan to incorporate a simplified moisture model known as Effective Moisture Penetration Depth (EMPD) to estimate

moisture interactions among the space air and interior surfaces and furnishings. EMPD is useful for estimating impacts associated with moisture where detailed internal geometry and/or detailed material properties are not readily available.

Another important feature of the EnergyPlus heat balance engine is that it is essentially identical in functionality to the Loads Toolkit being developed by UI for ASHRAE TC 4.7 under Research Project 987. UI is developing both the Loads Toolkit and the EnergyPlus heat and mass balance engine and is using 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.

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 a sequential simulation method (first building loads, then distribution system, and then plant) as found in DOE-2 and BLAST since this imposes rigid boundaries on program structures and limits input flexibility. Instead, we designed the Building Systems Simulation Manager with several objectives:

- fully integrated simulation of loads, systems, and plant
- modular
- extensible

Integrated simulation allows capacity limits to be modeled more realistically and provides tighter coupling between the air- and water-side of the system and plant. Modularity is maintained at both the component and system level. This eases adding new components and flexibly modeling system configurations and, at the system level, equipment and systems are clearly connected to zone models in the heat balance manager. 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; later, EnergyPlus will simulate head and thermal losses (pipe/duct losses) that occur as fluid moves in each loop.

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. Zone equipment includes diffusers, reheat/recool coils, supply air control (mixing dampers, fan-powered VAV box, induction unit, VAV dampers), local convection units (window air-conditioning, 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 can specify more than one equipment type for a zone. However, equipment must be listed 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. Node identifiers store loop state variables and set-point information for that location in the loop. We use an iterative solution technique to solve for unknown state variables along with control equation representations. These representations connect the set points at one node with the control function of a component, such as fan damper position and cooling coil water flow rate. In this schema, all the loop components are simulated first, and then the control equations are updated using explicit finite difference. This procedure continues until the simulation converges.

There are two water 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 its operating characteristics. In the first release of EnergyPlus we are supporting curve-based equipment models (such as in BLAST and DOE-2). However, 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.

A similar loop approach is proposed for a new electrical loop for simulating electrical systems—supply (utility, photovoltaic modules, and fuel cells), demand (plug loads, lighting, and other electrical loads), and measurement (meters). In the longer term, EnergyPlus users will have more systems and equipment options through a link to SPARK (Buhl et al. 1993), a new equation-based simulation tool.

SPARK is a better solver for complex iterative problems and is currently in beta testing. SPARK already has a library of HVAC components based on the ASHRAE primary and secondary toolkits. EnergyPlus will continue to have system types (in input file templates) but developers and advanced users will be able to build complex new HVAC models with SPARK.

INPUT, OUTPUT, AND WEATHER DATA

Instead of user readability, we designed the EnergyPlus input and output data 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 CADD systems, programs that also do other functions, and preprocessors similar to those written for BLAST and DOE-2. An EnergyPlus input file is not intended to be the main interface for typical end-users. We expect most users will use EnergyPlus through an interface from a third-party developer. 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 input to the new EnergyPlus input. Input comparisons for BLAST, DOE-2, and EnergyPlus are shown in Table 4.

During a simulation, EnergyPlus saves results for each time step in an output data structure. The heat balance time step is user-specified with a default of 15 minutes. HVAC results may proceed at the heat balance time step or at smaller time steps in order to reach stability. The EnergyPlus output processor provides these results in a simple variable-based format that can easily be read by post-processing programs.

The other major data input is weather. Rather than a binary 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 format 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 data are also comma-separated and contain much of the same data in the TMY2 weather data set (NREL 1995). EnergyPlus does not require a full year or 8760 (or 8784) hours in its weather files. In fact, EnergyPlus allows and reads subsets of years and even sub-hourly (5 minute, 15 minute) data—the weather format includes a ‘minutes’ field. EnergyPlus comes with a utility that reads standard meteorological service files and newer ‘typical year’ weather files such as TMY2

and WYEC2. For more information on the EnergyPlus weather format, see Crawley and Hand (1999).

In summary, all the data files associated with EnergyPlus—input, output, and weather—have simple, self-contained formats which can be easily read and interpreted by other programs—spreadsheets, databases, or custom programs. By working with third party interface developers early we will keep these files simple and easy to use by other programs that building designers use.

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 relatively simple. First, a developer defines a new module with model parameters and equations, specialized coefficients, and data needed. A developer then finds the ‘plug-in’ point—where the module would be called within EnergyPlus. Next the developer writes the module (using the EnergyPlus programming standard), breaking the simulation tasks into modules. Finally, the developer writes new input file syntax based on the input needed for the module, determines what variables will be available for output processing and uses EnergyPlus internal service routines to get the input and produce any output.

RELEASE 1.0 AND BEYOND

“More people have ascended bodily into heaven than have shipped great software on time.” (McCarthy 1995)

The first working version of EnergyPlus, an alpha version, was completed in December 1998 for internal testing by the team. A beta version of EnergyPlus will be available for testing by outside users and developers in late summer 1999. We plan to release Version 1.0 of EnergyPlus in 2000.

In early 2000 we will begin planning for Version 2.0 of EnergyPlus based on new features suggested by users, developers and the team. Working with a coordinating group of users and developers, we will then select the features and capabilities for that release. We plan to release updates to EnergyPlus on a regular, 18-month release cycle. New features already under development include a connection to the COMIS airflow program, improved ground heat transfer, and solar thermal and photovoltaic modules. Included in future developments are more HVAC equipment and lighting and electrical system simulation capabilities.

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Table 4 Comparisons of BLAST, DOE-2 and EnergyPlus Input

		BLAST	BDL (DOE-2)	EnergyPlus
Location (Simple Input)	Description	Location defined in library. Library includes name, latitude, longitude, elevation, and time zone.	Location information defined by input, defaults to information on weather file	Location information defined by input.
	Input Syntax	LOCATION = Name;	BUILDING-LOCATION Latitude = W, Longitude = X, Altitude = Y, Time-Zone = Z ..	LOCATION, Name, Latitude, Longitude, Elevation, TimeZone;
	Example Input	LOCATION = CHICAGO;	BUILDING-LOCATION LATITUDE = 41.98 LONGITUDE = 87.90 ALTITUDE = 673 TIME-ZONE = 6 ..	LOCATION, Chicago Illinois USA, 41.98, 87.90, 205, -6;
Material (More Complex)	Description	Material defined in library. Library includes material name, conductivity, density, specific heat, resistance, roughness, and moisture properties.	Material from library or defined in input, includes thickness, conductivity, density, specific heat, or resistance. Thickness restated during Layer input (optional).	All material information defined by input.
	Input Syntax	TEMPORARY MATERIAL: Usname = (L=usn1, K=usn2, CP=usn3, D=usn4, ABS=usn5, TABS=usn6, R=usn7, TRANS=usn8, IR=usn9, FILMTRANS=usn10, REF=usn11, SC=usn12, roughness, asg); END;	A = Material, Thickness = W, Conductivity = X, Density = Y, Specific Heat = Z ..	MATERIAL, Name, Thickness, Conductivity, Density, Specific Heat, Roughness, Moisture Permeance, Moisture Resistance;
	Example Input	Brick = (L=0.3333, K=5.6, CP=0.19, D=120, ROUGH);	BRICK = MATERIAL THICKNESS = 0.3333 CONDUCTIVITY = 5.6 DENSITY = 120 SPECIFIC-HEAT = 0.19 ..	MATERIAL, Brick, 0.1016, 0.721, 1922,837,46,0.022;

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WEB RESOURCES

Building Energy Tools Directory, a directory of information on more than 160 energy tools from around the world.

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

Next-Generation Simulation Workshops, description of the process and the results from two workshops on needs for new energy simulation tools.

http://www.eren.doe.gov/buildings/energy_tools/workshops.htm

EnergyPlus, up-to-date information on the current status of EnergyPlus and working with the team, and documentation such as input data structure, output data structure, and licensing opportunities.

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