Dynamic Simulation of Whole Building Systems

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KEYWORDS

Building Dynamics, Building Simulation, Building System Modeling, Computer Simulation Program, Dynamic Performance of Buildings, HVACSIM$^+$

ABSTRACT

In an effort to study the dynamic performance of whole building systems, a non-proprietary building systems simulation program called HVACSIM$^+$ has been developed at the National Bureau of Standards (NBS). The program HVACSIM$^+$, which stands for HVAC SIMulation PLUS other systems, is capable of modeling the dynamic interactions between the HVAC system and other building systems, including the building shell, the control system, the heating/cooling plant, and a building management system. Information is presented on the architecture, capabilities, numerical methods, and component models used in the current version of HVACSIM$^+$ and on its application to the simulation of whole buildings. An example simulation is presented to illustrate the use of HVACSIM$^+$ in analyzing the dynamic performance of a three zone building.

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Simulation dynamique de l'ensemble des systèmes d'un bâtiment

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MOTS CLEFS

Dynamiques des Bâtiments, Modèlisation des Bâtiments, Performance Dynamique des Bâtiments, Programme de Simulation Informatique, Simulation des Bâtiments, HVACSIM$^+$

SOMMAIRE

Pour étudier les performances dynamiques de l'ensemble des systèmes d'un bâtiment, un logiciel a été mis au point au National Bureau of Standards. Ce programme est appelé HVACSIM$^+$ des initiales de Heating Ventilation Air Conditionning SIMulation PLUS other systems. Il est indépendant de la structure même du bâtiment et simule les systèmes de ce bâtiment. Ce programme HVACSIM$^+$, est capable de modéliser les interactions dynamiques entre le système de Chauffage, conditionnement d'air et ventilation et les autres systèmes équipant le bâtiment y compris: la structure du bâtiment, le système de contrôle, les installations de chauffage et de ventilation et le système de gestion générale du bâtiment. Les informations présentées concernent l'architecture et les possibilités du programme, les méthodes numériques et les modèles théoriques utilisés dans cette version de HVACSIM$^+$, ainsi que ses applications à la simulation dynamique de l'ensemble des systèmes d'un bâtiment. Un exemple de simulation est présenté pour illustrer l'utilisation de HVACSIM$^+$ lors de l'analyse des performances dynamiques d'un bâtiment comprenant trois zones différentes.

1. INTRODUCTION

In an effort to carry out simulation studies involving the dynamic interactions between a building shell, an HVAC system, and building controls, a non-proprietary building system simulation program called HVACSIM$^+$ has been developed at the National Bureau of Standards (NBS). The program HVACSIM$^+$, which stands for HVAC SIMulation PLUS other systems, is capable of modeling the HVAC (heating, ventilation, and air-conditioning) system plus HVAC controls, the building shell, and the building heating and cooling plant. The program, which is written in the ANSI standard Fortran 77 language, has been developed primarily as a research tool.

The HVACSIM$^+$ program consists of a main simulation program, a library of HVAC system components models, a building shell model, and an interactive front end data generation program. The main program is called MODSIM and employs a hierarchical, modular approach and advanced equation solving techniques to perform dynamic simulations of building/HVAC/control systems. The modular approach is an extension of the methodology used in the TRNSYS program [1]. In the building shell model, a fixed (but user selectable) time step method is used, while a variable time step approach is employed in the HVAC and control systems portion and the zone model.

Some of the more important features of HVACSIM$^+$ were previously introduced to the public [2,3] and the results of some case studies were published [4,5]. The Reference Manual [6] and the Users Guide [7] are also available. A general overview of HVACSIM$^+$ was also presented [8]. Since then, the HVACSIM$^+$ program has been updated especially in the building loads calculation routines. This paper reviews the architecture of HVACSIM$^+$, presents highlights of the modular simulation program (MODSIM), gives a brief summary of the numerical methods employed in HVACSIM$^+$, and describes the building loads calculation procedures that have recently been added. A sample simulation illustrating the use of HVACSIM$^+$'s building and zone simulation features is presented to supplement the HVAC/control system and equipment simulation examples given in previous papers and reports [2-8].

2. ARCHITECTURE OF HVACSIM$^+$

The various portions of HVACSIM$^+$ can be divided into three categories: preprocessing, simulation, and postprocessing. Figure 1 shows a flow diagram of programs and data files comprising HVACSIM$^+$. During preprocessing, a work file for simulation is created and can be edited by the interactive front end program, HVACGEN [7]. This work file is then converted into the model definition file by the program SLIMCON. When a building shell is involved in a simulation, data files of weather conditions and conduction transfer functions for multilayered constructs must also be created. The program RDTAPE reads a weather tape (SOLMET, TMY, TRY, or WYEC tape) or equivalent and selects a portion of the weather data that is of interest. The selected weather data is transformed into the proper input form for MODSIM by the program CRWDTA. Use of a weather tape is optional, since the CRWDTA program can also generate artificial "design day" weather data.

The conduction transfer functions of multilayered building constructs are generated by the CTFGEN program. Except for the front end routines of CTFGEN, the main routines in CTFGEN are taken from the TARP program by

Walton [9]. The thermal properties of additional building materials can be added to an existing data file by using CTFGEN, and multilayered constructs can be formed interactively.

The MODSIM program is the heart of HVACSIM$^+$. As shown in Figure 2, the MODSIM program consists of a main program and many subprograms for input/output operation, block and state variable status control, integration of stiff ordinary differential equations, solving of a system of simultaneous non-linear algebraic equations, component models of the HVAC system and its controls, the building model, and supporting utilities. The simulation program, MODSIM, calls the model definition, conduction transfer functions, weather, and boundary data files. During the execution of MODSIM, simulation control input data can be entered interactively on a terminal. After a successful simulation, three data files are generated. These are the summary, raw output, and initialization data files. After renaming the initialization file as the input file to MODSIM, a new simulation can be performed starting from the point where the previous simulation ended.

Postprocessing is necessary if graphical representation of the raw outputs is desired. The program SORTSB sorts the raw output data if necessary, and removes all alpha numeric labels from the output. The output of this program may then be used for plotting with a user-supplied graphic routine. No data-plotting software is provided with HVACSIM$^+$.

3. MODULAR SIMULATION PROGRAM, MODSIM

MODSIM stands for MODular SIMulation. Many ideas for the design of MODSIM came from the TRNSYS program, which was developed at the University of Wisconsin Solar Energy Laboratory [1]. The original MODSIM was first written in Fortran IV by Hill [3]. Since then, MODSIM has been rewritten in structured Fortran 77 and modified significantly. Important features of the current MODSIM program are described below.

3.1 Hierarchical, Modular Approach

The hierarchical structure of HVACSIM$^+$ is comprised of superblocks, blocks, and units. As illustrated in Figure 3, a number of units form a block, and a number of blocks make up a superblock. One or more superblocks comprise a simulation. Figure 3 shows a setup involving 8 units, 4 blocks, and 2 superblocks. The system of equations in a block or in a superblock are solved simultaneously. The coupling of superblocks is done weakly through the state variables. In the interest of economy, the system of equations between superblocks is not solved simultaneously.

Using a modular approach, a UNIT in MODSIM represents a component model of a HVAC system, controls, or a building shell component. Each physical component is modeled in the TYPEn subroutine, where n is the index number of the type assigned to the specific component. More than one unit can call the same TYPEn subroutine if the same component model is used more than once. Each subroutine of a component model has inputs, outputs, parameters, and a workspace vector for saving intermediate results. The component model configuration data file, which is an input file to the HVACGEN program, contains information on the numbers of inputs, outputs, parameters, elements in the saved workspace vector, and a description of the inputs, outputs, and parameters.

This hierarchical, modular approach provides great flexibility in setting up a simulation model. The actual breakdown of a building system into blocks and superblocks is left to the user and depends upon the nature of the system and the type of interactions among its various components. Proper 'blocking' is required to produce good simulation results and to reduces computational time.

3.2 Controls of State Variables and Blocks

During a simulation, a large portion of time is spent in solving the system of simultaneous equations. Reduction of the number of equations solved simultaneously in a block or a superblock can result in considerable computational savings. In MODSIM, when some of the state variables reach steady state, these variables are removed from the system of state variables that are solved simultaneously and put aside (or 'frozen') until deviations from the steady-state values are encountered. Similarly, a block can be inactivated (or frozen) if all the input variables to the block are frozen. A block is again marked active as soon as one of its block inputs becomes unfrozen. When a block is frozen, it is no longer necessary to monitor the frozen state variables in the block.

3.3 Hybrid Simulation Time Steps

The MODSIM program incorporates two different types of time steps. One of them is a fixed time step, and the other is a variable time step. The building shell model uses a user-selected fixed time interval because the conduction transfer functions of building constructs are calculated on the basis of uniformly distributed time sampling. Variable time steps are used for all other component models. Each superblock in a simulation is an independent subsystem in the sense that it proceeds forward in time independently, with its own time step. The variable time step is determined for each superblock (excluding the superblock for the building shell) by the integration routine used to solve the systems of differential equations. The largest time step allowed in a superblock is, however, limited to the fixed time step used in the building shell model.

3.4 Time Dependent Boundary Conditions

State variables which are not determined by the system being simulated are called boundary conditions or boundary variables. Boundary conditions can be designated as time dependent boundary variables when the simulation work file is generated. Values for these variables must be stored in the boundary data file, which is read as the simulation progresses. Time intervals in this data file need not be equal, since a third order Lagrangian interpolation method is used.

4. NUMERICAL METHODS IN MODSIM

The numerical methods employed in the MODSIM program involve techniques for solving systems of simultaneous nonlinear algebraic equations, integrating stiff ordinary differential equations, and interpolating data sampled at

either a fixed period or variable time intervals. A large number of subprograms in MODSIM are related to these numerical algorithms.

4.1 Nonlinear Equation Solver

The subroutine SNSQ with its associate subprograms is used in MODSIM. This routine is a part of the mathematical software package SNLSE in the CMLIB package, NBS [10], and was coded by Hiebert at Sandia National Laboratories by combining the HYBRD and HYBRDJ routines in the MINPACK code developed by Argonne National Laboratories [11]. The method used in the SNSQ program is based on Powell's hybrid method [12]. Minor modifications were made to the SNSQ routine to achieve better simulations with HVACSIM$^+$.

4.2 Integration of Stiff Ordinary Differential Equations

The use of variable time step and variable order integration techniques to solve sets of differential equations can reduce the amount of computer time required for dynamic simulations significantly. The algorithm employed is the one developed by Brayton, Gustavson and Hachtel [13]. This is an extension of the famous Gear algorithm called DIFSUB [14], which uses the backward differential formulas associated with Nordsieck's method [15].

4.3 Interpolation of Data

Lagrangian and spline interpolation techniques are used in the MODSIM program. Interpolation of data points for the time dependent boundary variables is made by using a 3rd order Lagrangian interpolation procedure. For interpolating the hourly weather data, the computer program for cubic spline interpolation by Ferziger [16] is implemented by MODSIM.

5. BUILDING LOADS CALCULATION

In HVACSIM$^+$, a building shell model and a building zone model are used for building thermal loads determination. These models were developed based on Kusuda [17] and Walton [9]. The building shell model requires a user-selected fixed time interval, while the zone model may use variable time intervals.

5.1 Response Factor Method

Models for building loads calculation include the effects of different kinds of building shell materials, air temperature and humidity, lighting, equipment, occupancy schedule, solar radiation, wind velocity, orientations of the exterior building surfaces, and the effect of shadowing. Since there are so many factors involved, some simplifying assumptions had to be made. The major assumptions in the current HVACSIM$^+$ program include: (1) uniform temperature distributions on a building surface (one dimensional heat transfer across a wall), (2) uniform ground temperature distribution, and (3) no effects of wind direction, rain, and snow.

The approach taken uses the standard response factor method to calculate the conductive heat transfer rates through the building shell. The conduction transfer functions are computed once and stored prior to a simulation. The same time interval used in the calculation of conduction transfer functions of building constructs is applied as the period during which the conductive heat fluxes through the building surfaces are assumed to be invariant.

Primary routines for the building load determination are those dealing with the calculation of building surface temperatures and zone loads. Walls and zones are treated as component models, and are coded as TYPEn subroutines. Because of the use of the fixed time step, the units representing building surfaces must be in a superblock which is separate from those containing units which use a variable time step. In contrast, the zone model calculates indoor air dry-bulb temperature and humidity ratio on a variable time step basis and takes into account the dynamic operation of the HVAC system and its controls, and thermal loads.

5.2 Conduction Transfer Function Calculation

Conduction transfer functions of walls, floors, roofs, and windows are required by the subroutine for a building surface (TYPE51). The subroutine also needs a term related to conductive heat fluxes on both external and internal surfaces of constructs. The CTFGEN program (see Figure 1) calculates the conduction transfer functions and the flux transfer functions. Thermal properties of building materials (thickness, thermal conductivity, density, specific heat, and thermal resistance) are stored in a data file (THERM.DAT). By using CTFGEN, thermal properties of additional building materials can be added to this data file. User selected building materials can be composed to form the multilayered building constructs (sometimes called construction) for which transfer functions are required.

The main calculation routine originated in TARP, having been slightly modified from BLAST. Details of the calculation procedure may be found in references [18, 19].

5.3. Weather Data

When a simulation involves building thermal loads, weather data are required by MODSIM. The subroutine RDENV in MODSIM expects to read outside air dry-bulb temperature, humidity ratio, barometric pressure, wind speed, direct normal solar beam radiation, sky diffuse radiation, and total horizontal solar radiation for each hour. The hourly weather data are interpolated for a fraction of an hour by using the spline interpolating routine mentioned in the section 4.3.

The program RDTAPE reads a weather tape (see Figure 1) and writes the selected weather data on an output data file (WTPOUT.DAT). The weather data in the file are transformed into the proper input format required by RDENV by the program CRWDTA. If some information from a weather tape is missing, CRWDTA generates artificial data to fill in the missing portions. Use of a weather tape and the RDTAPE program is optional. Alternatively, CRWDTA can be used to generate smooth artificial weather data with characteristics specified by the user.

6. EXAMPLE SIMULATION

Figure 4 shows a single-story building with three zones which was simulated using HVACSIM$^+$. A simple system (inlet duct-fan-duct), which was connected

to one of the zones (Zone 3), is illustrated in Figure 5. A weather data file was created for Washington, DC, using the data from the "Weather Year for Energy Calculation" (WYEC) tape. Figure 6 shows solar radiation influxes from the weather tape for three days, from July 7 to July 9. Each zone space had the following internal loads: one person occupied the space (sensible and latent heat gains of 71.76W and 45.4W, respectively), the heat gains from fluorescent lights was 200W, and the sensible heat gain from equipment was 150W, while the latent heat gain was 20W. The fan serving Zone 3 was continuously run to supply the conditioned air from the inlet duct. The inlet air dry-bulb temperature was prescribed as a boundary condition in the boundary data file and was maintained at 15 C from 9:00 a.m. to 5:00 p.m., and at 20 C for the rest of the day.

The outdoor temperature and the zone, supply and inlet temperatures for Zone 3 are shown in Figure 7. The supply air is about 2 C warmer than the inlet air, due to a constant temperature rise across the fan. The Zone 3 air temperature is nearly equal to the supply air temperature. The zone air temperatures for the three zones are compared in Figure 8. Very significant variations of zone air temperatures can be observed. As seen in the figure, the unconditioned space temperatures are much higher than the conditioned space air temperature. The peak temperature of Zone 1 is also much higher than the outdoor air temperature. Three ceiling inner temperatures are presented in Figure 9. The inner surface temperatures of the ceiling, east wall, and floor of the Zone 1 are plotted vs. time in Figure 10. The floor temperature is always lower than other surfaces in the zone because the outer surface temperature of the floor was maintained at the ground temperature of 15 C.

The convective heat flow rates from the building inner surfaces across the air film are depicted in Figure 11 for the three zones. The value in the Zone 3 is quite different from the others due to the fact that the low zone air temperature caused a greater influx of heat from the building surfaces which were exposed to the outside air and to the sun.

7. SUMMARY

This paper has presented information on the important features of a new simulation program, called HVACSIM$^+$, that was recently developed at the National Bureau of Standards. This program was designed to be used as a research tool for investigating the dynamic interactions between the building shell, the HVAC system, the heating and cooling plant, and building control systems, and for exploring ways to optimize the performance of whole buildings. The paper discusses the architecture of HVACSIM$^+$, the hierarchical modular approach used, the freezing of state variables and blocks, the use of hybrid simulation time steps, the numerical methods employed, and building loads calculation procedures that were recently added to the program. An example illustrating the dynamic response of a building containing three zones is also presented to supplement the simulation examples given in previous reports [2-8].

REFERENCES

1. S. A. Klein, et al., TRNSYS, A Transient System Simulation Program, (University of Wisconsin, 1983), Report 38-12.
2. G. E. Kelly, C. Park, D. R. Clark, and W. B. May, HVACSIM$^+$, A Dynamic Building/HVAC/Control Systems Simulation Program, Proc. of Workshop on HVAC Controls Modeling & Simulation, (Georgia Inst. of Tech., Atlanta, 1984).
3. C. R. Hill, Simulation Techniques for Building Systems, Proc. of Workshop on HVAC Controls Modeling and Simulation, (Georgia Inst. of Tech., Atlanta, 1984).
4. C. R. Hill, Simulation of a Multizone Air Handler, ASHRAE Trans., ASHRAE (Atlanta, GA, 1985), Vol. 91, Part 1.
5. D. R. Clark, C. W. Hurley, and C. R. Hill, Dynamic Models for HVAC System Components, ASHRAE Trans., ASHRAE (Atlanta, GA, 1985), Vol. 91, Part 1.
6. D. R. Clark, HVACSIM$^+$ Building Systems and Equipment Simulation Program Reference Manual, (National Bureau of Standards, Gaithersburg, MD, 1985), NBSIR 84-2996.
7. D. R. Clark, and W. B. May, Jr., HVACSIM$^+$ Building Systems and Equipment Simulation Program Users Guide, (National Bureau of Standards, Gaithersburg, MD, 1985), NBSIR 85-3243.
8. C. Park, D. R. Clark, and G. E. Kelly, An Overview of HVACSIM$^+$, A Dynamic Building/HVAC/Control Systems Simulation Program, Proceedings of the 1st Annual Building Energy Simulation Conference, Seattle, WA, August 21-22, 1985.
9. G. N. Walton, Thermal Analysis Research Program Reference Manual, (National Bureau of Standards, Gaithersburg, MD, 1983), NBSIR 83-2655.
10. Guide to Available Mathematical Software (GAMS), (Center for Applied Math., National Bureau of Standards, Gaithersburg, MD, 1981).
11. K. L. Hiebert, An Evaluation of Mathematical Software that Solves Systems of Nonlinear Equations, ACM Trans. Math. Software, 1982, Vol. 8, No. 1, pp. 5-20.
12. M.J.D. Powell, A Hybrid Method for Nonlinear Equations, in Numerical Methods for Nonlinear Algebraic Equations, Edited by P. Rabinowitz, Gordon and Breach, (London, 1970).
13. R. K. Brayton, F. G. Gustavson, and G. D. Hachtel, A New Efficient Algorithm for Solving Differential - Algebraic Systems Using Implicit Backward Differential Formulas, Proc. IEEE, 1972, Vol. 60, No. 1, pp. 98-108.
14. C. W. Gear, The Automatic Integration of Ordinary Differential Equations, Comm. ACM, 1971, Vol. 14, pp. 176-179.
15. A. Nordsieck, On Numerical Integration of Ordinary Differential Equations, Math. Comp., 1962, Vol. 16, pp. 22-49.
16. J. H. Ferziger, Numerical Methods for Engineering Application, (John Wiley, N. Y., 1981).
17. T. Kusuda, NBSLD, The Computer Program for Heating and Cooling Loads in Building (National Bureau of Standards, Gaithersburg, MD, 1976), BSS 69.
18. T. Kusuda, Thermal Response Factors for Multilayer Structures of Various Heat Conduction Systems, ASHRAE Trans., ASHRAE (Atlanta, GA, 1969), Vol. 75, pp. 246-270.
19. D. C. Hittle, Calculating Building Heating and Cooling Loads Using the Frequency Response of Multilayered Slabs, (Construction Engineering Research Lab., Champaign, IL, 1981), Report CERL-TM-E-169.

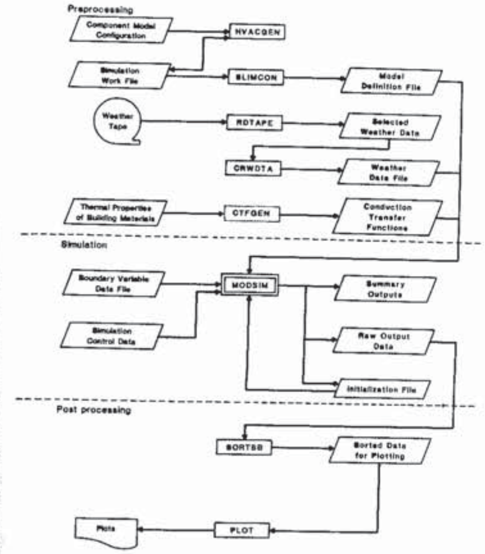

Figure 1. Flow diagram of programs and data files of HVACSIM$^+$

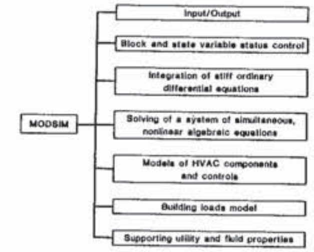

Figure 2. The structure of MODSIM

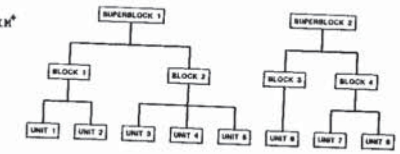

Figure 3. Hierarchical simulation setup

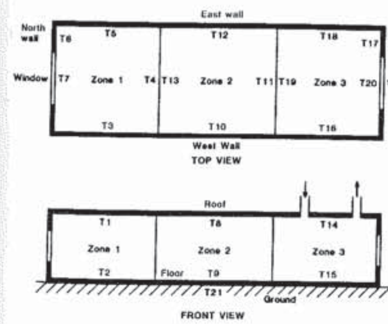

Figure 4. A three-zone model

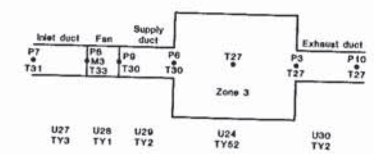

Figure 5. A simple system (fan and ducts) for Zone 3

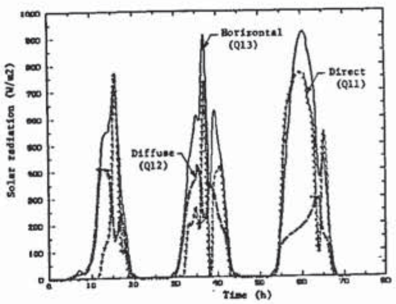

Figure 6. Solar radiation influxes from a weather tape

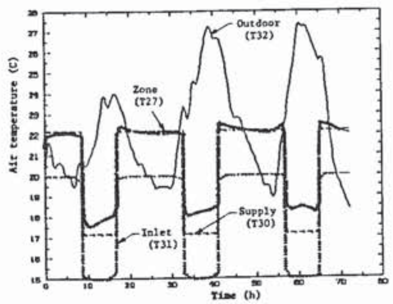

Figure 7. Outdoor temperature and the zone, supply, and inlet air temperatures for Zone 3

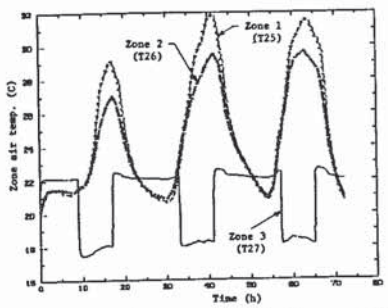

Figure 8. Zone air temperatures in the three-zone model

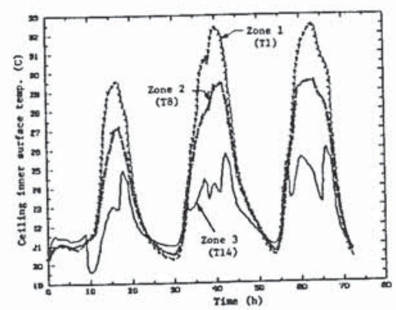

Figure 9. Ceiling inner surface temperatures of the three-zone model

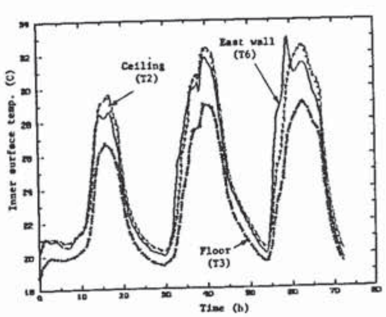

Figure 10. Inner surface temperatures of the selected building surfaces in Zone 1

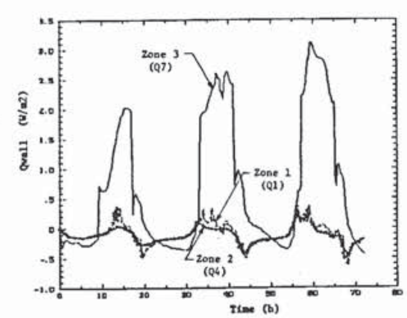

Figure 11. Convective heat flow rates from the building inner surfaces

The BESA Approach

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ABSTRACT

Public Works Canada (PWC), responsible for the design and management of federal real property in Canada, has embarked on a major program involving the improvement and enhancement of state-of-the-art energy analysis techniques for a variety of building types.

The program, Building Energy Systems Analysis (BESA), has three distinct phases. Phase I - "Review" was completed in September 1982 and aimed at identifying software development needs. Phase 2 - "Development" will see the development of a comprehensive building design and analysis software package. Phase 3 - "Support" will address the maintenance and support of the software on a national basis.

Phase 1 addressed itself to the identification of current and potential uses of various energy analysis tools, present weaknesses in existing software, and the industry's views on energy analysis in general. Based on a nation-wide survey of practicing engineers, architects, property managers, and researchers, and subsequent discussions with program developers, PWC developed a philosophy for the BESA package.

The author presents an account of the development phase, including specific details of the software development strategy with emphasis on user interface capabilities, reviews the status of the project, and discusses plans for nation-wide support.