This paper presents an overview of the DOE-2 Computer Program. It was presented at the ASEAN Conference on Energy Conservation in Buildings in Singapore, 5/84.

LBL-18046
EEB-DOE-2 84-3

THE DOE-2 BUILDING ENERGY ANALYSIS PROGRAM

Richard B. Curtis, Bruce Birdsall, W. Fred Buhl, Ender Erdem, Joseph Eto, James J. Hirsch, Karen H. Olson, Frederick C. Winkelmann

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
U.S.A.

April 1984

Summary

The DOE-2 Building Energy Analysis Program was designed to allow engineers and architects to perform design studies of whole-building energy use under actual weather conditions. Its development was guided by several objectives: 1) that the description of the building entered by the user be readily understood by non-computer scientists, 2) that, when available, the calculations be based upon well established algorithms, 3) that it permit the simulation of commonly available heating, ventilating, and air-conditioning (HVAC) equipment, 4) that the computer costs of the program be minimal, and 5) that the predicted energy use of a building be acceptably close to measured values. These objectives have been met. This paper is intended to give an overview of the program upon completion of the DOE-2.1C edition.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

I Background

As with many advances in the fields of energy conservation and renewable energy sources, the impetus for the development of a computer program that would allow the simulation of the energy use in buildings was the Oil Embargo of 1973. By 1976 both the Energy Research and Development Administration (ERDA) and the Energy Commission of the State of California had determined that existing programs were inadequate for the non-academic researcher and that a development program should be undertaken. Initially, it was hoped that existing programs could be combined and a user-interface could be written to satisfy the immediate need. A project was established among several National Laboratories (Argonne National Laboratory and Los Alamos National Laboratory) with the project leadership centered at Lawrence Berkeley Laboratory. This project, sponsored by both the State of California and ERDA, produced a program in 1976 called Cal-ERDA [1]. At that point the joint sponsorship came to an end and ERDA was absorbed into the new Department of Energy. A slightly improved version of the program was labeled DOE-1 [2] and became the first of a series of versions [3,4,5,6,7,8] culminating to date in a much more sophisticated program labeled DOE-2.1C.

The development of the program has been driven by several different goals. In the late 1970's, the proposed and Congressionally mandated Building Energy Performance Standards (BEPS) required that a standard evaluation technique be established and, after some study, a decision was made that DOE-2 be upgraded to meet the requirements for such a standard [9]. Simultaneously, a growing user community, able for the first time to make building energy studies, demanded improvements in almost every phase of the program.[1] Finally, the lessened sense of an energy emergency in the United States coupled with the realization that the basic algorithms of the program have been stretched to their limits, have lead to a decision to bring the development of DOE-2 to a close with the DOE-2.1D version. Current development activities are designed to leave the user community with a flexible and fairly complete simulation tool. With that end in view the authors of the program want to take this opportunity to summarize what has been done.

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[1] It is not possible to determine how many users of DOE-2 there are in the world, however, the program has been purchased by 67 institutions or firms and is available on all the major computer service bureaus in the United States. In addition, the it has been installed on computers in over 12 countries including Austria, Canada, Chile, France, Italy, Japan, Kuwait, New Zealand, Peoples Republic of China, Singapore, and Sweden.

II DOE-2 Design Strategy

A building, examined thermodynamically, involves non-linear flows of heat through and among all of its surfaces and enclosed volumes and driven by a variety of heat sources. Mathematically, this corresponds to a set of coupled integral-differential equations with complex boundary and initial conditions. The function of a program like DOE-2 is to simulate the thermodynamic behavior of the building by approximately solving the mathematical equations. What distinguishes the various computational methods and energy analysis programs is the nature of the approximations made in the solution of the equations and the methods of data entry [10,11].

DOE-2 performs its energy use analysis of buildings in four principal steps.

First is the calculation of heat loss and gain to the building spaces and the heating and cooling loads imposed upon the building HVAC systems. This calculation is carried out for a space temperature fixed in time and is commonly called the LOADS calculation. It answers the question: how much heat addition or extraction is required to maintain the space at a constant temperature as the outside weather conditions and internal activity vary in time and the building mass absorbs and releases heat.

Second is the calculation of the energy addition and extraction actually to be supplied by the HVAC system in order to meet the possibly varying temperature set-points and humidity criteria subject to the schedules of fans, boilers and chillers, and to outside air requirements. This calculation results in the demand for energy that is made on the primary energy sources of the building. This step, called the SYSTEMS calculation, answers the question: How are the accumulative heat extraction and addition rates modified, when the characteristics of the HVAC system, the time-varying temperature set-points, and the heating, cooling and fan schedules are taken into account?

Third is the determination of the fuel requirements of primary equipment such as boilers and chillers, of the energy production of solar collectors, and the electric generators, etc., in the attempt to supply the energy demand of the HVAC systems. This PLANT calculation answers the question: how much fuel and electrical input is required to feed the secondary HVAC system given the efficiency and operating characteristics of the plant equipment and components.

The fourth step, ECONOMICS, evaluates the costs of equipment, fuel, electricity, labor and retrofit components against the alternative of investing the money in other ways. It answers the question: Is the expenditure of funds for energy conserving materials and systems cost effective, when compared with alternative systems and investment possibilities?

The first three steps involve three structural approximations to the actual flow of energy in a real building, illustrated in a symbolic fashion in Figure 1. By "structural" is meant a fundamental approach to

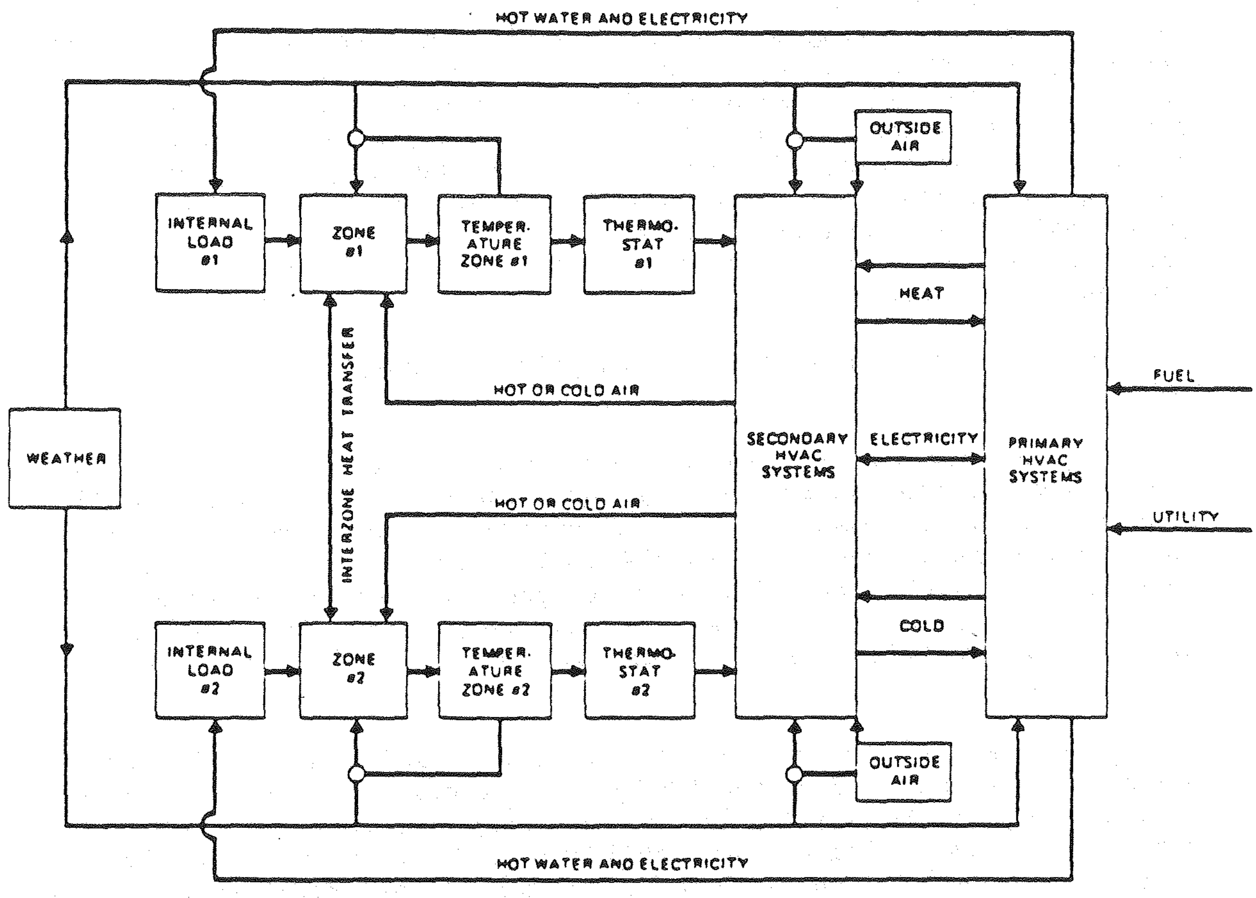

Figure 1. Schematic of Coupled Equations

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modeling the thermal behavior of a building that is mirrored in the structure of the computer code itself. First, because the steps are sequential and not re-entered, all of the feedback loops from later steps to earlier steps have been cut. For example, SYSTEMS assumes that PLANT will supply all the hot or chilled water that is required. Should PLANT not be able to do so, it will print a report that so many hours of loads were not met, but the reports from SYSTEMS, including the estimations of zone temperatures, will not be responsive to the undersized plant equipment. To correct these reports, a second run must be made with smaller sized air-side equipment that reflects the smaller plant equipment. Similar problems can arise between LOADS and SYSTEMS where the assumption of constant space temperatures in LOADS can lead to misleading loads to be met by the HVAC equipment.

Secondly, the continuous time dependence of phenomena is approximated by making the calculation in hourly time intervals. Although such an interval allows a more realistic approximation than energy analysis programs which use an average day per month, it is clear that there are phenomena within a building that occur with a time constant that is small relative to an hour. Averaging algorithms have been developed that hopefully simulate the net energy consumption effect of more rapidly changing events.

A third major approximation involves the use of weighting factors in place of, in principle, more accurate hourly detailed heat balance calculations [12,13,14]. In the weighting factor approach the detailed heat balance response in time of a zone with all its mass and walls and fenestration to a unit pulse of each of the major heat gains is calculated once at the beginning of the program resulting in a list of coefficients called weighting factors. These factors are stored and used henceforth in the hourly simulation. A similar set of factors is developed describing the variation of the temperature as the loads and extraction rates change. If the thermal characteristics of the zone and its walls and fenestration are constant in time, the weighting factor and the detailed thermal balance approach should agree.

II.A LOADS

II.A.1 General Considerations

The LOADS program computes for each zone of the building the hourly cooling and heating loads. A <u>cooling load</u> is defined as the rate at which energy must be removed from a space to maintain a constant air temperature in the space. A <u>space</u> is a user-defined subsection of the building. It can correspond to an actual room, or it may be much larger or smaller, depending upon the level of detail appropriate to the simulation.

The space cooling (or heating) loads are obtained by a two-step process. First, the space heat gains (or losses) are calculated; then the space cooling loads are obtained from the space heat gains. A <u>space heat gain</u> is defined as the rate at which energy enters or is generated within a space in a given moment. The space heat gain is divided into various components, depending on the manner in which the energy is transported into or generated within the space. The components are:

1. solar heat gain from radiation through windows and skylights,

2. heat conduction through walls, roofs, windows, and doors in contact with the outside air,

3. infiltration air (unintended ventilation),

4. heat conduction through walls and floors in contact with the ground,

5. heat conduction through interior walls, floors, ceilings, and partitions,

6. heat gain from occupants,

7. heat gain from lights,

8. heat gain from equipment.

The calculation of heat conduction through walls involves solving the one dimensional diffusion equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

each hour, where T is the temperature and α the thermal diffusivity. In DOE-2 the equation is solved before the hourly simulation for each wall for unit pulses and the response in time is stored. These "response factors" [15,16] are used in the hourly simulation modulated by the actual indoor and outdoor temperatures. This approach assumes that the wall properties, including inside film coefficients, do not change during the simulation.

The solar gain calculation starts with the direct and diffuse solar radiation components, which are obtained from measured data or computed from a cloud cover model, taking into account the actual position of the sun each hour. The radiation is projected onto glass surfaces, after taking into account the shading (for the direct component) of exterior shading surfaces, and transmitted, absorbed, and reflected in accordance with the properties of the glass in the window. As with the conduction through walls, the problem is presolved for a finite class of window properties.

Heat flow through interior walls and through surfaces in contact with the soil is treated as steady state, i.e., the capacitive effects of the walls is ignored in the hourly calculation, although they are taken into account in the calculation of the weighting factors. For interior walls that are light and not load bearing, this is a reasonable assumption. Interior walls between a sunspace and an interior space, on the the other hand, can be massive and such walls will be treated as such (see below).

The internal heat gains from people, lights, and equipment are basically fixed by the user's input of hourly schedules for these gains.

In general, space heat gains are not equal to space cooling loads. An increase of radiant energy in a space does not immediately cause a rise in the space air temperature. The radiation must first be absorbed by the walls, cause a rise in the wall surface temperature, and then (by convective coupling between the wall and the air) cause an air temperature rise. This is handled in DOE-2 through the weighting factors mentioned above. The user can choose either to use precalculated weighting factors or to have the program calculate them (custom weighting factors) for the space as input. The latter choice requires a more detailed description of the space and its surfaces than are required for using the precalculated variety. The advantage, of course, is that the custom weighting factors more accurately describe the space in question.

II.A.2 Special Features

Almost all building energy analysis programs include the features discussed above, although some, e.g., BLAST [17,18], use a detailed heat balance approach rather than the weighting factor approach. In DOE-2.1C there are several additional features that greatly extend the usefulness of the program. These include in the LOADS program the ability to take advantage of credit for daylighting (already available in DOE-2.1B), the ability to model sunspaces and the transmission of solar radiation through interior windows, and a mechanism by which users can substitute their algorithms for those used by the program.

II.A.2.a Daylighting Credit

Lighting accounts for about 20% of the total electrical energy consumption in the United States. A very cost-effective way of reducing this consumption, and at the same time enhancing the quality of the indoor environment, is to use daylighting. Architects and engineers have been using physical models, hand calculator programs, and sophisticated main-frame computer programs, like LUMEN-II, to determine the level of interior daylight for different building configurations. However, none of these tools determines the annual energy savings from daylighting -- information which can have an important effect on design decisions.

For this reason, a daylighting simulation has been added to DOE-2. Designers can now quickly and inexpensively determine the hourly, monthly, and yearly impact of daylighting on electrical energy consumption and peak electrical demand, as well as the impact on cooling and heating requirements, and perhaps most important, on annual energy cost.

The DOE-2 daylighting algorithms were developed in collaboration with the LBL Windows and Daylighting Group [19]. The calculation has two main stages. In the first stage, a preprocessor calculates in detail a set of "daylight factors" (interior illuminance divided by exterior horizontal illuminance) for later use in the hourly loads calculation. The user specifies the coordinates of one or two reference points in a space. DOE-2 then integrates over the area of each window to obtain the contribution of light from the window directly contributing to the illuminance at the reference points, and the contribution of light which enters the window and reflects from the walls, floor, and ceiling before reaching the reference point. Taken into account are such factors as window size and orientation, glass transmittances, inside surface reflectances of the space, sun-control devices such as blinds and overhangs, and the luminance distribution of the sky. Since this distribution depends on the position of the sun and the cloudiness of the sky, the calculation is carried out for standard clear and overcast sky conditions and for a series of 20 different solar altitude and azimuth values covering the annual range of sun positions. The resulting daylight factors are stored for later use. Analogous factors for discomfort glare are also calculated and stored.

Stage two is the hourly daylighting calculation performed every hour of the year that the sun is up. The illuminance from each window is found by interpolating the stored daylight factors using the current-hour sun-position and cloud cover, then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will automatically close window blinds or drapes in order to decrease glare below a pre-defined comfort level. Adding the illuminance contributions from all the windows then gives the total number of footcandles at each reference point.

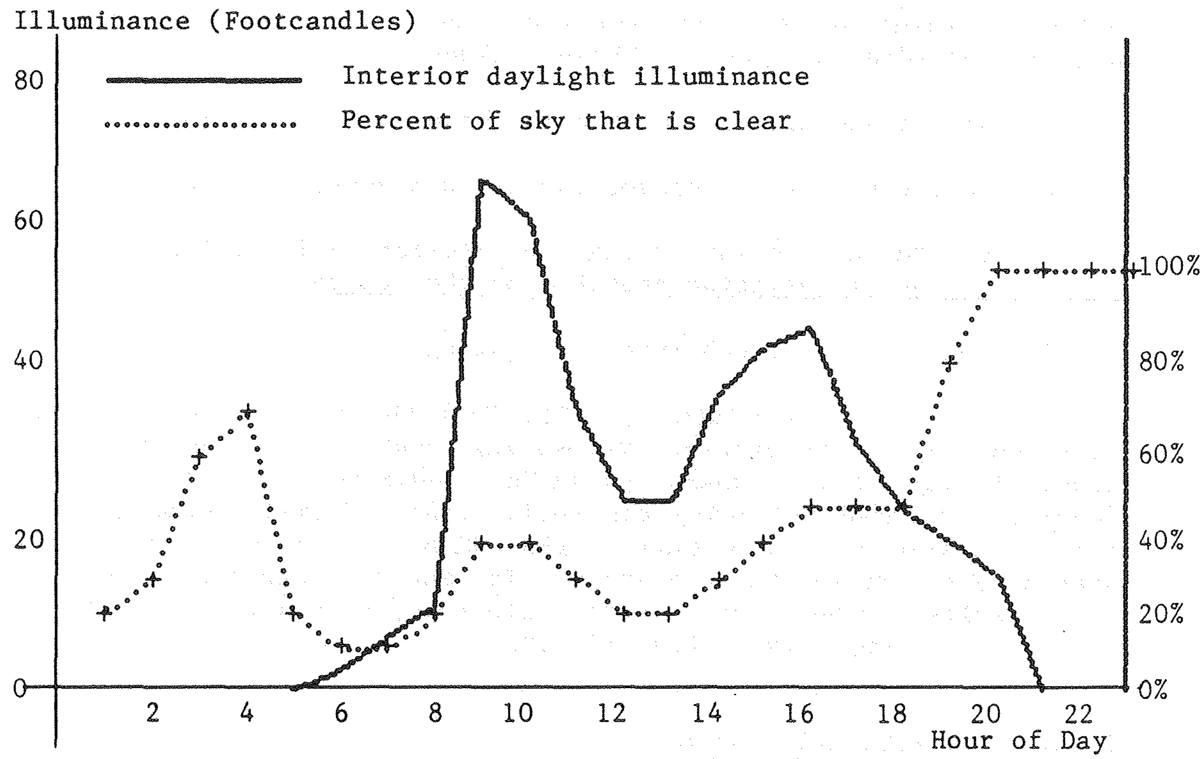
The program next simulates the lighting control system to determine the artificial lighting electrical energy needed to make up the difference, if any, between the daylighting level and the required illuminance.

Some results of the daylighting calculation are shown in Figure 2 for a partly cloudy June day in San Francisco. Under consideration is a space with an east-facing window with a glass transmittance of 80%. The window is covered on the inside by fixed drapery having a transmittance of 60%. A 4-foot deep overhang runs the entire length of the window. Wall, floor, and ceiling reflectance is 50%. The daylighting reference point is located at the center of the space at desk height. Overhead lighting of 2 w/ft^2 provides 50 fc of illuminance at full power, between 8:00 a.m. and 6:00 p.m. Continuously dimmable lighting control allows the lights to dim linearly to 10 fc at minimum (30%) power

Figure 2a shows that the daylight illuminance varies from a minimum of 0.4 fc at 5:00 a.m. to a maximum of 64.4 fc at 9:00a.m. Summing over the hours in Figure 2b gives a net reduction in lighting energy use of 59%.

To verify that the DOE-2 daylighting calculation gives accurate results, program predictions are being checked against illuminance measurements obtained by the Windows and Daylighting Group using scale models with various common window configurations. An offshoot of this cross-check will be the development of a method to allow daylight factors measured from models (or calculated by programs like LUMEN-II) to be used directly in DOE-2, thus enabling it to simulate virtually any daylighting configuration.

2a.



2b.

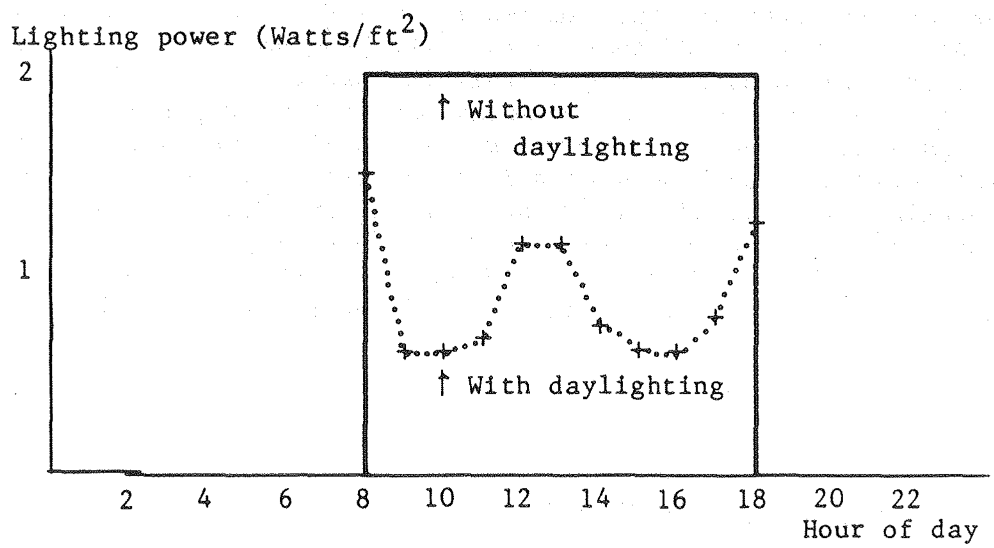


Fig. 2. Results of DOE-2 daylighting calculation for a June day in San Francisco. (a) Daylight illuminance at reference point and percent of sky that is clear. (b) Lighting power with and without daylighting controls.

II.A.2.b Sunspace Model

Algorithms have been added to DOE-2.1C to allow the program to model different forms of heat transfer that can occur between a sunspace (or atrium) and adjacent spaces. These include

1. direct and diffuse solar gain through interior glazing,
2. forced or natural convection through vents or an open doorway,
3. delayed conduction through an interior wall, taking into account the solar radiation absorbed on the sunspace side of the wall,
4. conduction through interior glazing.

The model also simulates (in SYSTEMS) the venting of the sunspace with outside air to prevent overheating, and, for residential application, the use of a sunspace to preheat outside ventilation air. The model is intended primarily for residential and small commercial building applications. The reason is that DOE-2 calculates only a single, average air temperature in a space. It cannot be expected to give accurate results for multi-story atria unless there is sufficient air mixing to eliminate temperature stratification.

II.A.2.c Functional Approach

For the sophisticated user with access to the DOE-2.1C source code there is a way of making changes in the way that DOE-2 does its calculations in LOADS without having to recompile the code. This "Functional Approach" involves writing limited-feature FORTRAN program(s) at the end of one's input to LOADS that compute the program variables as desired by the user. The possibilities of this feature are many and include changing the value of the glass shading-coefficient depending upon whether the space has a heating or cooling load, making the outside film coefficient dependent upon the wind direction, printing user designed reports, accounting for the effect of shading on the diffuse component of the solar radiation, and changing schedules depending upon the thermal state of the building. Although limited at present to LOADS only, this feature will be extended to the rest of the program in DOE-2.1D.

II.B SYSTEMS

II.B.1 General Considerations

The SYSTEMS program simulates the equipment that provides heating, ventilating and/or air conditioning (HVAC) to the thermal zones and the interaction of this equipment with the building envelope [20]. This simulation comprises two major parts:

1. Since the LOADS program calculates the "load" at constant space temperature, it is necessary to correct these calculations to account for equipment operation.

2. Once the net sensible exchange between the thermal zones and the equipment is solved, the heat and moisture exchange between equipment, heat exchangers, and the building can be completely calculated and the resultant primary equipment or utility "loads" can be calculated.

The constant air temperature calculation in LOADS has two major advantages. First, it greatly reduces the computation time of this part of the calculation, although introducing some approximations that preclude accurate modeling of certain configurations. Second, and more important, it allows tight coupling between the envelope and the equipment. This coupling is very important since the equipment operation in response to control actuation is most often a non-linear process. As a result, the energy input to the equipment is not always proportional to the envelope "load". Stated another way: the operation of and energy input to the HVAC equipment can quite often mask the base envelope load.

The dynamics of the interaction between the equipment and the envelope are calculated by the simultaneous solution of the room air-temperature weighting factor equation with the equipment controller relation. The former relates the "load" from LOADS and the heat extraction rate (the equipment output) to the zone temperature. The latter relates the heat extraction rate to the controlling zone temperature. Once the supply and thermal zone temperatures are known, the return air temperature can be calculated and the outside air system and other controls can be simulated. Thus the sensible exchange across all coils can be calculated.

The moisture content of the air is calculated at three points in the system: the supply air, the return air and the mixed air. These values are calculated assuming that a steady state solution of the moisture balance equations will closely approximate the real world. The return air humidity ratio is used as the input to the controller activating a humidifier in the supply airflow or resetting the cooling coil controller to maintain maximum space humidity set points. The moisture condensation on the cooling coils is simulated by characterizing the coils by their bypass factors and solving the bypass relation simultaneously with the system moisture balance.

Once the above sequence is complete, all coil loads are known. These values are then either passed to the PLANT program as heating and cooling loop loads or, in the case of direct-expansion and non-hot water or steam coils, equipment required to handle these loads is simulated in SYSTEMS.

II.B.2 System Types

The DOE-2 program provides the user with 22 generic system types with many sizing and control options, depending upon the type chosen. The following table lists them with their familiar trade names:

Index of System Types

Category	Trade Name
Single Supply Duct Types	Variable Temperature
	Packaged DX Variable Temperature
	Ceiling Induction
	Reheat
	Variable Air Volume
	Powered Induction Unit
	Packaged DX VAV
	Ceiling Bypass
Air Mixing Types	Multizone
	Packaged DX Multizone
	Dual Duct
Terminal Unit Types	Two Pipe Fan Coil
	Four Pipe Fan Coil
	Two Pipe Induction
	Four Pipe Induction
	Packaged Air Conditioner
	Water/Air Heat Pump
Residential	Furnace and Condensing Unit
Heating Only	Panel Heating
	Central Ventilation (e.g. schoolhouse)
	Unit Heater
	Classroom Unit Ventilator
Diagnostics	Sums Zone Loads

Baseboards, controlled either by zone thermostat or by an outdoor reset thermostat, are available in association with most of the system types. Depending upon the type, the coil temperatures can be controlled by calendar schedule, by outdoor reset schedule, by discrimination of warmest or coldest zone, or held constant. The humidity can be controlled where applicable to lie within limits. Outdoor air economizers are available that are either temperature or enthalpy controlled. Heat recovery options are included. Fans can be either draw-through or blow-through and the fan motor can be placed in or out of the airstream. Various night controls are available both for the system fans and for ventilation fans. Also, optimal start controls for the fans are an option for morning start-up. For packaged single zone systems a simulation of supermarket refrigeration cases is available.

II.B.3 System Design

Many equipment design parameters must be known before the hourly simulation can proceed. The user can specify these parameters in the description of the thermal zone or the HVAC system. To make the program easier to use in the early stages of analysis, a set of procedures has been included in the program to calculate most of these parameters, if the user has not provided enough information. Before the simulation can start, all air flow rates, equipment capacities, and off-design performance functions must be known. Default curves are available for all the off-design performance functions, however, the user can replace one or more of these curves through a curve fitting command.

Air flow rates and coil capacities, however, cannot be precalculated. These values depend, usualsually, upon heating and cooling requirements. If the user does not supply some or any of these, the program calculates values using whatever information has been supplied, supplemented by its own calculations and information from LOADS. The values so calculated by the program are designed to meet the peak loads <u>in a steady state situation</u>. This means that there can be problems of undersizing, if a night setback or setup is used, since the morning load may be too large for the available air flow rate.

II.C PLANT

The PLANT program simulates primary HVAC equipment, i.e., central boilers, chillers, cooling towers, electrical generators, pumps, heat exchangers, and storage tanks. In addition, it also simulates domestic or process water heaters, residential furnaces, and solar equipment. Its purpose is to supply the energy needed by the fans, heating coils, cooling coils, or baseboards (simulated in SYSTEMS), and the electricity needed by the building's lights and office equipment (simulated in LOADS). Building loads can be satisfied by using the user-defined plant equipment or by the use of utilities: electricity, purchased steam, and/or chilled water.

II.C.1 Plant Equipment

As in SYSTEMS, there are a number of generic plant equipment types whose characteristics and default performance curves can be shaped by the user:

Category	Trade Name
Heating Equipment	Fossil Fuel Steam Boiler Fossil Fuel Hot Water Boiler Electric Steam Boiler Electric Hot Water Boiler Residential Furnace Domestic Hot Water Heater Electric DHW Heater
Electricity Generators	Steam Turbine Diesel Generator Gas Turbine
Chillers	Open Centrifugal Open Reciprocal Hermetic Centrifugal Hermetic Reciprocal One Stage Absorption Two Stage Absorption Solar Absorption Double Bundle
Storage Tanks	Hot and Cold
Cooling Towers	Conventional and Ceramic
Solar Equipment	Collectors[2] Heat Exchangers[2] Storage Tanks[2] Pumps[2] Controllers[2]

[2] The solar equipment simulation was developed at Los Alamos National Laboratory and differs from the rest of DOE-2 in that it is a component-based model. That is, although there are preassembled systems, the user may also construct his/her own solar heating system by assembling components in any configuration.

II.C.2 Plant Management

The user may establish the management of the plant equipment by setting up schedules and/or load ranges under which specified equipment will operate. In the absence of a user-defined plant management scheme, the equipment is simulated by default in the following order:

1. The space heating loads are first reduced by the energy supplied by the solar equipment, if any.

2. Next, the hot and cold loop circulation pumps are simulated (again, if they exist). The heating and cooling loads are adjusted for any losses that occur in the circulation loops and for the addition of pump heat.

3. The following equipment is modeled iteratively to minimize source energy consumption (see below for a fuller discussion):

   a. The chillers, cooling tower, and cold storage tanks.

   b. The electrical generators, operating under several tracking options.

   c. Heat recovery equipment, if specified, are simulated to link the user-specified sources of waste heat to the user-specified heat demands.

4. Following the heat recovery, the boilers are operated to satisfy any remaining heating loads.

5. Finally, the program allocates any remaining heating, cooling, and electrical loads to the appropriate utility. If a utility has not been provided for, the remaining load is reported as an overload.

The 2.1C version of DOE-2 features an entirely reworked conception of the operation of chillers and, more importantly, the electricity generating prime movers [21]. Earlier versions of the code assumed simply that, in the case of the electricity generators, only the electrical demands of a facility were important to decisions concerning the operation of a central plant. This reasoning stemmed from the fact that utility and regulatory attitudes toward the on-site generation of power often meant that a decision to generate power on-site was tantamount to leaving the electric grid entirely. The Public Utilities Regulatory Policy Act of 1978 mandated changes in those attitudes by requiring that utilities abandon discriminatory practices and offer fair prices to cogenerators and small power producers. The outcome of this change is that the actual electrical loads of a facility need not be the only consideration utilized in determining the output of primary energy conversion equipment in a central plant.

The concept embodied in DOE-2.1C treats the diesel engine and gas turbine as energy conversion devices with two useful outputs: electricity and recoverable heat. Accordingly, the choice of which output to use in controlling the operation of these machines has been made an explicit option specifiable by the user. That is, the user can now specify that the machines generate enough heat to meet thermal loads, irrespective of the amount of electricity produced and vice versa.

This new freedom to choose which loads the central plant equipment is to meet has resulted in a substantial reworking of the equipment allocation routines and the heat recovery links. For example, the default allocation routines now ensure that the thermal and electrical output of the generators, when coupled with absorption and compression chillers, will be balanced when meeting heating and cooling loads.

II.C.3 Simulation Limitations

As mentioned in Section II, there are limitations that arise as a result of the flow of information between the subprograms. All of the information is propagated in one direction only. As a result, a subprogram "upstream" of the subprogram being simulated cannot make use of any information generated by the "downstream" subprogram. For example, the heat extraction rates of the coils in SYSTEMS cannot be adjusted for any overloads experienced in PLANT.

The one-way flow of information also does not allow several building control strategies to be simulated. For example, one energy management strategy is to reduce peak electrical load by turning out some lights when the electrical demand is high. Because the total electrical load is not calculated until PLANT, the lights in LOADS cannot be adjusted.

II.D ECONOMICS

The ECONOMICS portion of the program computes the costs of energy for the various fuels or utilities used by the equipment and provides life cycle investment statistics for the comparison of the current building configuration with a base case building. In DOE-2.1C all of the energy cost calculations have been moved from PLANT to ECONOMICS. In addition, a much wider variety of tariff schedules can now be encompassed as well as computations that simulate the sale of electricity to the utility.

II.D.1 Rate Schedules

DOE-2 allows the following energy resources to be used: chilled water, steam, electricity, natural gas, fuel oil, coal, diesel oil, methanol, LPG, and biomass. For each of these resources that is used by a building the user may specify uniform cost rates, escalation rates, fixed monthly charges by season, various block charges by season, whether there are demand charges and how much, time-of-day charges, and, for electricity only, details about ratchet periods and types and conditions of sale to utilities. Not all of these apply to every fuel or resource, of course, and defaults exist for the simplest of tariffs. On the other hand, most of the existing tariff structures can be simulated.

What cannot be done, because ECONOMICS follows the energy use simulation, is to alter the building operation in response to economic considerations in the middle of a run.

II.D.2 Investment Statistics

In addition to the possibility of treating the costs of energy, DOE-2 allows the user to simulate the life cycle costs of a building and to compare the costs between two configurations of the building. Assuming one is the base case and the other is a retrofit or an alternative design, investment statistics such as pay back period, savings to investment ratio, etc., are computed over the life cycle of the building.

III Data Entry

Before the simulation can take place the user must describe the building, its equipment and operating schedules, and the economics input data to the computer. This is done in DOE-2 through a quasi-English description of the building using specially designed input language called BDL for Building Description Language.

As with any language, BDL has a vocabulary and a syntax. The vocabulary in BDL consists of commands, keywords and code-words (all shown in upper case in the examples that follow), in addition to user-defined names of things and numerical values. The syntax is a set of rules that regulate the relative position of the words or symbols of the vocabulary and the punctuation. In BDL this syntax is quite simple and consists, basically, of the sequence:

```
u-name = COMMAND    KEYWORD1 = value1
                    KEYWORD2 = value2
                        .
                        .
                        .
                    KEYWORDn = valuen        ..
```

The symbol (..) is the terminator for the command and corresponds to the period in English. Some commands, like RUN-PERIOD or BUILDING-LOCATION, are required commands, while others, like DOOR or ENERGY-STORAGE, are optional and are entered into the input only when the building being modeled has the feature being described or the modeler thinks they are thermodynamically important.

Similarly, the keywords within each command can be required or optional. Thus, even though DOOR is an optional command, once it has been used, the user must supply values for its HEIGHT, WIDTH, and CONSTRUCTION. On the other hand, the optional keywords within a command often have default values, i.e., if the user does not enter the keyword and a value, the program will assume that the keyword should take on a preassigned value. This is the case for the TILT of an EXTERIOR-WALL, which the program assumes is vertical unless told to the contrary.

These default values can reduce the necessary input for a building considerably when they are appropriate.

Because BDL ignores extra blank spaces in the input, the user can arrange the commands and keywords to provide the most clarity. As can be seen from the examples of the BDL vocabulary above, an engineer or architect does not need to be a computer scientist to read the input and understand what has been done. This is important for two reasons. First, interested parties other than the author can read and evaluate the modeling with a minimum of effort. Second, the author can return to the input after several months or a year and quickly grasp what had been done earlier.

In addition to describing the building, the BDL portion of DOE-2 performs several other functions. From the user description of the layers of an exterior wall, BDL computes and stores for later use by the simulation part of the program the factors describing the delayed response of the wall to an impulse of heat flux. It also computes, for each space of the building, the weighting factors that describe the thermal response of the space to various heat gains. Since these calculations consume computer time and thus incur computer costs, a library feature exists that allows the user to store response factors and weighting factors permanently in a computer file.

Finally, BDL performs curve fitting for user input data describing the performance characteristics of equipment in both SYSTEMS and PLANT.

IV Output Reports

Although no one really wants or can use the detailed results of the literally millions of calculations involved in a year's simulation of the energy performance of a building, everyone seems to want a different set of summary data. Each successive version of DOE-2 has seen an expansion of the output reports, usually in response to the expressed needs of the user community. In DOE-2.1C there are three different types of reports that the user can choose to have printed: preformatted, hourly, and user-generated. For most purposes only a selection of the preformatted reports, the easiest to request, are of use.

IV.A Preformatted Reports

There are two kinds of preformatted reports in DOE-2: verification reports and summary reports. Verification reports, available in each of the subprograms, echo the user's input in a different form, allowing a check that the building being simulated has been properly described. These reports should be requested before one undertakes a series of full year runs to catch input errors and modeling flaws. The summary reports are the results of the simulation presented in various formats to stress different aspects of the building's performance. In Appendix A the preformatted report titles are given to show what is available.

IV.B Hourly Reports

Many of the internal program variables in each of LOADS, SYSTEMS, and PLANT are accessible to the user for listing on an hour by hour basis. These variables, such as solar gain through a particular window or the temperature in a particular zone, can be listed according to a schedule defined by the user. In DOE-2.1C it is possible to report these variables by day or month rather than hourly and automatically to get summary statistics such as maximum and minimum values during the period as well as averages and sums.

Hourly reports are generally useful for the purpose of reassuring the user that the simulation is reasonable or of examining the detailed performance of a building component. This latter use should be made with caution. An hourly time step in a building may be reasonable for the migration of the heat through a thick wall, but it may produce anomalies when applied to rapidly varying quantities associated with systems controls. Unless the user knows the algorithm that is designed to compensate for such processes, the hourly output may not be understandable. The daily and monthly statistics, on the other hand, can be very helpful.

IV.C User Designed Reports

Along with the ability to change program algorithms through the functional value approach introduced into DOE-2.1C and discussed in the LOADS section, it is now possible for the user to design an individualized report for the LOADS program. What is required is the writing of a FORTRAN program describing the variables and the format for the report. It is not expected that this will be a widely used option, but, for those who need it, the possibility now exists.

V Future Prospects

The future must be divided into two eras, the near term and the less definite long term. The near term involves work in progress and will culminate in the release of DOE-2.1D. The long term involves work anticipated or contemplated but not yet definite.

V.A DOE-2.1D Upgrades

There are three major modifications being made for the next version of the program: an expanded library capability, the extension of the functional approach throughout the program, and improved earth contact algorithms.

V.A.1 Expanded Library Capability

At present the user may create a computer library file containing construction material descriptions, response factors for layered walls and weighting factors for spaces. The use of the library feature not only saves computational time when repeated use is made of the items stored, but, perhaps as important, it simplifies the input to the program. The selection of a wall from a list already stored in the library involves giving the code word for the wall in question rather than having to describe its construction in detail. In the next version of the program it will be similarly possible to store curve fit parameters and, most importantly, schedules.

V.A.2 Functional Approach Throughout

Even though the functional approach, allowing user-substituted algorithms for those in the program, was first instituted in LOADS, most of the imagined applications would appear to be in SYSTEMS and PLANT. There are many more control strategies that one can imagine than have been allowed for in the program. The functional approach in these other subprograms will give the user almost total control over the program.

V.A.3 Improved Earth Contact Algorithm

At present the program assumes that the transfer of heat through an underground surface is a steady state phenomenon with the ground temperature constant for a month at a time. Further, the ground temperatures used are input by the user and are not necessarily related to the weather data. One knows that there are several empirically determined strategies for insulating underground surfaces that have different time dependent heat transfer profiles, but in its present form DOE-2 cannot simulate such behavior. An approach is currently being followed that will calculate and use factors analogous to response factors to treat the earth contact situation. Hopefully, such an approach will allow DOE-2 to support research in the energy conserving design of buildings using earth berming and similar design strategies.

V.B The Longer Term

A building is an enormously complex physical entity. A computer program like DOE-2 is, at best, a simplified model of that building. Not every imaginable building can be simulated by DOE-2 nor by any other computer program. In its evolution, DOE-2 has increased its applicability in each new version and, with every such increase, the demand from the user community for even greater flexibility has also increased.

Although it is possible to add new system types and to improve input and output options indefinitely, the limitations on DOE-2 set by its sequential structure are becoming more and more apparent. Recent suggestions for options in the program have begun to demonstrate the limitations involved in separating the program into LOADS, SYSTEMS, and

PLANT. Similarly and related, the weighting factor method is becoming more the problem than the solution. A more accurate simulation of the HVAC systems requires that the artificial separation of SYSTEMS and PLANT be removed. Passive effects could be more accurately treated if LOADS and SYSTEMS were part of the same subprogram. Ultimately, it would be desirable to incorporate mass flow as well as heat flow so that more detailed convective heat transport could be modeled. It would be useful to treat a combined SYSTEMS and PLANT on a component basis so that the user could assemble the equipment component by component. This approach would make it possible to simulate the time delay of the response of the HVAC system to controls and to model systems not yet conceived. Finally, a variable time step treatment would permit the program to match its algorithms to the underlying time constants of the micro-processes rather than to insist that everything keep an hourly beat.

Modifications like those suggested above could not be made in DOE-2 in its present form and require a radical restructuring of the program. For this it is necessary to contemplate an entirely new program, involving people from throughout the research and applications community and throughout the world. Such thinking has already begun.

Acknowledgement

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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APPENDIX A

Preformatted Reports

LOADS Verification Reports

GENERAL PROJECT AND BUILDING INPUT
SUMMARY OF SPACES OCCURRING IN THE PROJECT
DETAILS OF SPACE
DETAILS OF EXTERIOR SURFACES IN THE PROJECT
DETAILS OF UNDERGROUND SURFACES IN THE PROJECT
DETAILS OF INTERIOR SURFACES IN THE PROJECT
DETAILS OF SCHEDULES OCCURRING IN THE PROJECT
DETAILS OF WINDOWS OCCURRING IN THE PROJECT
DETAILS OF CONSTRUCTIONS OCCURRING IN THE PROJECT
DETAILS OF BUILDING SHADES IN THE PROJECT
WEIGHTING FACTOR SUMMARY
DAYLIGHT FACTOR SUMMARY
DOE-2 UNITS TABLE (English/Metric Conversion Table)

LOADS Summary Reports

SPACE PEAK LOADS SUMMARY
SPACE PEAK LOAD COMPONENTS
BUILDING PEAK LOAD COMPONENTS
BUILDING MONTHLY LOADS SUMMARY
SPACE MONTHLY LOAD COMPONENTS IN MBTU
BUILDING MONTHLY LOAD COMPONENTS IN MBTU
SPACE DAYLIGHTING SUMMARY
PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHT (SPACE)
PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHT (BUILDING)
DAYLIGHT ILLUMINANCE FREQUENCY OF OCCURRENCE
SPACE INPUT FUELS SUMMARY
MANAGEMENT AND SOLAR SUMMARY FOR SPACE

SYSTEMS Verification Reports

SYSTEMS DESIGN PARAMETERS

SYSTEMS Summary Reports

SYSTEM MONTHLY LOADS SUMMARY
SYSTEM MONTHLY LOAD HOURS
PLANT MONTHLY LOADS SUMMARY
PLANT MONTHLY LOAD HOURS
ZONE DEMAND SUMMARY
ZONE LOADS SUMMARY
SYSTEM MONTHLY LOADS SUMMARY
SYSTEM MONTHLY SOURCE-LATENT SUMMARY
SYSTEM PEAK HEATING AND COOLING DAYS
SPACE TEMPERATURE SUMMARY
FAN ELECTRIC ENERGY
FAN ELECTRIC ENERGY FOR PLANT
HUMIDITY RATIO SCATTER PLOT
TEMPERATURE SCATTER PLOT

REFRIGERATION EQUIPMENT SUMMARY

PLANT Verification Reports

EQUIPMENT SIZES
COST REFERENCE DATA (USED FOR DEFAULT COSTS)
EQUIPMENT COSTS
EQUIPMENT LOAD RATIOS
EQUIPMENT QUADRATICS

PLANT Summary Reports

PLANT ENERGY UTILIZATION SUMMARY
MONTHLY PEAK AND TOTAL ENERGY USE
EQUIPMENT PART LOAD OPERATION
PLANT LOADS SATISFIED
ELECTRICAL LOAD SCATTER PLOT
EQUIPMENT USE STATISTICS
EQUIPMENT LIFE-CYCLE COSTS
ESTIMATED BUILDING ENERGY PERFORMANCE

ECONOMICS Verification Reports

LIFE-CYCLE COSTING PARAMETERS AND
 BUILDING COMPONENT COST INPUT DATA
COST OF FUELS AND UTILITIES

ECONOMICS Summary Reports

ANNUAL ENERGY AND OPERATIONS COSTS AND SAVINGS
LIFE-CYCLE BUILDING AND PLANT NON-ENERGY COSTS
ENERGY SAVINGS, INVESTMENT STATISTICS, AND
 OVERALL LIFE-CYCLE COSTS
SUMMARY OF FUEL AND UTILITY USE AND COSTS
SUMMARY OF ELECTRICITY CHARGES
SUMMARY OF ELECTRICITY SALES