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BUILDING ENERGY SYSTEMS PROGRAM

March 1987

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APPLIED SCIENCE DIVISION ANNUAL REPORT

BUILDING ENERGY SYSTEMS PROGRAM

FY 1986

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BUILDING ENERGY SYSTEMS PROGRAM

INTRODUCTION

During FY 1986, the Building Energy Systems Program was formed as part of a reorganization of the Applied Science Division. The Program consists of the Simulation Research Group (formerly part of the Energy Efficient Buildings Program), the Building Systems Analysis Group, and the Active Solar Cooling Project (the latter two formerly part of the Solar Energy Program). In the new Divisional structure, the Building Energy Systems Program is one of four programs that constitute the Center for Building Science, the others being the Windows and Lighting Program, the Energy Analysis Program, and the Indoor Environment Program.

With the exception of the Active Cooling Project, which deals specifically with research on solar cooling equipment and analysis of solar cooling systems, the main theme of the Program is the comprehensive simulation and analysis of the energy performance of whole buildings. The emphasis is on nonresidential buildings, developing and applying the types of comprehensive computer models that enable integrated analyses of heating, cooling, and daylighting system performance.

The Simulation Research Group has two major activities. The first is the maintenance and continued development of DOE-2, a public-domain computer program for detailed, hour-by-hour simulation of energy use in buildings. DOE-2 is in wide use in the U.S. and thirty other countries for design of energy-efficient buildings and for research studies of innovative building technologies. During FY 1986 work continued on adding new capabilities to DOE-2 to enhance its usefulness.

The second main activity of the Simulation Research Group is the development of the next generation simulation software for use in the 1990's and beyond. In collaboration with other groups in the U.S., France, China, and the U.K., a plan has been formulated to create an "Energy Kernel System" consisting of an extensive library of software modules and an executive program which will allow users to produce a wide variety of customized simulation programs. In FY 1986 LBL developed the Simulation Problem ANalysis Kernel (SPANK) as the first prototype of the Energy Kernel System. In addition, LBL initiated the establishment of a new professional society — the International Building Performance Simulation Association (IBPSA) — in order to foster and guide collaborative research in advanced simulation.

The Building Systems Analysis Group continued investigation of the energy performance impacts of passive heating, cooling, and daylighting technologies in nonresidential buildings. An examination of energy use in educational buildings, carried out in FY 1985, had implied that daylighting technologies could prove beneficial in this sector; however, a more comprehensive examination was conducted in 1986 and showed that the benefits have marginal cost advantages over conventional, efficient, electric lighting. Investigations of the ways in which thermal energy storage systems can beneficially impact building energy use continued. The studies conducted in FY 1986 focused on the integration of structural thermal energy storage (presumably present to enhance the performance of passive cooling technologies) with the mechanical cooling system.

Under the Solar Federal Buildings Program, a simplified technique was developed for evaluating the long-term performance of daylit buildings based on short-term monitored data, and plans were made to test the methodology in collaboration with researchers in the United Kingdom. This project is being coordinated with researchers at SERI who are developing thermal performance evaluation methodologies.

During FY 1985 a new project was undertaken by the Building Systems Analysis Group with participation by the Energy Analysis Program. This project is an evaluation of the Institutional Conservation Program and is being conducted in collaboration with Argonne National Laboratory. The DOE Institutional Conservation Program provides grants to schools, colleges, and hospitals to identify and implement energy conservation measures (ECMs). The evaluation project was designed to assess the success of the program in serving the needs of the institutional sector. In FY 1986 data collection plans were developed and implemented; the plan includes assembly of existing data from a variety of sources and collection of new data through mail surveys and phone interviews. In parallel with the surveys and interviews, two additional studies are underway: one is directed at assessing the technical quality of the analysis on

which ECM selection is based, and the other is attempting to estimate the overall impact of the grants on energy use in the institutional buildings sector.

The Active Solar Cooling Group continued research on new types of advanced-cycle absorption heat pumps that can more than double the efficiency of today's solar cooling systems. The analysis and evaluation of the experimental results of testing the first of these advanced-cycle machines, using a double-effect regenerative absorption cycle, was completed during FY 1986. Very good agreement was observed between the experimentally measured and theoretically calculated efficiency values, over the full range of operating conditions. These results indicate that the predicted higher efficiencies for more-advanced regenerative absorption heat pumps can also be achieved through continued research and development.

In parallel with the experimental work, simulations and analyses of solar cooling systems have been performed to establish the operating parameters, thermal performance, and parasitic electric power requirements of current and advanced space conditioning systems. The FY 1986 activities concentrated on developing simplified bin methods of analyzing the performance of ventilation-mode desiccant and advanced absorption cooling systems, and on improvements in system performance possible through the use of indirect and regenerative evaporative cooling subsystems.

Active Solar Cooling*

M. Wahlig, J. Rasson, M. Warren, P.L. Chen, and I. Parmaksizoglu

The purpose of this project is to make major contributions to the technology base necessary for solar energy to become a viable option for the cooling of buildings. This project has two major tasks: (1) research on improved absorption cycles for high-efficiency active solar cooling and heating systems and (2) systems analysis of active solar cooling and heating systems to establish operating requirements, research needs, and thermal performance of current and advanced space conditioning systems.

Absorption Chiller Research

The objective of the research on absorption-cycle chillers is to achieve a significantly higher conversion efficiency than is possible in other approaches to solar cooling and heating of buildings. Being essentially heat pumps, absorption-cycle chillers can be used for heating as well as cooling if the refrigerant fluid does not freeze in the outdoor coil during heating applications. We restrict our fluid choices to those for which this heating option is available.

The absorption-cycle research program consists of four phases, each successive phase leading closer to the final machine. The first phase was successfully completed some time ago.[1] By modifying a conventional gas-fired ammonia-water absorption chiller, we demonstrated the capability of our analysis techniques to predict accurately the performance of single-effect (i.e., single-stage) absorption-cycle chillers under operating conditions appropriate for solar-powered cooling.

In the second phase, a completely new solar-driven single-effect chiller was designed, fabricated, and tested, using the experience gained during the first phase. This new ammonia-water chiller had several unique features for recouping thermal and mechanical energy. The second phase was successfully completed[2] in FY 1982.

In the present, third phase, we are investigating the performance improvement obtained by adding a unique second stage to the single-effect chiller tested in the second phase. The concept of the resulting double-effect regenerative cycle (or cycle 2R) has been described previously.[3] Basically, with the addition of the second stage, the overall chiller efficiency increases continuously as a function of the inlet temperature from the solar collectors. This 2R chiller has been designed,[4] fabricated, and assembled; the debugging and testing was started in FY 1983 and was successfully completed in FY 1985. The analysis, evaluation, and first publication of the experimental results occurred during FY 1986.

In the fourth phase, it was planned to investigate an extension of the regenerative absorption technology — to a cycle that should yield a still higher efficiency while requiring less heat-exchanger area, for potentially a lower cost. The basic concept of this single-effect regenerative cycle (which we call cycle 1R) has also been described previously.[5] The probability of successful development of the cycle 1R chiller has been greatly enhanced by our successful experience in developing the cycle 2R chiller. However, budget reductions in the solar cooling program may preclude the development of the cycle 1R chiller as originally planned.

Systems Analysis

The objectives of the systems analysis activities are: (1) to perform systems simulation and analysis of active solar absorption and desiccant cooling/heating systems to establish the operating requirements and thermal performance of current and advanced space conditioning systems; (2) to develop methods to analyze different cooling systems in a common comparative framework; and (3) to evaluate by computer simulation the impact of system controls and control strategies on annual energy savings of advanced solar-driven heating, ventilating, and air conditioning systems.

ACCOMPLISHMENTS DURING FY 1986

Absorption Chiller Research

The analysis and evaluation of the experimental results of testing the 2R chiller were completed in FY 1986.

The 2R chiller is a double-effect, regenerative absorption chiller/heat pump. Ammonia-water is used as the refrigerant-absorbent working fluid pair. The 2R heat pump consists of two stages, as shown in Figure 1 on an ammonia-water Pressure-Concentration-Temperature (PXT) diagram for cooling-mode operation. In the first, higher temperature stage, the boiler element is driven by the heat source (such as solar collectors) at a temperature

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Solar Buildings Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

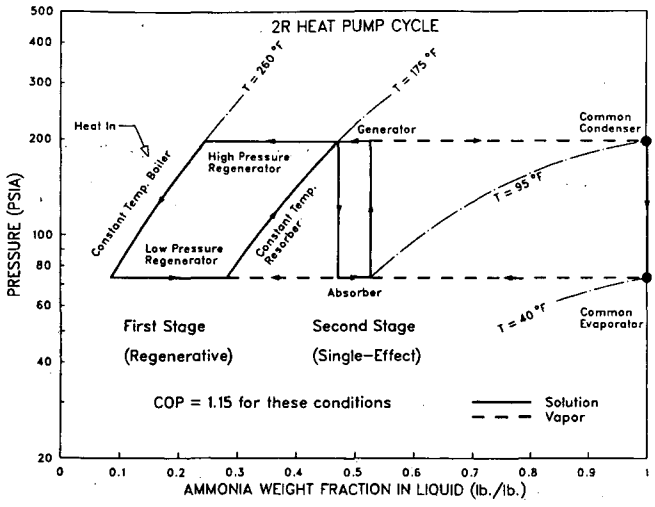

Figure 1. Schematic diagram of 2R absorption heat pump cycle on a pressure-concentration-temperature diagram for the ammonia-water working fluid pair. (XBL 871-155)

ranging from 170 F to 260 F. The resorber element rejects heat at about 170 F to the second stage. The boiling and the resorption are nearly constant temperature, multi-pressure processes. Each pressure step in the boiling process is connected to an equal pressure step in the resorption process through vapor feed lines.

The second, lower temperature stage of the 2R heat pump is a conventional single-effect absorption cycle. Its generator element, as shown in Figure 1, is driven by heat rejected from the first-stage resorber at a temperature of about 170 F. The high-pressure refrigerant vapor produced by both stages is condensed in the common (to both stages) condenser. The refrigerant passes through an expansion valve into the common evaporator, in which the refrigerant vaporization produces the cooling effect.

The important characteristic of this 2R cycle is that its COP is predicted analytically to increase continuously with temperature, at about 55% of the theoretically maximum Carnot efficiency, which is given by:

$$COP_{Carnot} = (T_B - T_0)/(T_B + 459)*(T_E + 459)/(T_C - T_E),$$

where T_B, T_C, and T_E are the boiler, condenser, and evaporator temperatures in °F. T_0 is the saturation temperature of the solution leaving the second-stage absorber.

The 2R heat pump experimental unit had a nominal capacity of 3 tons. The first, regenerative stage consisted of seven boiling and resorption steps. The unit was operated in a controlled manner over a broad range of temperature conditions, using the capabilities of the LBL absorption heat pump test facility.

Highlights of the experimental test results[6] are shown in Figures 2 and 3. Figure 2 shows that the experimentally measured cooling COP is approximately 55% of the ideal Carnot COP, as predicted, over a wide range of operating temperature conditions. In fact, the overall agreement between experimentally measured and theoretically calculated COP values, over the full range of operating conditions, is remarkably good, as shown in Figure 3. This good agreement lends confidence to the analytical methods used to predict the performance of regenerative absorption heat pump cycles.

The successful completion of this 2R-chiller phase of the work bodes well for the future development of yet higher efficiency regenerative-cycle absorption heat pumps, such as the cycle 1R design and its variations.

A parallel activity during FY 1986 consisted of the continuation of the joint U.S./Israel project on modeling high efficiency, advanced absorption cycles. In the U.S., LBL is pursuing the application of powerful, well-developed, public-domain chemical process flowsheet computer programs, such as

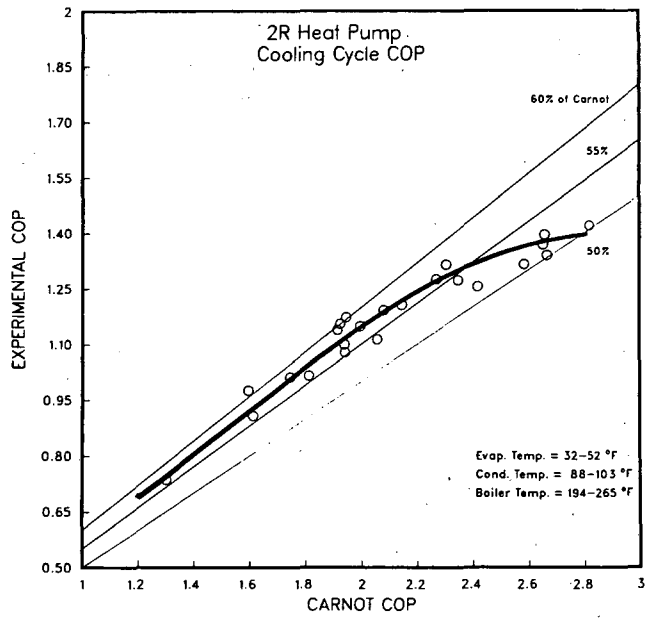

Figure 2. Experimentally measured values of the cooling cycle COP for the 2R heat pump vs. the calculated Carnot COP for the same operating conditions. The solid straight lines represent constant percentages of Carnot efficiency. The solid curved line is a fit to the experimental data points. (XBL 871-157)

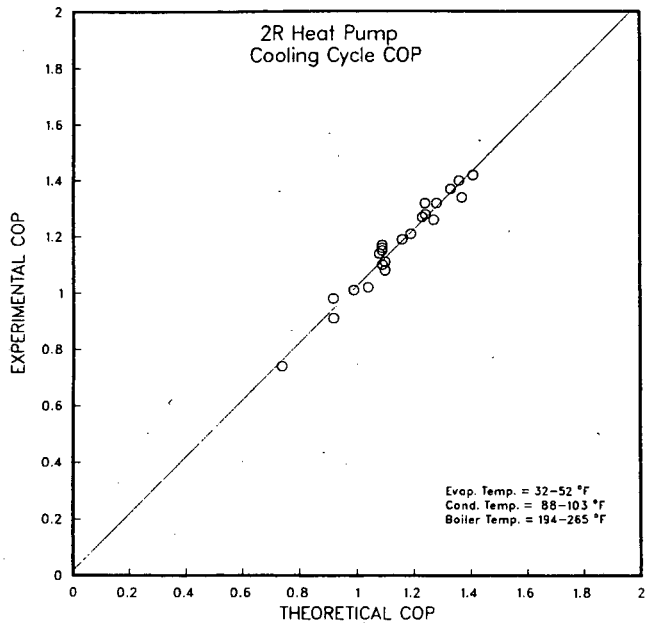

Figure 3. Comparison of the experimentally measured and theoretically calculated cooling cycle COP values, over a broad range of operating conditions. The solid line is a least squares fit to the data points. (XBL 871-156)

ASPEN (Advanced System for Process Engineering), to the solution of complex absorption cycles. In Israel, Gershon Grossman's group at the Technion is extending the capabilities of his previously developed absorption-cycle simulation code to undertake the modeling of open-cycle absorption systems.

In FY 1986, LBL first tested ASPEN's ability to solve **closed-loop** refrigeration systems, a capability that was in question because of unsuccessful solution attempts by other research groups. We successfully modeled and solved a simple closed-loop cooling system, using component subroutines already in ASPEN.

Next, mathematical models of absorption components were prepared and added to ASPEN, along with data on properties of absorption fluids. With the assistance of a consulting firm (Jay S. Dweck Co.) experienced in the use of ASPEN, necessary changes to fluid property relationships were made, convergence problems were identified and solved, and single-effect absorption cycles were simulated successfully.

This was followed by the detailed modeling and simulation of the 2R heat pump, achieving an important milestone in the capability to model complex advanced absorption cycles. The simulation results indicated that the simplified mathematical model of the 2R heat pump that we have been using for years is indeed an adequate method to estimate the performance of this regenerative-cycle heat pump.

Systems Analysis

In FY 1986 work has continued on comparing the performance of desiccant and advanced absorption cooling systems. To the extent possible, all cooling systems take advantage of the ability to reject heat directly to the atmosphere. Desiccant systems obtain their cooling effect from evaporative cooling and heat exchange. Advanced cycle desiccant systems have improved heat rejection capabilities. Advanced absorption cooling technology offers the possibility of chillers with thermal COP's of 1.55 or greater at design conditions. When evaporative cooling and heat exchange components are added, the performance of an advanced absorption cooling systems are further enhanced.

A bin method of analysis developed in FY 1985 to evaluate the impact of indirect and regenerative evaporative cooling on reducing cooling loads for active solar cooling systems[7] has been extended to carefully model the air-side transport and delivery system for a commercial building. Detailed information is needed to model advanced HVAC systems that differ from the simple cooling coil and economizer configuration. Our approach has been to use a standard DOE-2.1C simulation of a commercial building to develop the cooling load information. The building chosen for study is a medium-sized, 50,000 ft^2 (465 m^2), commercial office building[8] which has been simulated using Weather Year for Energy Computation (WYEC) data in five cities: Miami, Atlanta, Fort Worth, Phoenix, and Washington, DC. Hourly reports are generated with the detailed information.

Two computer programs have been developed as post-processor programs for the DOE-2.1C hourly reports. A program, CLEAN, reads the hourly reports file, ignores irrelevant information, and writes a data file containing two lines of identifying information and one line of data for each hour. Because of the number of data fields, the hourly report generator produces three pages of data for each day and three data files are produced. These files are then binned to give the mechanical system conditions that must be met to simulate the cooling system. The program NEWBINS reads the three data files, compiles bin statistics, and writes a summary report presenting bin tables for different variables. NEWBINS produces a bin summary file that contains one line of data for each temperature and humidity bin. The temperature bins are in incre-

ments of 5 C. The humidity ratio bins are in increments of 0.0002 above 0.0007 kg/kg-air.

The bin summary file contains: the number of hours of system operation at that bin; the average barometric pressure; the average temperature and humidity ratio of the cold supply air, the heating supply air, and the return air; the total volume of supply air, outdoor air, cold supply air, and return air; the supply and return fan power; the total building electrical use; and the average hourly cooling coil load. The annual operating conditions for the building are then summarized in a single table of data that will fit on one page. Bin summary files can be developed for any building that can be modeled using DOE-2.1C for any city with available weather files.

A computer program, BINSYS, has been developed and is used to model the operation of advanced HVAC systems for each temperature and humidity bin, to summarize the total energy use for that bin, and to calculate the annual energy and water consumption. BINSYS is an executive program that reads the bin summary file, calls other routines to calculate the performance at those conditions, and summarizes and prints out the results. The actual system modeling is done in subroutines that calculate the psychrometric state of the air stream at each point in the cycle by calling component subroutines from a library, and by iterating the cycle calculation as necessary to achieve convergence. Advanced HVAC systems are modeled using heat exchangers, evaporative coolers, economizers (dampers), one or more cooling coils, solid desiccant wheels, liquid desiccant dehumidifiers, chillers, etc. As component models are improved the simulation can be rerun easily. The modular nature of the program makes it straightforward to model additional cycles, by calling the components and setting up iteration as needed. The program is still under development.

Other solar system analyses in FY 1986 included TRNSYS simulation of the energy performance of advanced absorption cooling systems,[9] evaluation of the performance of solar thermal storage options,[10,11] and cooling cost requirements.[12] Analysis techniques developed for active solar cooling systems have been applied to conventional HVAC systems as well. There is widespread interest in thermal energy storage with ice or chilled water for utility peak demand avoidance. Using the same cooling loads generated for our solar analysis, the annual performance of a thermal storage system was modeled on an hourly basis. Results[13] show that the method of operation and control of these systems will have a significant impact on the value of the system to both the customer and the utility. Technology advances in variable motor speed drives have generated significant interest in variable speed fan operation. Using the fan volume data from previous simulations, it is possible to determine the number of hours that the fan delivers different volumes. Analysis was done[14] to show that significant fan energy savings can result from application of variable speed drives.

PLANNED ACTIVITIES FOR FY 1987

Absorption Chiller Research

The final report on the 2R chiller program will be completed, reviewed, and published. Because of funding reductions in the DOE solar cooling program, it is unlikely that development of the 1R absorption chiller, the previously planned next phase of the chiller research, will proceed. Other avenues will be explored to continue this development, probably concentrating on gas-driven variations of the 1R-cycle technology. The predicted efficiencies of these cycles substantially exceed those of all other proposed advanced-cycle absorption heat pumps.

Work on the modeling and simulation of advanced absorption cycles will continue, as part of the U.S./Israel joint project. The ASPEN computer program will be used to study the sensitivity of 2R cycle performance to variations in major design parameters, such as flow distribution, operating temperatures, and number of pressure stages. Thus the suitability of ASPEN for use as a design optimization tool for absorption cycles will be determined. In addition, the capabilities of ASPEN will be expanded to the simulation of higher performance and more complex absorption cycles, including the 1R cycle and its variations.

Systems Analysis

Comparative analysis of the performance of advanced absorption and desiccant solar cooling systems will continue during FY 1987. The program BINSYS will be refined and applied to: (1) evaluating the impact of indirect and regenerative evaporative cooling on reducing cooling system loads; (2) comparing advanced absorption and ventilation-mode desiccant systems with electrically driven vapor compression chillers; and (3) evaluating the operation of advanced desiccant cooling systems that incorporate regenerative evaporative cooling.

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Passive Solar Buildings Program*

R.C. Kammerud, H. Akbari, B. Andersson, B. Birdsall, W.L. Carroll, J.P. Coutier, J.W. Place, and K. Whitley

The amount of conventional fuel used to heat, cool, and light buildings is determined by (1) the interaction of the building with its environment, (2) the thermal gains associated with the activities occurring within the structure, (3) the thermal storage characteristics of the building, and (4) the operating characteristics of the equipment used to convert conventional fuels to end-use energy. Traditionally, the building design process has not adequately accounted for the combined influence of these four factors on building energy consumption. To do so requires that the designer have access to techniques for properly controlling the interactions of the building with the environment and for managing the energy flow within the structure.

Passive heating, cooling, and lighting strategies integrate the energy control and management schemes into the building design. The design parameters are selected so that they enhance and control the coupling of the building to the environment, thereby reducing the requirements for auxiliary heating, cooling, and lighting energy. In this context, the Passive Program at Lawrence Berkeley Laboratory is directed at theoretical and experimental investigations of the energy performance implications of passive design strategies, with emphases on natural lighting and passive and hybrid cooling of commercial buildings. The specific objectives of the program are the following:

(1) Develop analytic descriptions of the energy processes that occur within a building and between a building and the environment.
(2) Evaluate the effectiveness of passive systems in reducing energy consumption for space heating, space cooling, and lighting.
(3) Develop techniques for integrating effective passive technologies into conventional building systems and structures.
(4) Develop appropriate design tools as a mechanism for transferring newly gained knowledge on passive technologies to segments of the design and building communities.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Solar Buildings Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

The strategy used to meet these objectives consists of coordinated experimental and theoretical tasks leading to advanced energy analysis capabilities that can be used in passive system design and evaluation. The emphasis to date has been on improving our understanding of how energy is transferred within passive buildings, how that relates to energy savings exhibited by existing passive buildings, and how future passive systems can be integrated with the structure, mechanical systems, and functional requirements of buildings to improve their energy, functional, and economic performance. Accomplishments and plans in each of these areas are described below.

ACCOMPLISHMENTS DURING FY 1986

Natural Lighting

A great deal of research has been done within this program over the past several years to characterize and refine a variety of roof aperture daylighting systems. Roof apertures are valuable sources of daylight because of their ability to provide daylight evenly distributed throughout a space with a minimum of interference with view glazing, their potential for effective use with aperture controls, and the possibilities for integration with other building elements.

This work has taken the form of experimental projects,[1,2] parametric computer simulation studies,[3,4,5] system designs,[6] and investigation of integration issues.[7,8,9,10] During FY86, much of this information has been gathered and organized into a design tool for designers with various levels of expertise.

The design tool resulting from this work is in the form of a manual, consisting of three major sections. The sections of greatest interest will depend on the expertise of the designer using the tool. The first section deals with the fundamental nature of light, including spectral components, the response of the eye to light, and different means of gauging the performance of a lighting environment, from both energy and visual standpoints. This section will be used by those interested in daylighting, but who lack some of the fundamental information on the way light is used and perceived.

The second section describes general daylighting characteristics and the application of those characteristics to roof aperture daylighting systems. Techniques for dealing with both beam and diffuse light are discussed, effects of aperture orientation and tilt are evaluated, and methods for system evaluation

are described. Design guidelines for roof aperture systems, based on both energy and functional issues, are presented.

The final section deals with the most difficult aspect of roof aperture system design, integration of the daylighting design with other building systems. Integration of daylighting with electric lighting systems, structural systems, HVAC design and layout, electrical distribution networks, and passive heating and cooling techniques are all discussed. Sample integrated solutions using wood, steel, and concrete building techniques are given.

Passive Cooling Systems

Building on earlier work that assessed the relative potential of various passive and hybrid cooling technologies to reduce energy use in office buildings, work this year has concentrated on the benefits of simultaneous use of structural thermal mass in conjunction with several heat removal strategies, such as night ventilation and thermal radiation to the sky.

Simulation-based studies showed that when a 10,000 ft^2 office building has its structure modified to include the maximum practicable amount of thermal mass compared to a typical current-practice design (primarily partitions and roof), in over half of the U.S. climates analyzed the added thermal mass alone not only did not significantly decrease cooling energy consumption, but actually raised it somewhat (see Fig. 1).

When a night ventilation cooling strategy is also assumed to be operating in the building, the picture changes dramatically. As seen in Figure 2, the cooling requirements in almost all climates are reduced below that of the low-mass building as thermal mass levels are increased, thus indicating that some combination of the two strategies is more desirable than either singly. However, using the highest possible mass levels in conjunction with ventilation may not always lead to the greatest energy savings in all climates. Figures 3 and 4 indicate some of the complexity introduced by climate variations, by showing detailed monthly breakdowns of the cooling requirements for Los Angeles and Phoenix, respectively. In the mild Los Angeles climate, which exhibits relative constancy throughout the year, significant cooling reductions are achieved in every month, and continue to increase as the mass levels are increased. In

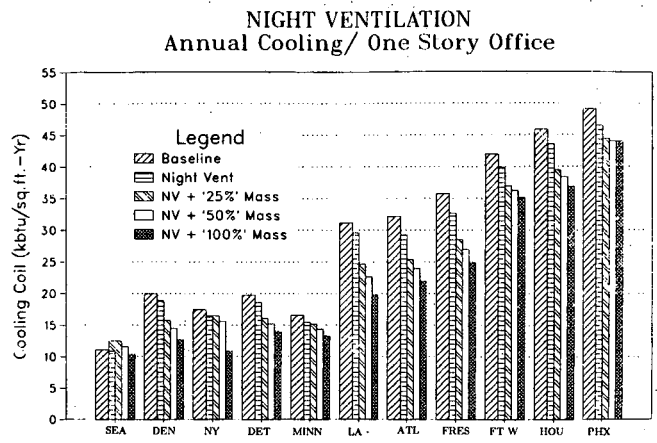

Figure 2. Comparison of annual cooling coil requirements for a typical small office building constructed with varying amounts of internal structural thermal mass, where night ventilation is also used to cool the building. (XBL 871-138)

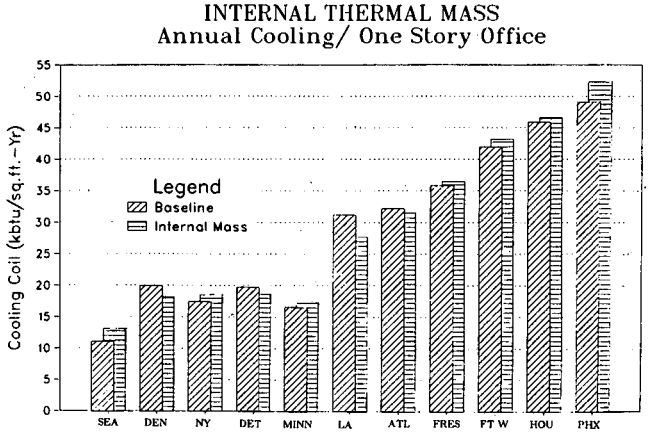

Figure 1. Comparison of annual cooling coil requirements for a typical small office building constructed with and without internal structural thermal mass, across a wide range of U. S. climates. (XBL 871-137)

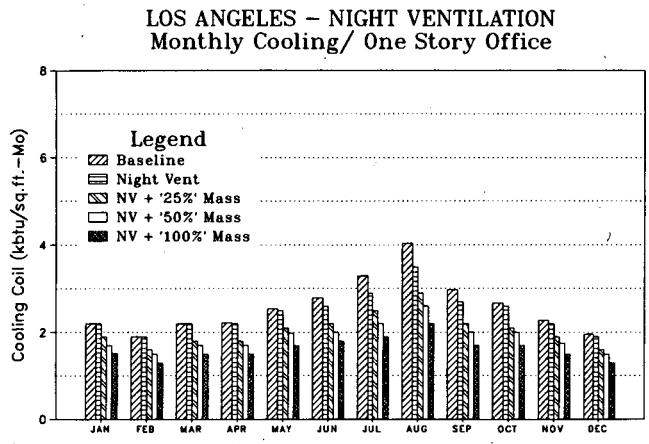

Figure 3. Detailed monthly cooling coil energy requirement breakdown for the Los Angeles analyses summarized in Figure 2. (XBL 871-139)

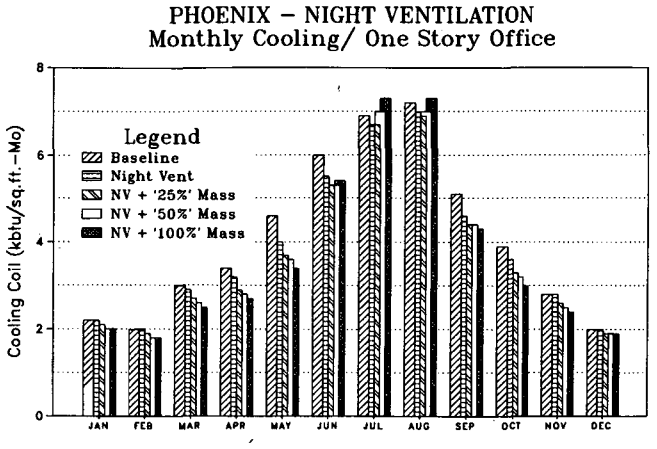

Figure 4. Detailed monthly cooling coil energy requirement breakdown for the Phoenix analyses summarized in Figure 2. (XBL 871-140)

contrast, the Phoenix climate shows far wider seasonal variations, with the greatest cooling reductions in the spring and autumn months; moreover, summer cooling requirements stop decreasing and can even increase when mass levels become too great. The difference in performance for the two cities can be traced to the number of hours (both as a function of the time of year and time of day) that outside ambient temperatures are within the comfort band.

Building Optimization

A whole-building optimization method has been developed that is applicable to conduction-dominated buildings and that simultaneously optimizes selected building thermal integrity and equipment efficiency parameters, using life-cycle cost as the optimization criterion.[11] The method is numerical and embeds a fast but accurate simplified energy simulation model, together with a cost estimation algorithm, into commercially available general nonlinear optimization software. In general, the life-cycle-cost objective function used as the optimization criterion is a nonlinear function of its arguments. Further, while the objective function is continuous, closed-form expressions for the first and second partial derivatives are not available, and have to be determined numerically. Aside from range constraints on the optimization parameters that keep them within physically meaningful limits, the optimization itself can be either constrained or unconstrained. For constrained optimization, the numerical methodology has been developed to allow for either initial-cost or energy-consumption constraints (which are in general nonlinear functions of the optimization parameters).

Exploitation of the specific form of the life-cycle-cost objective function for buildings led to the formulation of a concept termed the "Conservation Index," a ratio indicating the importance of annual operating costs relative to initial costs. The objective function can be expressed in a simple way in terms of the initial cost, the annual operating cost, and the Conservation Index. It also turns out that any specific economic scenario can be expressed simply as a particular equivalent Conservation Index value. Thus, unconstrained optima can be systematically precalculated for a wide range of Conservation Index values, and the correct optimal building configuration for a specific economic scenario subsequently determined by simply calculating its corresponding Conservation Index. It is also possible to show that for the particular form of the life-cycle-cost objective function for buildings, constrained optimum configurations can be related in a simple way to the unconstrained optima through the Conservation Index. Thus, there is no need to calculate them using a separate procedure once the unconstrained optima have been determined.

An example of the kind of information that can be generated with this method is shown in Figure 5, which shows constrained optimal configurations and related building energy performance for a typical residence as a function of incremental first cost relative to a "minimally performing" building, assuming national average utility costs and New York City weather. In general, there is a wide range of uses for a building life-cycle-cost optimization methodology, which in the aggregate can result in information that has a significant potential for increases in economic efficiency and in reductions in energy consumption, and can also provide specific evaluation mechanisms that could greatly increase the ease and feasibility of implementing policies that would lead to actual realization of the potential for savings. Specifically, some of these uses are:

- To identify optimal configurations for the design community, and thus ways of designing buildings that meet or exceed the energy budget requirements of standards.
- To provide information to designers regarding the best way of optimally allocating costs to various design features in order to achieve prescribed performance levels.
- To provide design trade-off mechanisms that maintain optimality.
- To provide information for the development of energy standards (of both the prescriptive and performance types), and

New York City

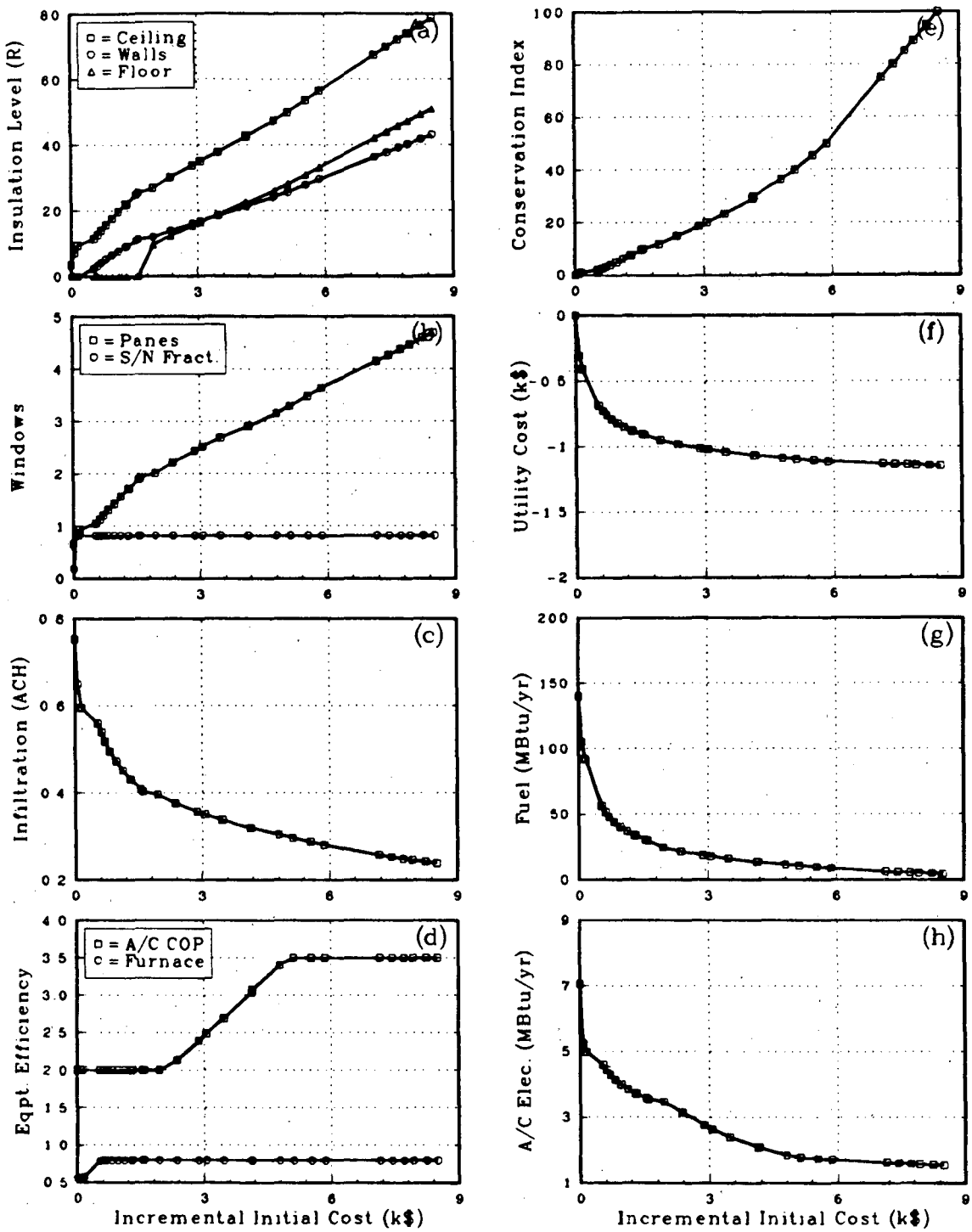

Figure 5. Plots of initial-cost-constrained optimal configurations as a function of the incremental initial cost for a typical residence in New York City. Left column plots (a-d) are optimized building configuration parameters; right column plots (e-h) are selected performance characteristics of the configuration. (XBL 871-141)

mechanisms for evaluating the impact of their implementation.

- To provide a rational, quantitative mechanism for evaluating economic inefficiency resulting from non-optimal current design practices.
- To provide ways of rationally building flexibility into building energy standards.
- To identify new design and/or construction techniques and related new products not currently available that need to be developed or marketed in order to build optimally designed buildings.
- To provide rational, quantitative mechanisms to determine what types and corresponding levels of incentives are justified to encourage new building designs and new product development.

PLANNED ACTIVITIES FOR FY 1987

Natural Lighting

The design tool will be extended, based on new information and existing work not yet incorporated into the current document. In addition, alternative forms of presentation to the designers will be investigated in order to identify the most effective methods for transfer of the information and concepts of roof aperture daylighting system design. Forms which will be investigated are hard copy manuals, algorithmic calculations for design and evaluation, and knowledge-based computer system (expert system) modules.

Passive Cooling Systems

This project will broaden its focus from strictly energy consumption performance of nonresidential buildings to the characterization of electricity demand profiles, including relationships between peak loads and weather, operating strategies, and building design. This information will be used to identify novel HVAC system design modifications, particularly integration with passive cooling strategies such as ventilation and thermal mass, that can provide desirable changes in the size and shape of the building demand profile.

Building Optimization

No FY 1987 activities in this area are planned at this time.

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Daylighting Performance Evaluation Methodology Development*

B. Andersson, W.L. Carroll, B. Erwine, R.J. Hitchcock, R.C. Kammerud, J.W. Place, and K. Whitley

Daylighting is an increasingly popular form of solar utilization for energy conservation in buildings. In the near term, as energy prices have stabilized, and the *perception* of an energy crisis has receded, the use of passive techniques has become more dependent on the impact of the technologies on the architecture and occupants. Because of daylighting's potential for a positive contribution to the appreciation and enjoyment of buildings, it is expected that daylighting will become an even more important element in passive building applications than it is now.

In daylighting applications, indeed in any passive building, it is important to evaluate the success of the application in terms of energy savings, economic impact, architectural effects, and occupant response. In this methodology development, which is part of the DOE Solar Federal Buildings Program, investigations will be limited to daylighting's impact on energy savings. A methodology for determining energy savings due to solar heating and cooling technologies is being developed by the Solar Energy Research Institute (SERI) in parallel with this effort. Functional, economic, and environmental evaluation methodology development is planned for later research efforts.

This methodology development will provide a straightforward, reasonably simple, documented means of daylighting evaluation for the building owner, designer, or researcher. In order to avoid protracted monitoring and data manipulation, the method will rely on a relatively limited set of measured data, both in terms of the number of quantities measured and the length of time the data is collected. The measured data will be compared to more detailed, varied, and extensive data from simulation of the daylighting configuration, from which the energy savings performance of the daylighting system can be determined for a full year.

In short, the planned procedure can be summarized as using (1) detailed simulation of the daylighting system, plus (2) specific short-term measurements to adjust the simulation, to provide a realistic estimate of the long-term energy savings. The evaluation technique is expected to be usable at the energy consultant/engineering level. However, the techniques will be developed such that an interested and informed practitioner should be able to apply them effectively.

ACCOMPLISHMENTS DURING FY 1986

The methodology development has been planned as a two-year project, in two phases:

- Phase I: Development of a technique for evaluation of daylighting performance in comparison to a nondaylit building. The technique is presented as a set of procedures for measurement, analysis, adjustment, and evaluation of the daylighting performance.
- Phase II: The techniques identified in Phase I are given practical form for the direct utilization of the evaluation methodology. The method will also be demonstrated in a full-scale application.

1986 has seen the completion of Phase I, development of the evaluation methodology. The basic technical approach is to track a sequence of dependent characteristics. There are three primary characterizations to be made, illustrated diagrammatically in Figure 1. The first is the solar resource; the characterization must have sufficient detail (intensity, spectrum, direction) to allow determination of its incidence on the daylighting glazing and its characteristics as it passes through the daylighting configuration. The second is the interior illumination;

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Solar Buildings Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

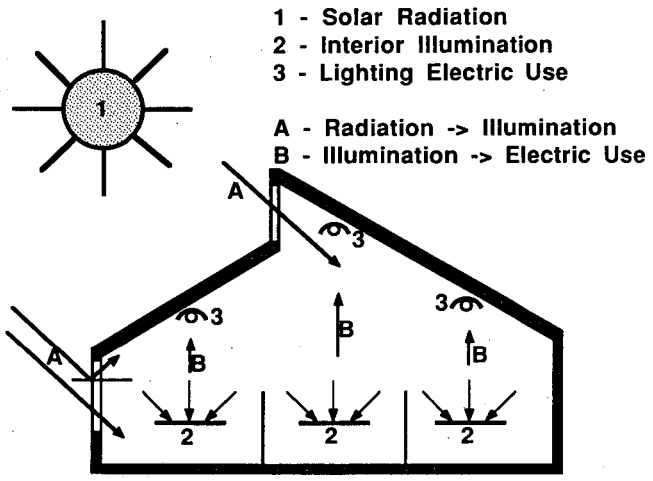

Figure 1. Key components and relationships in the daylighting evaluation methodology. (XBL 871-136)

the characterization must include information (intensity, distribution) that allows determination of its suitability for the tasks and standards in the space. The third is electric lighting response to the daylighting. In this case the characterization must be integrated over time and distributed over time and location.

The ability to make reliable predictions of the daylighting performance is dependent upon accurate characterization of the two key relationships: interior illumination as a function of the solar resource and the daylighting configuration (see A in Fig. 1); and electric lighting energy use as a function of the interior illumination and control of the lights (B). If an understanding of these relationships can be provided by observing the building for a short time, then a long-term prediction of effectiveness can be made, using a detailed daylighting performance model calibrated to the measurements of the actual building. Three types of measurements at the building will be used to adjust the simulation models developed for the building: exterior solar radiation, interior illumination, and electric lighting use. These data will be used to determine (1) interior illumination response to solar radiation, and (2) lighting control response to interior illumination, both under actual operating conditions. With this information, both the model which results in illumination levels under varied sky conditions and the model which results in electric lighting use predictions can be adjusted to properly represent the *actual* conditions and operation of the building, as shown schematically in Figure 2.

In order to support and test the daylighting performance methodology development, a test building was instrumented. The Clarklift West maintenance facility is part of a lighting controls evaluation project of the Sacramento Municipal Utility District (SMUD). The electric use monitors installed by SMUD were supplemented by interior photometric measurements and exterior solar radiation measurements. The data has been collected and reviewed, and a subset of that data will be used in exercising the candidate computer simulation models during Phase II.

Computer simulation will form the basis of both the illumination model and the electric lighting control model. Because of the adjustment made during calibration with actual building data, the simulations need not be so complex that they predict each hour's activities with high precision. As long as the simulations give a reasonably consistent interpretation of how the results respond to the forces driving them, the calibration will pick up the variations due to building and operation anomalies.

An existing public domain program, either DOE-2.1B or SUPERLITE, will be selected as the basic illumination model. The DOE-2.1B illumination prediction model is based on validated algorithms and has been tested against measured data. The same is true of the SUPERLITE illumination model. Still, like any models, the programs have limitations in terms of the range of aperture geometries, glazing materials, light diffusion, and aperture controls that can be simulated and that have been validated. In order to calibrate the illumination model to reduce inaccuracies, the degree of error will be determined with respect to sensor location, time of day, and the character of the solar resource.

PLANNED ACTIVITIES FOR FY 1987

Phase II will be completed in FY87. There will be two major thrusts to that work. One is the instrumentation and analysis of a full-scale nonresidential building in order to test, refine, and demonstrate the methodology. This will be carried out in collaboration with the Energy Performance Assessment program in the United Kingdom as part of a bilateral agreement. The second part of the work will be to translate the methodology into a set of microcomputer software for direct application of the methodology by practitioners.

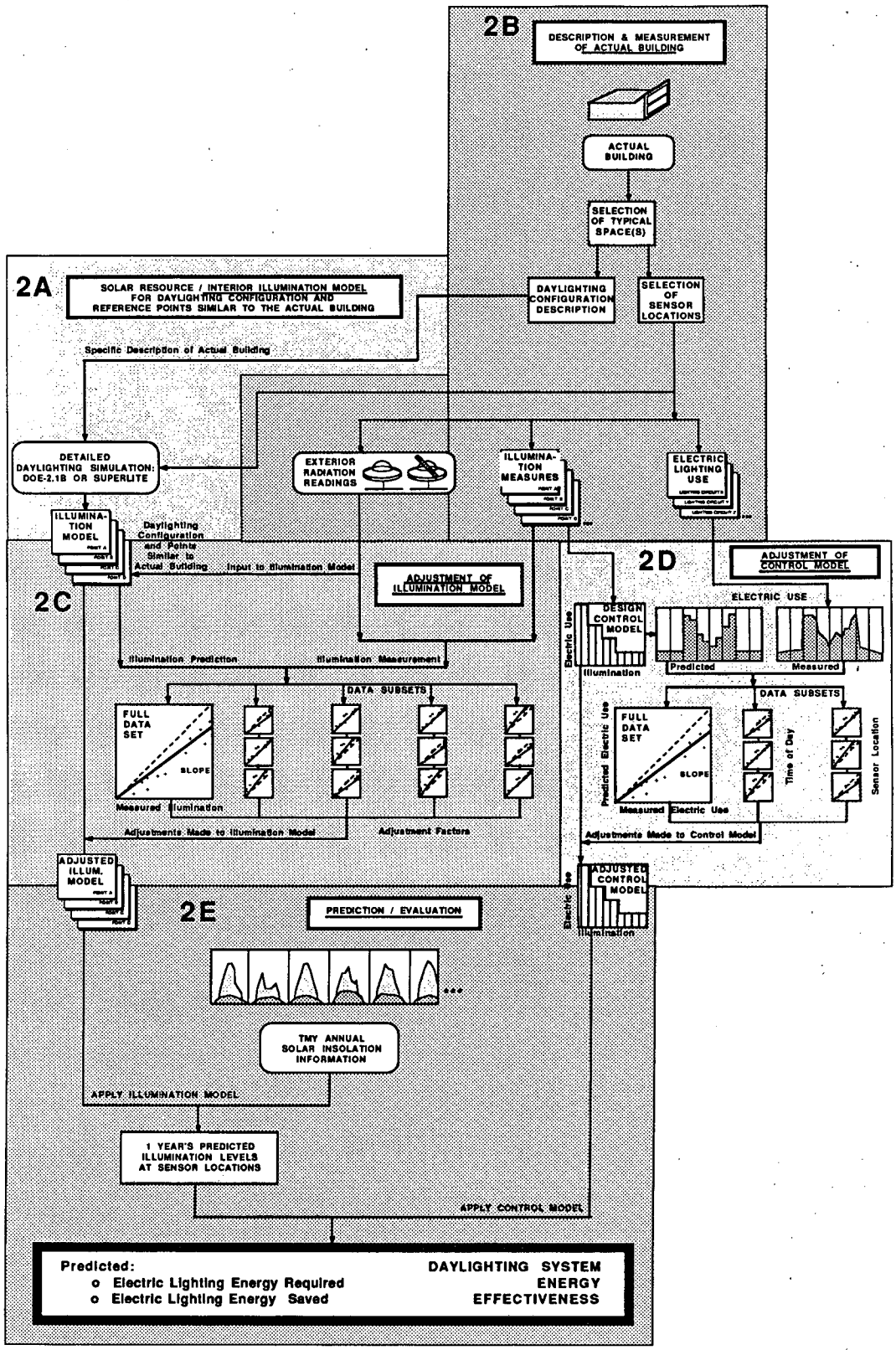

Figure 2. Flow chart of full daylighting evaluation methodology. (XBL 871-142)

Institutional Conservation Program Evaluation Project*

R.C. Kammerud, B. Birdsall, W.L. Carroll, B. Gardiner, B. Hatfield, B. Lebot, J. Noring, and E. Vine

The Institutional Conservation Program (ICP) was enacted by Congress in 1978 to provide matching grants to nonprofit hospitals, elementary and secondary schools, and colleges and universities for energy conservation actions. ICP was considered necessary because nonprofit institutions are less able to budget money for the capital equipment and personnel time required for an energy-saving program than are businesses. The grants are used to fund energy audits, technical analyses, and installation of energy conservation measures (ECMs).

Recently Congress mandated an evaluation of ICP. The Building Systems Analysis Group at LBL, in collaboration with Argonne National Laboratory, was chosen to carry out this project. The overall goal of the evaluation project is to identify the most successful measures—both equipment and activities—available to the institutional buildings sector. The researchers have identified four objectives to achieve this goal:

(1) Determine the impact of ICP in fostering energy efficiency and in saving energy.
(2) Determine key characteristics of institutional conservation efforts outside the federal program.
(3) Determine the technical, organizational, and institutional conditions that create the opportunity for energy conservation measures to be most effective.
(4) Identify key technology transfer opportunities.

These objectives emphasize two closely related, underlying thrusts of the evaluation project, one retrospective and the other prospective. Accomplishing the first two objectives will provide a retrospective evaluation of ICP. The thrust of this work is towards examination of (1) energy use data and (2) nonfederal expenditures on ECMs that have resulted from increased awareness of energy conservation potentials engendered by ICP. Through the third and fourth objectives, we hope to understand what makes a program successful and how to disseminate this information. These latter two objectives therefore are prospective and serve as a guide for future conservation efforts.

ACCOMPLISHMENTS DURING FY 1986

Review of Existing Data

GTS Data

An analysis of data already reported (existing data) neared completion at the end of FY 1986. The Grant Tracking System (GTS) data base, the primary source of information about ICP grants and grantees, includes technical and administrative information. The GTS data analysis allowed examination of (1) ICP penetration by subsector (hospitals, colleges, and schools), by geographic region, and by the degree of urbanization of the institutions' locations; and (2) distribution of funds by subsector, by type of grant (for technical assistance or energy conservation measures), and by unit of people affected (total population, students, or patient capacity). Some key findings of the GTS analysis follow.

- There has been significant penetration by ICP: 37.2% for colleges (1231 out of a possible 3313 colleges have received grants), 26.3% for hospitals (1826 out of 6950), and 28% for public school districts.
- There is a relatively strong regional bias in the penetration (higher in the northeast and lower in the southwest), perhaps due in part to climate and/or to differences in the way ICP is operated in the different DOE regions. Figure 1 illustrates this finding for hospitals.
- In recent years, more than half of the grants for colleges and hospitals have been awarded to institutions that received grants in previous years. Strategic actions that would decrease the fraction of grants going to past participants could substantially increase the rate of penetration, thereby increasing the energy savings attributable to federal expenditures.
- Over its lifetime, ICP has invested approximately $0.62 in energy conservation in colleges for each person in the U.S., or about $20.21 for each full-time college student. For hospitals, ICP has invested about $0.74 for each person in the U.S., or about $130 per hospital bed.

* This research was supported by the Assistant Secretary for Conservation and Renewable Energy, State and Local Assistance Programs, Office of Building Efficiency Programs, Institutional Conservation Program Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

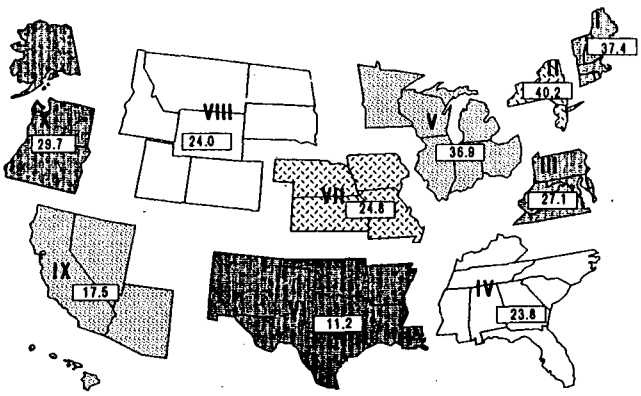

Figure 1. Percent of hospitals in each DOE region receiving ICP grants. (XBB 871-849)

Literature Search

A literature search surveyed periodicals, technical and trade journals, theses, and special interest reports. This analysis provides a basis for comparing institutions participating in ICP and those not participating in terms of (1) geographic location, (2) measures installed, (3) activities and funding from other than federal sources, and (4) energy savings and energy cost savings. The literature search also provides information on institutional and organizational factors that influence the effectiveness of energy conservation programs, such as motivation for taking action and barriers to action. The key findings of the literature search are described below.

- Half of the hospitals in the content analysis data base had taken significant actions without ICP funding. This could mean that penetration of energy conservation activities in the hospitals subsector is double the ICP penetration, or 50%. To what extent these actions resulted from awareness of ICP is an area we will examine in FY 1987.
- In hospitals and colleges, there have been trends toward some ECMs and away from others. There is also evidence of a visible distinction between the two subsectors in the type of measure being installed most often.
- Funding for energy conservation actions is seldom obtained by borrowing money; the extent to which this pattern is due to institutional or organizational constraints cannot be determined from the available information.

Energy Data

Energy use data play a central role in the evaluation project, because one key indicator of success is energy savings. Energy use data are being examined to resolve three subsets of issues: energy savings, quality of technical assistance audits (which predicted savings and recommended energy conservation measures), and persistence of energy savings. In 1986 energy data from Wisconsin schools and hospitals that have participated in ICP were analyzed. Key results are highlighted below.

- Energy Performance: The preretrofit energy use of ICP participants in recent years is noticeably better than that of participants in earlier years of the program. The extent to which this reflects a general improvement in the performance of institutional buildings (as compared with reflecting a bias in the sample) is a subject to be pursued during 1987.
- Energy Savings: Our examination of Wisconsin's data base shows little correlation between the preretrofit predictions of the energy savings that would result from ECMs in schools and actual energy savings determined from utility bill records (Fig. 2). While there are apt to be legitimate explanations for many of the differences in predicted and actual energy use, it is difficult to avoid the conclusion that uncertainties exist regarding the accuracy of the technical analyses performed before the retrofit.
- Persistence of Energy Savings: Energy savings resulting from the installation of conservation measures are typically determined by comparing energy use from immediately before installation with that immediately following installation. Of comparable importance is maintaining the improved energy performance over the long term. Analysis of Wisconsin's ICP data shows persistence of energy savings, although there is some degradation in the third year.

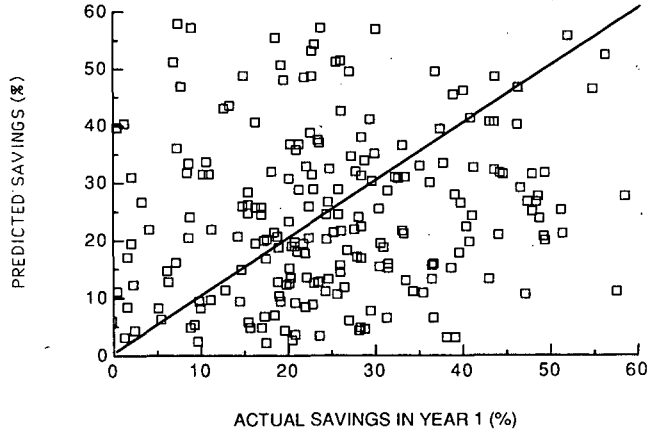

Figure 2. Comparison of predicted and actual energy savings for Wisconsin schools participating in ICP cycles 1 through 4. (XBL 871-263)

Collection of New Data

The many issues that this evaluation encompasses have required the collection and analysis of new data. We have begun developing extensive questionnaires for each of the three types of institutions taking part in ICP, which will be sent to hospitals, colleges, and schools that have not participated in ICP as well as to institutions that have. Information solicited includes motivation for pursuing energy conservation; decision-making processes within the organization; problems and successes with technology, management, funding, and occupancy comfort; and information about the institution itself.

PLANNED ACTIVITIES FOR FY 1987

During the 1987 fiscal year we will complete collection of data and then concentrate on analyzing it and attempting to answer questions raised by the analysis of existing data. The following text describes this future work in more detail.

The questionnaires will reach their final form and be mailed to institutions across the country. We will analyze the responses for correlations between success of conservation programs and technical, organizational, and institutional characteristics. Followup telephone interviews will be made to collect more detailed information on energy use.

Further analysis of the GTS data base will allow us to refine penetration rates. The rates presented in this article are based on a total population of institutions that is larger than the number of institutions actually eligible for ICP grants (buildings constructed after 1977 and for-profit hospitals are not eligible). The present figures also do not distinguish between ECM grants and technical assistance (TA) grants, nor do they account for individual schools, only for school districts. We will examine possible factors—climate, population distribution, and program operation, for instance—that account for regional variations in ICP participation and how participation is related to specific ECMs or groups of ECMs. And finally, the data will be examined for correlations at the state level, so that states can be compared in terms of heating degree days, rate of new construction, and more definitive demographics.

Three techniques for estimating energy savings directly and indirectly attributable to ICP are under consideration. One or more of them will be pursued. The methods are alternatives to the direct measurement of the energy savings from all participants, which is impractical and suffers from many of the same complications as the alternatives.

(1) Measure-specific method: If energy savings can be meaningfully attributed to individual measures, then we can derive total energy savings from GTS records of ECMs funded through ICP.
(2) Institution-specific method: Energy savings would be derived from TA estimates modified by correction factors that account for the observed differences between predicted and actual savings.
(3) Subsector aggregation method: This method uses national energy use and building demographic data to derive the energy savings without reference to individual buildings or measures. Existing historical data would be used with corrections for the changes in the building stock and its regional distribution.

It is hoped that the evaluation project can contribute to fulfilling the need for objective criteria for evaluating technical analyses by examining the technical issues relating to the accuracy of analyses. Calculations in several TA reports will be compared with a benchmark computer program that predicts energy use by a whole-building calculation. The thrust here will not be to find errors or bad assumptions in the analyses, but rather to identify the characteristics of analyses that are most representative of reality as evidenced by monitored data. One such characteristic that will receive close attention is the calculation methods used in the TA analyses. We also hope to discover what relationship exists between high-quality TA reports (e.g., those that are accurate and are useful as long-term guides for energy management) and institutional characteristics (such as an institution's size or location).

The findings will be widely disseminated so that all hospitals, colleges, and schools can benefit from the experience of other institutions.

Simulation Research*

F.C. Winkelmann, B.E. Birdsall, W.F. Buhl, K.L. Ellington, A.E. Erdem, J.J. Hirsch, D.J. Hopkins, L.A. Leedom, and E.F. Sowell†

The Simulation Research Group (SRG) has the long-term objective of providing the architectural, engineering, and research communities with software tools to assist in the design of significantly more energy-efficient and cost-effective buildings. The ongoing research of the SRG has two main focuses: (1) the development and maintenance of the current-generation benchmark program (DOE-2), and (2) advanced simulation, the development of the next generation of building performance calculation tools (the Energy Kernel System).

As can be seen in Figure 1, DOE-2 is composed of two major segments: the Building Description Language (BDL) processor, which accepts quasi-English descriptions of building components, and the LOADS, SYSTEMS, PLANT, and ECONOMICS (LSPE) processor, which uses building descriptions to simulate building energy performance. Details of the development and structure of the DOE-2 program are available in past annual reports and other published material.[1-18]

The main efforts in the advanced simulation area at this time are the creation of the Energy Kernel System (EKS) and the organization of the simulation development community to enhance collaboration. The kernel system has three main components: software primitives, including a component model library and simulation tools; a software harness to facilitate the construction of simulation programs by allowing general linkage of component models and support models; and a knowledge base which will contain the rules of simulation development and use so as to allow, at a future time, the construction of expert systems for building performance simulation. These three aspects of the kernel system will provide the basic tools and information to allow the SRG and other groups to develop the simulation programs of the future. They will also provide a mechanism to facilitate exchange of research results and technology advances, and a basis for integrating performance simulation into computer aided design (CAD) and expert system software.

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

†Visiting Industrial Scientist; Supported by the Div. of University and Industry Programs, Ofc. of Field Operation Mgmt., Office of Energy Research of the U.S. Dept. of Energy.

ACCOMPLISHMENTS DURING FY 1986

DOE-2

The SRG maintains a research effort that continues to develop new versions of DOE-2. This ongoing research is divided into three parts: (1) the introduction of algorithm description techniques into the code; (2) the modeling of building envelope components and systems; and (3) the simulation of HVAC equipment and associated control systems. The next version of the program, DOE-2.1D, is scheduled for release to the public in 1987. Its major new features are described below.

User Defined Functions. Direct user interface with the operation of DOE-2 is currently possible in the LOADS section of the program through the use of the FUNCTION command added during FY 1985. This feature allows direct modification, enhancement, or replacement of DOE-2 algorithms without requiring any manipulation of the computer code. Users can write their own algorithms in a FORTRAN-like language and place this information in their building description, along with information indicating how/where these new algorithms are to be used. This is a major step forward in allowing designers and researchers to "fine tune" the simulation program to their specific needs. In the past this was not feasible without a major investment of time. This capability has now been added to the SYSTEMS portion of the program, which, for the first time, makes it possible for a user to add new HVAC simulation features such as innovative control schemes.

Generalized Library. In the past it has only been possible to create libraries of materials, envelope constructions, and transfer functions. A new general library feature is being designed which will allow the users of DOE-2 to create custom libraries containing descriptions of any building component or system of components. This will allow definition of libraries containing data which might consist, for example, of standard operation schedules for different building types or of complex component descriptions. Even libraries of whole building descriptions can be created. This new library capability will greatly facilitate use of the program.

Macro Definitions. This feature will allow the users of DOE-2 to define a parameter equal to an arbitrary string of characters. The defined string can contain other nested defined macros. This will allow

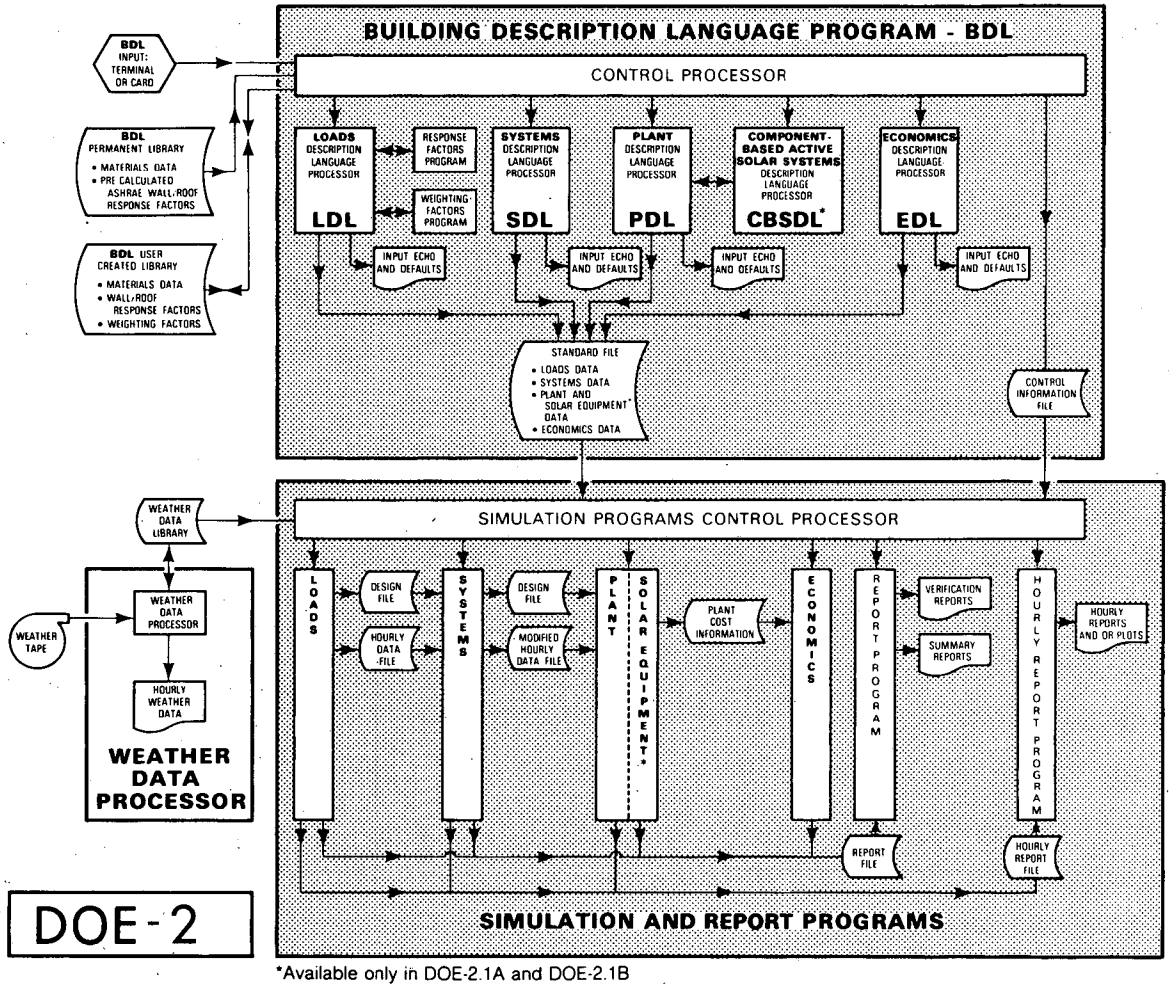

Figure 1. DOE-2 computer program configuration. (XBL 8010-2210B)

complex building description sequences to be defined once and later referenced, thus shortening and simplifying the program input. This feature, combined with the general library feature, will greatly increase the power of the DOE-2 BDL input processor as well as reduce the time and training required to describe a complicated building.

Fenestration. The fenestration calculations are being upgraded to allow modeling of advanced window systems and to improve the thermal and daylighting simulation for windows with common but complex shading devices such as Venetian blinds.

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† University of Strathclyde, Scotland; University of Paris-South (CNRS), France; Chinese Academy of Sciences, Beijing, China; and Centre Scientifique et Technique du Batiment, France

Advanced Simulation

The Simulation Research Group and collaborating institutions in the U.S.* and in other countries† have formulated a proposal for creating the software tools essential for the next generation of building energy simulation models.[19–21] The intention of this project is not to develop a single new model but, instead, to provide a kernel system of highly portable software modules and linking protocols which will enable groups in the public and private sectors to construct a variety of customized programs. The work plan has been developed in the context of the following guiding principles: (1) Researchers developing building performance simulation techniques can no longer afford to work as independent groups creating non-interchangeable software. Some mechanism must be found to give all developers access to the developments of others while retaining the flexibility to tailor a simulation system to indivi-

dual needs. (2) As many energy sources become more expensive, and as improved efficiency technologies become more complex, designers of the future will be required to focus more critically on the intimate relationship between design and performance. This will require a quantum jump in the capability and accuracy of the energy simulation techniques then available. (3) The private sector of architectural and engineering firms, HVAC equipment manufacturers, and CAD system vendors does not necessarily support the development of large public domain simulation codes. However, they *will* support developments of the kind proposed, which seek to create and order the building blocks of energy simulation. Private and public sector organizations can then use the resulting kernel system to construct customized simulation systems which embody an appropriate level of detail, offer wide-ranging application potential, and use the most up-to-date techniques. (4) Increasingly, energy simulation models will form part of a building's operating system, allowing controls to be optimized in real time before being applied to the building. (5) The building design profession will increasingly rely on advanced CAD software packages. As systems possessing a drafting function proliferate, a demand will grow for explicit performance appraisal software. Designers will then come to rely on simulation techniques to test alternative hypotheses throughout the design stages and after occupancy. Indeed, CAD system integration is perhaps the most effective mechanism for market penetration of advanced energy analysis systems. (6) It is likely that, with the advent of powerful, integrated CAD systems, the design profession will seek to refine the building model and associated performance database beyond the construction phase. One possible scenario is that a client of the future will expect delivery of a computer-based model and performance database, in addition to the building itself. The information regarding building performance is then readily available for inspection. And, of course, the model can be used at any time as the basis for HVAC system maintenance, trouble shooting, and retrofits.

Each of these factors calls for the existence of a modular approach to energy simulation and, it could be argued, would be badly served if only free-standing, monolithic programs continue to be developed.

Proposed Workplan

A model-creation system has been proposed which consists of three main elements: (1) a public-domain library of *software primitives*; (2) a *software harness*, i.e., executive software for controlling how the primitives are linked into a modeling system, and (3) a *knowledge base*, which contains the rules for model construction. The system is schematically illustrated in Figure 2. The characteristics of these elements and the tasks required to construct them are as follows.

(1) Software Primitives. Many useful models and techniques already exist within contemporary modeling systems. And much additional software continues to emerge as existing codes are extended or new developments pursued. The first task is to divide the useful, existing software into small, logically independent units called "software primitives," and place them within a central, public domain library. Each library entry is then a small software module which performs a single task. The library entries will be independent in the sense that each primitive will have no "knowledge" of any overall data structure. The primitives will obtain data and return results in a standard way, by invoking special primitives which will fetch data from and return data to a central storage area. There will be no attempt to prescribe an overall modeling technology; instead, we hope to allow the free evolution of useful *software tools* for those concerned with developments in building energy simulation. Naturally, portability will be a necessary attribute for all of these tools.

The library will have different types of entries: first-principle, governing equation generators for building and system components; self-contained algorithmic approaches; data manipulators; software development and management tools; and simulation support modules. By accepting a high level of pluralism it is likely that a rich modeling base can be formed, entirely free of application assumptions.

(2) Software Harness. The second stage addresses the development of harness, or executive, software, which will allow primitives extracted from the library to be combined into an actual modeling system. This software will consist of a *data manager* used to define and control data traffic among the modules (primitives) and a *simulation controller* to control the sequence in which the modules (or groups of modules) will be executed. Creation of the software harness is analogous to the development of a computer operating system, such as UNIX, where the problems of concurrent processes and communication among processes have already been addressed. Using techniques from this field will facilitate the use of parallel processing at some future point in time. It will also permit the construction of any modeling approach (so long as the necessary software

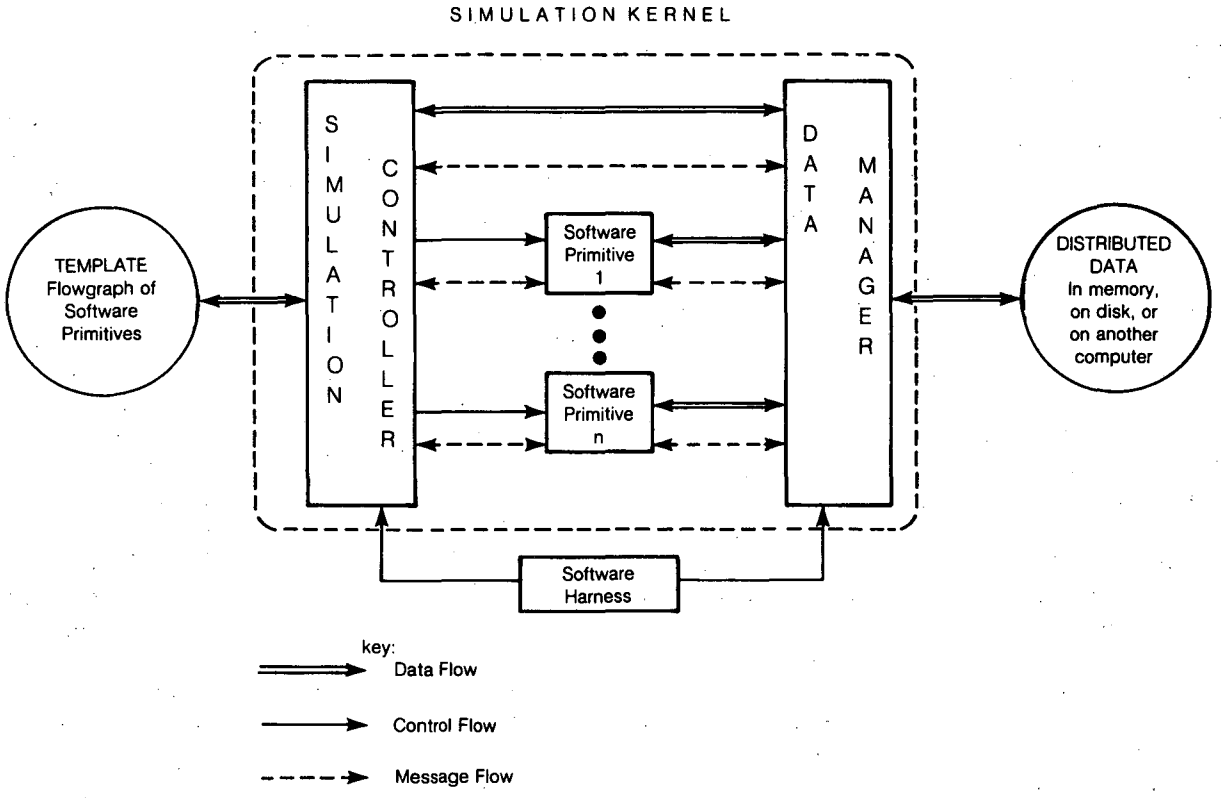

Figure 2. Proposed kernel system for creating building energy simulation models. (XBL 862-10304)

primitives exist), from the establishment and integration of matrix equations representing energy and fluid flow within buildings and their systems, to more pragmatic models which apply simplifications appropriate to the problem in hand.

It is important to note that the harness software is designed for use by model *developers*, not by model users. It is an efficient way of building appropriate models which can be easily improved as the underlying techniques are refined. Users would continue to use prescribed programs, the only difference being that their architecture would be highly modular and so easy to change.

(3) Knowledge Base. The third important stage consists of setting down the rules which govern model construction and use in a design, educational, or research context. This is essential if it is desired to move to so-called "expert" systems.

Concerning model construction, the rules employed by some contemporary programs will be set down as a first step template. This would include those rules commonly applied to component models, as well as those applicable to overall solving strategies. Normal academic interchange would then serve to modify these templates or to create alternative approaches. Each participant can have a say, allowing the more effective templates to become prominent with time.

Model use is a different problem. The intention here is to explain how existing and planned energy simulation systems work. This knowledge is required by those future developers who will construct expert systems in this application area. It is proposed not to develop decision-making software, but simply to organize a database of information in this one area.

International Association

One of the elements of the proposal to develop an Energy Kernel System is the formation of a broadly-based group or association to foster and guide research and development in the building performance simulation field. The first organizational meeting of this group was held January 19, 1986, in San Francisco in conjunction with the 1986 ASHRAE Winter Meeting. At that meeting, an enthusiastic group of supporters selected the name "International Building Performance Simulation Association" (IBPSA), and formally put the organizational process in motion. By the second organiza-

tional meeting on June 22, 1986, in Portland, subcommittees had drawn up a draft Mission Statement and initiated the incorporation process. The Mission Statement, which has since been approved by the charter members, defines IBPSA to be an organization "founded to advance and promote the science of building performance simulation in order to improve the design, construction, operation, and maintenance of new and existing buildings world-wide." Objectives listed include identification of building simulation research and development needs, and the enhancement/transfer of new developments and technology to the user community. IBPSA will seek participation of building designers, owners, operators, and developers in order to provide a broad base of support and to assure technical input from the entire building community. At the most recent meeting, held September 21, 1986, in Washington, these objectives were explained to an international group of attendees of the CIB meeting. The next IBPSA meeting will be held January 20, 1987, in New York in conjunction with the 1987 ASHRAE Winter meeting. At this meeting the SRG will participate in forging IBPSA into an effective industrial advisory group for overseeing development of the Energy Kernel System and other building energy simulation efforts.

SPANK: A Prototype Kernel System

During FY 1986 the SRG developed new software called the Simulation Problem ANalysis Kernel (SPANK) as a first prototype of the Energy Kernel System.[22,23] SPANK views a simulation problem as a network — the nodes represent nonlinear equations, and the lines linking the nodes (called links or arcs) represent variables in the equations. The network representation of a simulation problem is completely equivalent to describing the problem as a set of simultaneous, nonlinear equations. The network representation has the advantage of allowing graph theory techniques to be used to reduce the size of the problem to be solved. The existing version of SPANK only allows algebraic equations, but the next version will handle first-order differential equations.

A simulation problem in SPANK consists of a set of coupled equations. Each equation or relation among variables is known as a "primitive object." Primitive objects may be combined into "macro objects," and primitive and macro objects can be combined into more complex macro objects. Thus modules (sets of equations) which represent complicated physical processes or entities can be built up from simple components. Once the necessary objects, either simple or complex, are defined, the problem description is completed by "linking" the objects together, i.e., by specifying which variables are common to which equations.

Once the simulation problem is defined, SPANK does the rest. The user does not have to choose a computation sequence (that is, write a procedural algorithm in FORTRAN or some other language) that solves the set of equations. SPANK creates the solution sequence in two steps. First, a particular relationship (equation) has to be selected for each variable and inverted to give a formula for that variable. Selecting a relationship to be used in solving for a particular variable is a classic matching problem from graph theory, and algorithms for performing this matching are well known.

Once the matching has been accomplished, the second step is to find a set of break variables, called a "cut set." These variables become the iteration variables in the solution sequence. That is, initial values are guessed, then used to solve for all the variables using the set of relationships, yielding new values for the cut set variables. Then a scheme such as Newton-Raphson iteration is used for choosing the next guess for the cut set.

Most simulation programs, when faced with solving a system of nonlinear equations, simply iterate on all the variables; i.e., the cut set includes all the variables in the problem. One of SPANK's major contributions is to use graph theory methods to reduce the cut size greatly, and thus to effectively reduce the problem size.

At this time the largest practical problem solved with SPANK is a simulation of a constant volume reheat HVAC system. The model contains 23 equations and 23 variables. The cut set found by SPANK contains 1 variable, a 23 to 1 reduction in problem complexity. The model structure of the SPANK problem description (objects and macro objects) allows a model to be easily comprehended and altered. SPANK inherently allows simultaneity and nonlinearity. Lastly, the use of data flow concepts will allow SPANK to take optimal advantage of multiprocessor machines.

Other Accomplishments

The following was also accomplished in FY 1986 in the area of advanced simulation software development:

(1) A prototype timestep controller for the Kernel System was implemented and tested in the ESP simulation program. The controller improves the accuracy of an energy calculation by dynamically changing the simulation timestep

in response to variations in climatic variables, such as outside temperature or solar radiation, or to building control variables, such as thermostat setpoint.

(2) The University of Wisconsin Solar Energy Laboratory, via contract to LBL, began work on advanced techniques for obtaining transfer functions for fast and accurate multidimensional heat transfer calculations for walls, attics, earth-contact structures, and whole buildings or zones.

(3) Our collaborators in the U.K. (University of Strathclyde, Glasgow, and Rutherford-Appleton Laboratory, England) obtained funding from the U.K. Science and Engineering Research Council to begin the U.K. effort on Energy Kernel System development. As a result of meetings at LBL, an agreement was drafted on UK/USA collaborative intentions for the development of the Energy Kernel System.

(4) Our collaborator in China, Lan-Chieh Huang of the Chinese Academy of Sciences, completed Phase 1 of a new method for calculating unsteady, multidimensional natural convection in enclosures. (This work was begun in FY 1985 while Prof. Huang was a visiting scientist with the SRG.) The results of this work are described in Ref. 24.

(5) A review paper was written describing the recent advances that have been made in building energy simulation in North America.[25]

Analysis Efforts for Others

The SRG provided technical expertise to the Energy Analysis Program for their ASEAN project. (ASEAN is the Association of South East Asian Nations — Indonesia, Malaysia, Singapore, Thailand, and the Philippines.) We provided instruction for a 5-week training course in the use of different energy analysis tools, including DOE-2, PC-DOE (a personal computer version of DOE-2), TRAKLOAD, and Carrier Corporation's Carrier E-20. There were 14 participants, each of whom had brought a set of construction drawings for a building from their community, which they then proceeded to analyze. Comparisons were made of the different analysis techniques and a number of participants left in anticipation of teaching these methods for energy audit purposes and/or research in their respective countries.

The SRG provided support in the evaluation of the Institutional Conservation Program, a joint project with Argonne National Laboratory. Our work has centered on the accuracy and quality of the technical assistance (TA) reports. These are reports prepared by professional engineers upon completion of a study to determine appropriate energy conservation measures. It was observed that there has been little correlation between the energy savings predicted in TA reports and the actual savings determined by pre- and postretrofit monitoring of energy use data. One of the leading technical problems is the accuracy of calculation techniques used in the analysis, i.e., whether a "whole building" or "envelope-dominated" calculation technique is used. A crosscheck of TA accuracy is being performed by re-analyzing selected cases with the TRAKLOAD program.

In support of the LBL Lighting Group, a numerical model was developed to determine what combination of mercury isotopes maximizes the light output from fluorescent lamps. First a computer program was written to evaluate the integrals that are used to calculate the radiant emittance of the lamp. Next, a maximization routine was incorporated into the program to find the optimum combination of isotopes subject to the physical constraints governing the problem. A sensitivity analysis was then performed to see which physical parameters were most critical to the calculation. For this model, results indicate that the proper selection of isotopes can increase the light output by a few percent. (Each 1% increase in light output would save the United States about $250,000,000 annually in energy costs for fluorescent lighting.)

PLANNED ACTIVITIES FOR FY 1987

DOE-2

The DOE-2 program will continue to be maintained and supported and its documentation enhanced. The quarterly *DOE-2 User News* will continue to be published. An improved version of the program, DOE-2.1D, will be completed and released to the public.

Advanced Simulation

The SPANK program will be released for outside testing after some additional features are added, including dynamic simulation and a graphics-based input processor. Detailed specifications for the Energy Kernel System will be formulated by the U.S. and U.K. and distributed, via IBPSA, for review and comment. Collaborative agreements will be drafted for joint LBL/France and LBL/People's

Republic of China work on the Energy Kernel System. Contracts from LBL will go to SERI and NBS to perform Kernel-related research: SERI will cast its macrodynamic simulation approach into the form of primitives that can be used in the Kernel; NBS will investigate the technical feasibility of using a generalized finite element approach for building energy simulation. The University of Wisconsin will complete work on advanced transfer function techniques. The convection calculation methods being developed at the Chinese Academy of Sciences will be extended to model turbulent flow.

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Active Solar Cooling

Building 90, Room 2024
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