APPENDIX E

THE DOE-2 COMPUTER PROGRAM FOR THERMAL SIMULATION OF BUILDINGS

B. E. Birdsall, W. F. Buhl, R. B. Curtis, A. E. Erdem,
J. H. Eto, J. J. Hirsch, K. H. Olson, F. C. Winkelmann

Applied Science Division
Lawrence Berkeley Laboratory
Berkeley, California 94720

Summary

The DOE-2 building energy analysis computer 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 thermal calculations be based upon well established algorithms, (3) that it permit the simulation of commonly available heating, ventilating, and air-conditioning (HVAC) equipment, and (4) that the predicted energy use of a building be acceptably close to measured values. Applications of DOE-2 include design of energy-efficient buildings, analysis of the performance of innovative building components and systems, and energy standards compliance. It is also widely used as an educational tool in the building sciences.

DOE-2 Program Structure

A building, examined thermodynamically, involves non-linear flows of heat through and among all of its surfaces and enclosed volumes, 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.

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

First is the calculation of the hour-by-hour 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 at the heating and cooling coils 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

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.

0094-243X/85/1350642-8$3.00

calculation, answers the question: what are the heat extraction and addition rates when the characteristics of the HVAC system, the time-varying temperature set-points, and the heating, cooling and fan schedules are all taken into account?

Third is the determination of the fuel and electricity requirements of primary equipment such as boilers and chillers, 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 by the 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 building envelope components. It answers the question: Is the expenditure of funds for energy conserving materials and systems cost effective, when compared with alternative systems?

A detailed description of the simulation algorithms used in DOE-2 is given in Ref. [3].

LOADS

General Considerations

The LOADS program computes the hourly cooling and heating loads for each space of the building. A *load* is defined as the rate at which energy must be added to or removed from a space to maintain a constant air temperature in the space. A *space* 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 loads are obtained by a two-step process. First, the heat gains (or losses) are calculated; then the space loads are obtained from the space heat gains, taking into account the storage of heat in the thermal mass of the space. A *space heat gain* 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 radiative and convective 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 appliances or office 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 presolved for each wall or roof using triangular temperature pulses as excitation functions. The resulting solutions, called "response factors" are then 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 is 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 are 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 delayed conduction through such walls can be modelled.

The internal heat gains from people, lights, and equipment are basically fixed by the user's input of peak values multiplied by hourly values in the 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 weighting factors. The weighting factors are determined from a detailed heat balance which gives the response in time of a zone (with all its mass and walls and fenestration) to a unit pulse of each of the zone heat gains. The weighting factor method is based on the assumption that the superposition principle applies to heat transfer processes occurring in a space. In effect, this means that the heat gain due to solar radiation, for example, can be calculated independent of the other heat gains.

Fig. 1 shows DOE-2 predictions for solar heat gain and the resulting cooling load for a passive solar home in Chicago. Note that the weighting factors attenuate and delay the effects of the heat gain, so that a cooling load from solar radiation extends through the nighttime hours long after the sun has set.

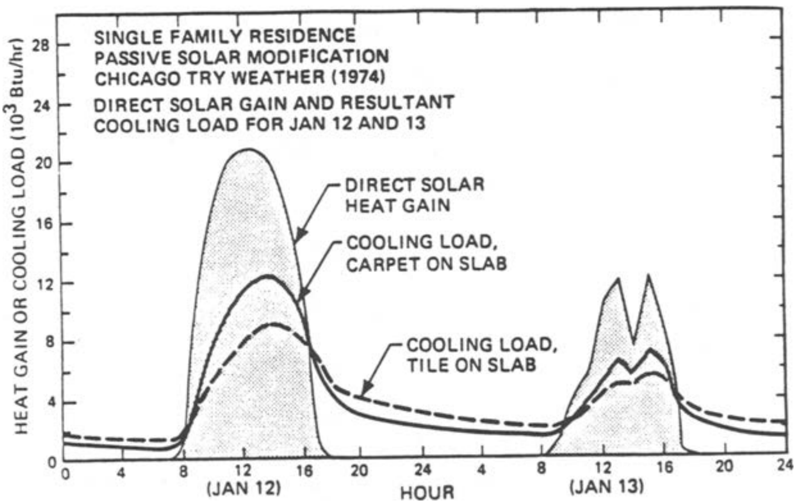


Fig. 1: DOE-2 predictions for solar heat gain and resultant cooling load for tile floor vs. carpetted floor.

Special LOADS Features

In DOE-2.1C, the latest version of the program, there are several additional features that greatly extend its usefulness. These include in the LOADS program the ability to take advantage of credit for daylighting, 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.

- **Daylighting Credit**

The daylighting simulation in DOE-2, coupled with the thermal loads and HVAC analysis, allows users to evaluate the energy- and cost-related consequences of daylighting strategies. The program takes into account the availability of daylight from sun and sky, window management in response to solar gain and glare, and various electric lighting control schemes.

The daylight illuminance calculation in DOE-2.1C considers such factors as: window size and orientation, glass transmittance, inside surface reflectances of the space, sun-control devices such as blinds and overhangs, luminance distribution of the sky, and discomfort glare.

For each daylit space, a preprocessor calculates and stores a set of daylight factors for a series of sun positions covering the annual ranges of solar altitude and azimuth at the specified building latitude. These factors relate interior illuminance and glare levels to outdoor daylight levels.

In the hourly daylighting calculation, the illuminance from each window or skylight 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 then 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. Finally, the lighting electrical requirements are passed to the thermal calculation which determines hourly heating and cooling requirements for each space.

- **Sunspace Model**

DOE-2.1C allows the user to model the 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 the venting of the sunspace with outside air to prevent overheating, and, for residential applications, the use of a sunspace to preheat outside ventilation air.

- **Functional Approach**

DOE-2.1C allows the user to modify the way that DOE-2 does its calculations in LOADS without having to recompile the code. This "Functional Approach" involves writing FORTRAN-like functions in the LOADS input that compute the program variables as desired by the user. The possibilities of this feature are many and include, for example, deploying window shades to block the sun if a space has a cooling load, making the outside air film conductance dependent upon the wind direction, entering measured values of daylight factors, printing user designed reports, and modelling innovative products and control strategies.

SYSTEMS

General Considerations

The SYSTEMS program simulates the equipment that provides heating, ventilating and/or air conditioning to the thermal zones and the interaction of this equipment with the building envelope. 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 heating and cooling coil loads can be passed to the primary energy conversion equipment or utility.

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 sensible coil load) 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 are calculated.

The moisture content of the air is calculated at three points in the system: the supply air leaving the cooling coil, the return air from the spaces, and the return air after being mixed with outside ventilation air. These values are calculated assuming that a steady state solution of the moisture balance equations each hour 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 solving the coil leaving air temperature and humidity ratio simultaneously with the system moisture balance.

Once the above sequence is complete, all sensible and latent coil loads are known. These values are then either passed to the PLANT program as heating and cooling water circuit loads or, in the case of direct-expansion cooling equipment, the energy conversion is simulated in SYSTEMS.

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. Among the systems which can be modelled are: variable air volume, powered induction unit, dual duct, fan coil, water-to-air heat pump, air and air-to-air heat pump, packaged air conditioning, and residential furnace.

Special SYSTEMS Features

The DOE-2 program allows the simulation of a large number of special features within the generic system types. These features include (1) baseboard heaters, (2) humidity control, (3) "economizer cycle", i.e., use of outside air for cooling when its temperature or enthalpy is low enough, (4) natural ventilation through open windows, (5) optional start-up time for fans, (6) night temperature setback, (7) nighttime pre-cooling of building mass, and (8) recovery of sensible heat from the exhaust air stream.

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, and residential furnaces. Each type of equipment is modelled using empirically determined performance curves which characterize thermal performance as a function of part load, entering fluid temperatures, and other variables.

The purpose of the primary equipment is to supply the energy needed by the fans, heating coils, cooling coils, or baseboards, and the electricity needed by the building's lights and office equipment. 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.

Plant Management

The management of a plant is determined by setting up time schedules and/or load ranges under which specified equipment will operate. An example of such management is scheduling chillers to run at night to produce cold water or ice, which is stored for use the following day to cool the building; a strategy of this kind can avoid the high peak electrical demand charges incurred by running chillers during the day.

ECONOMICS

The ECONOMICS portion of the program computes the costs of energy for the various fuels or utilities used by the equipment. A wide variety of tariff schedules can be modelled. In addition, sale to the utility of electricity generated at the building can be simulated.

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 tariffs. On the other hand, most of the existing tariff structures can be simulated.

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.

Validation

DOE-2 has been verified against field measurements on existing buildings [4]. Examples of DOE-2 comparisons with measured data are shown in Figs. 2 and 3. The general conclusion of the verification studies is that total energy usage for a well-modelled building can be predicted within 15%.

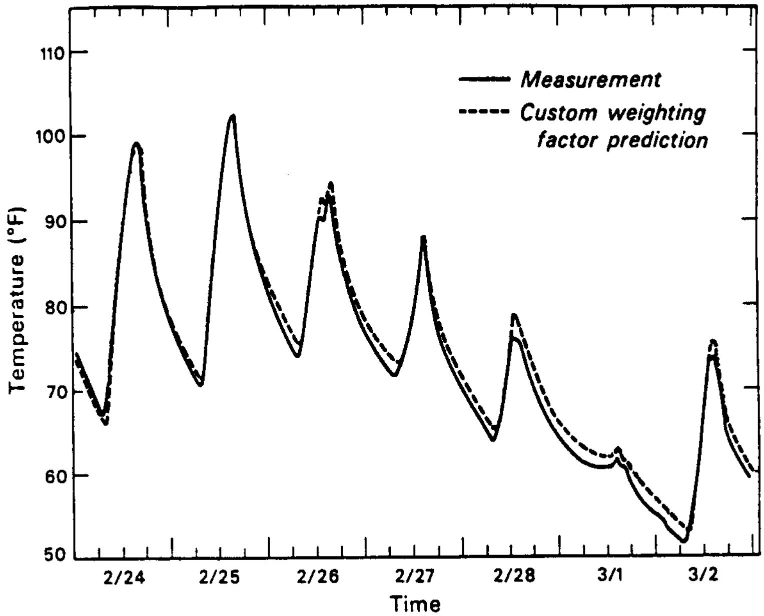
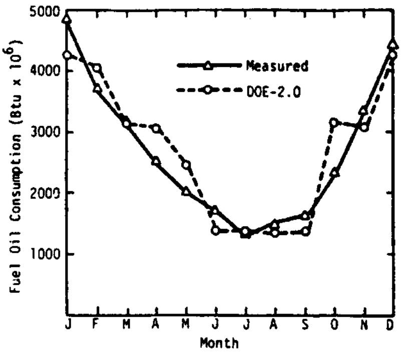


Fig. 2: Comparison of DOE-2 predictions and temperature measurements in the Los Alamos National Laboratory direct-gain passive solar test cell.



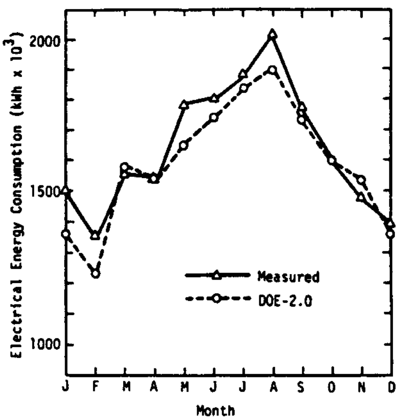


Fig. 3: Comparison of DOE-2 and measured data on fuel oil and electricity consumption for the Marriott Hotel in Boston (from Ref. 4).

Applications

DOE-2 is now in wide use throughout the world. Its applications span a broad spectrum from research to education to building design. As a research tool, DOE-2 is commonly used to study the thermal behavior of individual building components and the interaction of these components with the rest of the building. As an example of this type of research application, the Windows and Daylighting Group at Lawrence Berkeley Laboratory (LBL) is using DOE-2 to study the annual performance of advanced glazing materials (e.g., electrochromic or photochromic glass) whose transmittance can be actively or passively controlled based on temperature, solar radiation, or other environmental variables [5].

The program has also been extensively used to perform parametric analyses to determine the energy use response of a building as a function of one or more variables. The resulting database of DOE-2 results can be quite large, so that statistical approaches, such as multiple regression analysis, are valuable in summarizing the data. For example, in the recent upgrade of the ASHRAE 90 standard for energy conservation in non-residential buildings, thousands of DOE-2 runs were made varying important building envelope parameters for different U. S. climates [6]. For each climate, a regression analysis yielded coefficients in a linear fit which gave cooling energy, heating energy, and cooling peak for office buildings as a function of envelope conductance, window aperture, and electrical lighting power density.

A similar statistical approach was used by the Energy Analysis Group at LBL for houses [7]. A data base of residential energy use was generated from 10,000 DOE-2 runs for seven prototype houses in 45 U. S. locations, covering a wide range of typical conservation measures. Linear regression was then used to relate heating and cooling loads to key building components, such as wall conductance or infiltration air change rate. From the regression equations, two simplified energy prediction tools were developed -- an Energy Sliderule and the PEAR microcomputer program, both of which allow energy estimates to be made in a fraction of the time required by a full DOE-2 simulation.

For more information on DOE-2, contact Karen H. Olson, Building Energy Simulation Group, Lawrence Berkeley Laboratory, Building 90, Room 3147, Berkeley, CA 94720.

REFERENCES

1. "DOE-2 REFERENCE MANUAL", Lawrence Berkeley Laboratory, Report. No. LBL-8706 Rev. 2, 1981.
2. "DOE-2 SUPPLEMENT", Lawrence Berkeley Laboratory, Report No. LBL-8607 Rev. 4, Suppl., 1984.
3. "DOE-2 ENGINEERS MANUAL", Lawrence Berkeley Laboratory, Report No. LBL-11353, 1982.
4. "DOE-2 Verification Project, Phase I, Interim Report" Los Alamos National Laboratory, Report No. LA-8295-MS, 1981.
5. R. Johnson, D. Connell, S. Selkowitz, and D. Arasteh, "Advanced Optical Materials for Daylighting in Office Buildings", Lawrence Berkeley Laboratory, Report No. LBL-20080, 1985.
6. R. Johnson, R. Sullivan, S. Nozaki, S. Selkowitz, C. Conner, and D. Arasteh, "Building Envelope Thermal and Daylighting Analysis in Support of Recommendations to Upgrade ASHRAE/IES Standard 90", in "Recommendations for Energy Conservation Standards and Guidelines for New Commercial Buildings", Pacific Northwest Laboratory, Report No. PNL-4870-4, 1983.
7. Huang, Y. J., Bull, J. and Ritschard, R., "Simplified Calculations for Residential Energy Use Using a Large DOE-2 Data Base", Lawrence Berkeley Laboratory, Report No. LBL-20107, 1985.