Building Energy Simulation and the C-2000 Program

Prepared For:

CANMET Energy Technology Centre - Ottawa
Buildings Group - Energy Sector
Department of Natural Resources Canada
Ottawa, Ontario, Canada, K1A 0E4
Call-up File No. 234440-94-1261
March 1996

Prepared By:

Caneta Research Inc.
7145 West Credit Avenue
Suite 102, Building 2
Mississauga, Ontario, L5N 6J7
Tel: (905) 542-2890; Fax: (905) 542-3160

Scientific Authority:

Nils Larsson
Buildings Group - Energy Sector
CANMET Energy Technology Centre - Ottawa
Department of Natural Resources Canada
580 Booth Street, 13th Floor
Ottawa, Ontario, Canada, K1A 0E4

Re-Print February 12, 2003

CITATION

Caneta Research Inc. *Building Energy Simulation and the C-2000 Program.* Call-up File No. 23440-94-1261. Buildings Group, Energy Sector, CANMET Energy Technology Centre – Ottawa, Department of Natural Resources Canada, Ottawa, Ontario, 1996. (12 pages).

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CANMET Energy Technology Centre (CETC)
Energy Sector
Department of Natural Resources Canada
580 Booth Street, 13th Floor
Ottawa, Ontario, Canada, K1A 0E4

DISCLAIMER

NOTE

Funding for this project was provided by the Government of Canada under the Green Plan.

EXECUTIVE SUMMARY

Building energy simulation is an analytical tool used to simulate and predict the energy consumption of a building and its systems. The tool can either be simple and easy to use, such as an analysis based on heating degree days, or complicated and requiring time to learn and operate, such as with hour by hour programs. This report briefly describes different energy simulation methods, but focusses on one program, DOE-2.1E, and how it relates to the C-2000 Program. An overview is given on the DOE-2.1E program describing required inputs, potential trouble spots and limitations. Results from the DOE-2.1E program generated by various C-2000 design teams are also presented and discussed. The report concludes with a discussion of what may be the future for building energy simulation and its relation to the C-2000 Program.

RÉSUMÉ

La simulation énergétique d'un bâtiment est un outil analytique utilisé pour simuler et prévoir la consommation énergétique d'un bâtiment et des systèmes qu'il contient. Cet outil peut s'avérer simple et facile à utiliser, comme une analyse qui se base sur le degrés-jours de chauffage, ou compliqué et nécessiter un certain temps à comprendre et à faire fonctionner, comme dans le cas des programmes à l'heure. Ce rapport contient une courte description des diverses méthodes de simulation énergétique, mettant particulièrement l'accent sur un programme, le DOE-2.1E, et sur la façon dont il se rapporte au Programme C-2000. On y donne un aperçu de ce programme en expliquant quels renseignements sont nécessaires, les points névralgiques éventuels et les limites. D'autre part, sont présentés et examinés les résultats du Programme DOE-2.1E qui découlent de l'utilisation de différentes équipes de conception C-2000. Enfin, la conclusion du rapport englobe un exposé au sujet de l'avenir possible de la simulation énergétique dans les bâtiments et de son rapport avec le Programme C-2000.

BUILDING ENERGY SIMULATION AND THE C-2000 PROGRAM

WHAT IS BUILDING ENERGY SIMULATION

Building energy simulation is the science of estimating the energy interactions within a building. These interactions include the direct purchase of energy, such as electricity for lighting or natural gas for heating, but also the exchange of energy due to such things as the infiltration of air into a building or the heat generated by a building's occupants. Simulation attempts to account for these factors, plus many more, in determining the heating, cooling and ventilation loads within a building, the equipment types and sizes needed to meet these loads, and the cost to operate this equipment plus other non-HVAC (heating, ventilating and air-conditioning) equipment.

Building energy simulation is used as a tool in the design of buildings, for determining compliance to building standards and for the economic optimization of building components. It can be used on buildings of any size, from one zone residential houses to multi-zone large commercial buildings, or any occupancy, such as schools, offices, hospitals, supermarkets, etc.

There are different methods of building energy analysis which vary in complexity, but all have three common elements, the calculation of space heating and cooling loads, the load on secondary equipment, and the energy requirements of primary equipment. Secondary equipment is that equipment which distributes the heating, cooling or ventilating medium to the conditioned space, while primary equipment is central plant equipment that converts fuel or electricity to the heating or cooling effect. Generally, as a method becomes more complex it becomes more accurate. However, the improved accuracy usually comes with increased effort and time to perform a simulation.

Simpler Energy Analysis Methods

The simplest method of building energy analysis is the degree-day method. This method provides a simple estimate of annual loads based on tabulated degree-day values for a location and the balance point of the building (the outdoor temperature where space conditioning is not required). The degree day method can only be used with accuracy where building use, HVAC equipment efficiency, indoor temperature and internal gains are relatively constant.

Where HVAC equipment efficiency or conditions of use vary with outdoor temperature, energy consumption can be calculated for different values of outdoor temperature and then multiplied by the number of hours at which that temperature occurred. This energy analysis method is called a bin method and is often used where ventilation or internal loads vary with time of day or where equipment such as air-source heat pumps have efficiency as a function of outdoor air temperature.

Hour-by-Hour Energy Analysis

These methods, however, do not yield accurate estimates for commercial and institutional buildings. Large buildings (i.e. larger than one zone residential) have wide-ranging and constantly changing internal and external factors that determine space heating and cooling loads. These factors need to be evaluated on a relatively small time step, such as an hourly basis, to obtain accurate estimates. Such repetitive and detailed calculations are best handled by a computer, and a number of software programs are available. Most of these programs are based on ASHRAE endorsed heating and cooling load algorithms. Hourly simulation software steps through each hour of a year performing calculations. With this type of analysis the dynamic nature of large buildings can be modelled.

Hour-by-hour energy programs, however, are only as good as the programmer using them and the information supplied to them. This is their major disadvantage. It takes time to learn the complex software, and it takes time to translate the input from building drawings and schedules to the computer. Other disadvantages, common to all methods of building energy analysis, include they idealize the control of HVAC systems; the programs tend to yield demands more representative of an average for a building type rather than a peak demand; and, for this last reason, often do not accurately size HVAC equipment. The advantages of computer simulation include the ability to accurately simulate the details of complex systems; to evaluate a large variety of system types; they provide a standardized and repeatable method of calculation; and the flexibility to optimize systems based on energy consumption or cost.

BUILDING ENERGY SIMULATION AND THE C-2000 PROGRAM

A C-2000 building is required to meet more stringent criteria for energy efficiency than ASHRAE/IES Standard 90.1 - 1989, "Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings". ASHRAE Standard 90.1 is an internationally recognized standard for good building energy performance. The C-2000 Program requires a builder to demonstrate that their office building will use only 50% of the energy of a reference building meeting ASHRAE 90.1, or 55% for multi-unit residentials.

In order to demonstrate compliance to the C-2000 guidelines, a builder must perform hourly simulations using a software program specified by CANMET. All building projects which have progressed through the C-2000 Program to-date have had simulations performed using the DOE-2 building energy analysis program. DOE-2 is discussed further in the following section.

The reference building is defined using ASHRAE 90.1 which details lighting and equipment levels, occupancy, infiltration and ventilation, envelope insulation levels, percentage glazing, hot water use, HVAC system type, thermostat setpoints, etc. plus all related schedules. Schedules and occupancy are consistent between the reference building and the C-2000 design. This ensures that the energy efficiency improvement of the C-2000 design over the

ASHRAE 90.1 reflects design changes only. A third party independently reviewed the simulations to maintain quality control, to assist designers in identifying problems or errors with their simulations, and to confirm that C-2000 criteria were met.

THE DOE-2.1E BUILDING ENERGY SIMULATION PROGRAM

DOE-2 is a public domain PC-based program for energy analysis of residential, commercial and institutional buildings. The program was developed by Lawrence Berkeley Laboratory with support from the U.S. Department of Energy. DOE-2 calculates the hourly heating and cooling loads, and the total energy use of a building given information on the building's location, construction, operation, and HVAC system. The most recent version of DOE-2 is DOE-2.1E.

A listing of the "engine" behind the DOE-2 program would consist of well over 70,000 lines of FORTRAN source code. To interface the details of the building and its system with the source code, a Building Description Language (BDL) was developed. The BDL uses words and numbers to describe the building and includes coordinate systems to relate the positions of zones, walls and windows to each other.

DOE-2 consists of four sequential subprograms: loads, systems, plant, and economics. The function of each subprogram is as follows:

The **loads** subprogram calculates hourly heating and cooling loads based on heat gains and losses through the building envelope and internal gains. It is a dynamic modelling which uses hourly weather data and takes into account the thermal storage effects of the building elements. Internal lighting, equipment and occupant loads are calculated based on user-defined schedules. Simulation of daylighting and electric lighting controls is an option.

The **systems** subprogram simulates the operation of secondary HVAC (airside) distribution systems used to control the temperature and humidity within each zone of a building. The subprogram takes into account outside air requirements, operating and control schedules, and transient building responses. It uses the hourly output from the loads subprogram to calculate the hourly thermal and electrical energy requirements of the HVAC system.

The **plant** subprogram calculates the performance of the primary energy conversion equipment based on hourly operating conditions and part-load performance characteristics. The program models conventional central plants, and plants with on-site generation, waste heat recovery and sell-back of electricity. It also permits load management of plant equipment and energy storage. It calculates the monthly and annual amount of each type of fuel used and the daily electrical load profile. The user selects the type and size of equipment or can allow the program to automatically size the equipment based on either peak heating or cooling loads or design day conditions.

The **economics** subprogram calculates the cost of consumed energy based on user-defined rates. The subprogram can also be used to compute the present value of the life cycle cost of the building, including fuel and electricity, equipment, operation and maintenance.

There are a number of vendors of the DOE-2 program. A listing and contact information for these companies is contained in Attachment A to this document.

CONSTRUCTING A SIMULATION INPUT FILE

The goal of any simulation is to take something that is extremely complex (a building) and to model it as simply as possible yet as accurately as necessary. The initial step and perhaps one of the most important, is the zoning of the building. The more complex the building the more important this step becomes.

HVAC Zone Description

A modelling zone is similar to an HVAC zone. An HVAC zone is defined by an individual thermostat and that part of the air distribution system that responds to that thermostat. Often different occupants of an area will have individual thermostatic control even if the area is expected to be relatively homogenous in temperature. A model zone, however, would represent this area as one zone on which an energy balance is performed. Often there is more than one HVAC zone per modelling zone, but rarely is there more than one modelling zone per HVAC zone.

Zoning is usually based on blueprints or design drawings. Since simulations are often performed before a design is finalized, blueprints may not be available and the analyst must use the best information available. The analyst positions each zone relative to other zones and relative to the building as a whole using a space coordinate system. This step, to ensure correct orientation, is most important with an option such as daylighting control, or where unconditioned zones or disproportionate amounts of glazing on one building face exist.

Building Envelope Details

The next step in the construction of the input file is to describe the building envelope components. This includes detailing the thermal resistance, thermal capacity and reflectance for all walls, roofs and floors. The DOE-2 program provides a library of materials (such as brick facing, concrete blocks and insulation materials) from which a user can construct the envelope component. It is also necessary to describe for each window the thermal resistance, shading coefficient and frame effect. Again, the DOE-2 program has a library of different glazings that can be used if one does not have specific details. For C-2000 validation, all envelope characteristics are detailed for the reference building in the ASHRAE 90.1 standard.

Zone Conditions

The conditions within each space must be determined based on the best information available at the time of simulation. These conditions include lighting and equipment levels, the number of people, infiltration, whether daylighting control is to be used and if the zone is to have space conditioning. Along with the levels describing the peak conditions in each space there are associated schedules which dictate how these levels vary with time of day, day of the week or by the time of year.

Once the zones and the conditions in them have been defined, the physical dimensions of each zone must be described. This includes the floor area and volume of each zone, the type (i.e. construction) and location of each wall, floor, ceiling and window, as well as the length and height of each envelope component. Internal walls between zones, especially where one zone is unconditioned, should be defined and can include "air walls" or air partitions between zones.

HVAC System Description

This generally completes the input relating to the loads subprogram of DOE-2. Now it is necessary to describe the system that serves these loads. Initially, the schedules of when heating or cooling are available, when ventilation is to occur and how the space heating and cooling thermostat setpoints vary with time are defined. The characteristics of each zone, such as fan air volumes, which schedules apply, heating or cooling capacities, etc., are inputted. Many of these variables can be sized automatically by DOE-2 if the design values are not known.

The system supplying the heating or cooling medium to each zone is now defined. The important parameters are the system type (i.e. variable air volume, water-loop, etc.), supply air temperatures in heating and cooling, whether ventilation heat recovery equipment is present, preheat temperature setpoints and other system controls. Again, for the C-2000 reference building many of these inputs are outlined in the ASHRAE 90.1 standard. Also detailed in the systems section are energy uses that do not influence the HVAC energy, such as outdoor lighting, elevator usage and service hot water requirements.

Central HVAC Plant Description

The characteristics of the primary HVAC plant need to be determined from design information, or from the ASHRAE 90.1 standard in the case of the C-2000 reference building. These details include the efficiency of plant equipment (boilers, chillers, cooling towers) and how it is influenced by part loads, entering air or water temperatures, etc., the size and performance of circulating pumps, and the load management of all plant components. Thermal storage and cogeneration equipment, if present, are also defined here.

The final section in constructing an input file deals with the economics for the building. This includes obtaining the local utility rates for electricity and any other fuel to be consumed. The DOE-2 program is very flexible in handling a variety of utility rate structures. If a more detailed economic analysis other than annual operating costs is desired, the user must input first costs, replacement costs, annual costs for non-plant items and baseline data for comparative runs.

Extensive documentation is available to a DOE-2 user who is attempting to complete a simulation input file. The user, however, needs to have a good understanding of the simulation program and how it models the various components, as well as a firm knowledge of building components and energy analysis. Learning the DOE-2 program is an investment in time and effort that a designer needs to consider. The modelling of complicated buildings, as exist in the C-2000 Program, will take an experienced user of the program at least a week to complete. Any design optimization, changes or debugging may add considerably to this time.

Other simulation programs that are easier to use than DOE-2 are available. In fact, the developers of the DOE-2 program are currently working on a more user friendly program. In any case, a analyst must have knowledge of the tool being used and of the real life applications and physics being modelled. While other programs are available, DOE-2 is the industry benchmark program to which all others are compared and has had more development, research, background support and public use than the others. It is not perfect and, at times difficult to work with, but it is the most accurate, versatile and reliable tool available.

POTENTIAL ERRORS, PITFALLS AND LIMITATIONS

All simulation files contain errors regardless of the number of times the file has been reviewed and checked. These errors arise due to analyst error while inputting data, misinterpretation of design information, design information that changes over time, poor assumptions or judgements, or errors in the code of the simulation program. This final error source can be minimized by selecting a program that has been used and tested over many years. The other errors cannot be eliminated but can be minimized with modelling experience, careful choice of assumptions and having a second experienced analyst review the input file. This is the path that was taken in the C-2000 program. An experienced analyst was to be part of the design team and input files from all teams were reviewed by another independent analyst designated by the C-2000 Program. This assured conformity to the Program requirements and also minimized human error.

There are a number of building components which cannot be modelled within current building energy analysis programs. The analyst has to use a method outside the energy analysis program to estimate the impact of these components on overall energy use. The following is a list of such components:

- operable windows;
- multi-story atriums where the air is allowed to stratify;
- with respect to daylighting: light shelves or scoops, directional blinds, daylighting from an adjoining space, or roof monitors;
- wind generated power;
- active solar systems;
- photovoltaics.

There are some components within the current DOE-2 program that are limited in how they are modelled. The analyst should recognize these limitations and check the output to be certain it reflects reality and, if necessary, modify the energy results outside the program. Such components include:

- outside ventilation air - for zonal systems in DOE-2, like water-loop heat pumps or fan coils, outside ventilation air cannot be directed to the zones through a central system. This prevents the use of a preheating coil, unless the user tries to "trick" the program by using a dummy zone;

- heat recovery - independent heat recovery ventilators (HRVs) cannot be modelled with zonal systems, heat recovery is only available with central systems;

- basement heat loss - DOE-2 recommends using the basement floor perimeter as the area in its heat loss calculation, a relatively simplistic approach;

- breakdown of system loads - dividing the load on the system into components (ventilation, envelope, etc.) as an intermediate check is difficult and frustrating.

If the building that is being modelled is small, the analyst should focus on the envelope U-values, infiltration and the heat loss to ground. These are the more important factors in overall energy use of small buildings. If the building is large, one should focus instead on the zoning of the building, the economizer, system controls and system type. These factors are more important in larger buildings because of the greater need for cooling in the building core, sometimes year round. In the case of a retrofit the analyst needs to determine how the existing equipment is controlled and what the current airflow rates are, capacities, fan use and circulating pump use.

RESULTS OF C-2000 MODELLING EFFORTS

Table 1 displays the results of the simulation efforts for five C-2000 designs. The designs vary from 2,174 m^2 to 22,860 m^2 in floor area. The predicted energy consumption for the C-2000 designs vary from 82 $ekWh/m^2$ to 124 $ekWh/m^2$. This energy consumption represents anywhere from 44% to 55% of the predicted energy consumption of a building just meeting the ASHRAE 90.1 requirements.

Table 1 C-2000 Simulation Results

Name	Q-Lot	Bentall 8	Kamloops	Green on the Grand	Tour des Voyageurs
Location	Victoria, BC	Richmond, BC	Kamloops, BC	Kitchener, ON	Hull, PQ
Size (m^2)	22,860	7,435	4,182	2,174	21,819
Annual Energy Consumption ($ekWh/m^2/y$)	123	92	124	82	82
% of ASHRAE 90.1	50	49	45	44	46

Of the five buildings shown in Table 1, three are definitely going ahead with construction (Bentall 8, Kamloops and Green on the Grand). Interestingly, these three buildings are the three smallest shown in Table 1. The decisions to proceed with construction of the other two are currently on hold.

The simulations that were performed in determining the energy consumptions shown in Table 1 were performed by four different C-2000 teams (one organization was responsible for simulating both Q-Lot and Bentall 8). These companies varied in their abilities and experiences with the DOE-2 program and, as a result, the simulation input files varied in accuracy and amount of detail. The following describes some of the errors encountered while reviewing the input files:

- unfamiliarity with DOE-2 was the most serious error found, e.g. misunderstanding of the coordinate systems, improper modelling of ventilation and infiltration levels, and misuse of some commands such as floor multiplier;
- schedules for lighting, equipment, HVAC system etc. were not modelled as defined in ASHRAE 90.1;
- incorrect amounts of glazing were used in the ASHRAE 90.1 reference simulation;
- other inputs were varied between the ASHRAE 90.1 and C-2000 simulations which were not due to efficient design, such as the use of interior shading, floor to floor height, or equipment load;
- space temperatures in some zones were unrealistically high and were obviously not checked;
- centerline U-values for glazing were used to describe entire windows (i.e. the frame and edge effects were ignored);

- efficiency levels for chillers were set to values higher than currently available equipment.

Of the five buildings listed in Table 1, two had simulations performed by people who had little or no DOE-2 simulation experience. This lack of experience was quite evident in how they attempted to construct their simulation input files. In any future C-2000 or similar program, it should be made mandatory that only experienced users of the simulation program be involved with the design team. This would decrease the time required to construct and review files, as well as ensure higher quality simulations.

At one point during the early planning stages of the C-2000 Program consideration was given to using one experienced person to perform the simulations for all the teams. This would have ensured a high degree of quality as well as consistency between the different designs and adherence to the C-2000 guidelines. However, such simulation support does not allow full interaction between the analyst and the design team as they try to optimize the design, nor does it contribute to the teamwork process that C-2000 endorses.

FUTURE OF BUILDING SIMULATION AND THE C-2000 PROGRAM

The C-2000 Program was designed to be a small demonstration program for high-performance office buildings. So what is the role for building simulation when the C-2000 Program is no longer on the Canadian building scene?

It is expected that building simulation will see increased use as a design tool for two reasons:

- the success of the C-2000 Program in developing and demonstrating high-performance buildings has encouraged the development of a team approach to building design. Integral to these teams has been a building energy analyst;

- sometime in the near future the National Energy Code for Buildings will be published and may be adopted by several provincial governments. Building energy performance software will be used in the performance path to determine compliance to the Code. If designers are constructing input files for compliance there is little additional effort to use the same input files to optimize the design.

The C-2000 Program has encouraged the use of building simulation in some organizations that have never used it before. But with the adoption of the National Energy Code and the use of compliance software, many more organizations will have to become familiar and comfortable with energy analysis. The Program should view this as an opportunity to encourage building energy efficiency. A series of promotional workshops could be conducted to encourage the use of building energy analysis software. At the same time the results of the C-2000 Program could be promoted, encouraging the designers to go beyond the National Energy Code criteria to develop truly energy efficient buildings.

The current C-2000 Program has been linked to the ASHRAE 90.1 standard, using it as a benchmark of good building practice. When the National Energy Code is published the C-2000 Program should be redesigned so that the C-2000 performance level is linked to the Code. In any event, with changes in the ASHRAE 90.1 standard expected by 1997, C-2000 will have to review the energy criteria.

To further encourage the use of energy simulation in efficient building design, C-2000 needs to provide evidence of the accuracy of energy simulation by comparisons of simulated energy use and actual monitored results. The monitoring of C-2000 pilot projects provides an excellent opportunity. A comparison could be made between monitored results, initial simulations which were based on assumed conditions and ASHRAE 90.1 schedules, and final simulations taking into account as-built and as-occupied conditions. Presenting validation results for C-2000 buildings at promotional workshops will advance the C-2000 goal of high-performance innovative building design by encouraging designers to use energy analysis software.

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Attachment A

Retailers of PC Versions of DOE-2.1E Program

ADM Association, Inc.
(ADM-DOE2)
3239 Ramos Circle
Sacramento, CA 95827
Contact: Marla Sullivan
Phone: (916) 363-8383
Fax: (916) 363-1788

Partnership for Resource Conservation
(PRC-DOE2)
140 South 34th Street
Boulder, CO 80303
Contact: Paul Reeves
Phone: (303) 499-8611
Fax: (303) 499-8611

James J. Hirsch & Associates
(DOE-2.1E)
12185 Presilla Road
Camarillo, CA 93012-9243
Contact: Jeff Hirsch
Phone: (805) 532-1045
Fax: (805) 532-2401

Eley & Associates
(Visual DOE)
142 Minna Street
San Francisco, CA 94105
Contact: Charles Eley
Phone: (415) 957-1977
Fax: (415) 957-1381

Acrosoft International, Inc.
(MICRO-DOE2)
3435 South Yosemite St., #220
Denver, CO 80231
Contact: Gene Tsai
Phone: (303) 696-6888
Fax: (303) 696-0388

Finite Technologies, Inc.
(FTI-DOE)
821 N Street, #102
Anchorage, AK 99501
Contact: Scott Henderson
Phone: (907) 272-2714
Fax: (907) 274-5379