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RESEARCH & DEVELOPMENT CONFERENCE

CIEE

PROGRAM

1992

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WELCOME

to CIEE's 1992 R&D Conference

CIEE's second annual Research and Development Conference will introduce you to some of the results achieved to date through CIEE-sponsored multiyear research performed in three programs: Building Energy Efficiency, Air Quality Impacts of Energy Efficiency, and End-Use Resource Planning. Results from scoping studies, Director's discretionary research, and exploratory research will also be featured.

We at CIEE wish to thank Pacific Gas and Electric, Southern California Edison, Southern California Gas, San Diego Gas and Electric, the Los Angeles Department of Water and Power, the Sacramento Municipal Utility District, the California Public Utilities Commission, the California Energy Commission, the University of California, and Lawrence Berkeley Laboratory for supporting and guiding CIEE's 1991-1992 research program.

CIEE's Background and Mission

The California Institute for Energy Efficiency was established in 1988 by the University of California in cooperation with California's electric and gas utilities, the California Public Utilities Commission, the California Energy Commission, and the U.S. Department of Energy's Lawrence Berkeley Laboratory. CIEE's mission is to coordinate, plan, and implement a statewide program of medium- to long-term (5 to 15 years) applied research aimed at advancing the energy efficiency and productivity of all end-use sectors in California. This research is conducted primarily at colleges, universities, and university-affiliated research laboratories statewide and is designed to complement the research efforts of CIEE's sponsors and of other significant public and private research organizations.

CIEE's R&D has two primary goals. The first is to identify, develop, and demonstrate efficient end-use energy technologies and processes that:

- Increase the security and sustainability of energy systems in California.
- Help assure continued access to reliable, affordable energy services for all California end users.
- Enhance the productivity and competitiveness of California's agricultural, manufacturing, and service industries.
- Contribute to improving the environment, including regional air and water quality and the quality of the indoor built environment, while remaining sensitive to global-warming issues.

The second overall goal is to improve the data and analytical tools related to the end use of energy. The objective is to support sound utility and public-sector planning decisions on the balanced development of demand- and supply-side energy resources in California.

CIEE emphasizes collaboration in its multisponsor structure, multicampus approach to research, and commitment to translating successful energy-efficiency R&D into practical products and processes. CIEE incorporates sponsor input into the design and management of its R&D programs, primarily through guidance from the Research Board, technical support from the Planning Committee, and ongoing input from Project Advisory Committees as part of research management.

CIEE's R&D approach emphasizes sponsor input throughout all phases of multiyear research planning and project selection, research management, and the rapid transfer of promising research results.

1992

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AGENDA

TUESDAY, OCTOBER 13

3:00 pm - 5:00 pm — REGISTRATION — BAY ROOM, PRE-FUNCTION AREA

5:30 pm - 7:30 pm — BARBECUE — GARDEN DECK OR GRANHALL

All participants and their spouses/guests are invited to attend an informal dinner.

7:30 pm - 9:00 pm — PLENARY SESSION — BAY ROOM

Opening Remarks:

Edward Vine, CIEE Conference Chair
James Cole, CIEE Director
Commissioner Arthur S. Kevorkian (CEC), CIEE Research Board Chair

Keynote Address:

Commissioner Daniel William Fessler, President of the California Public Utilities Commission

WEDNESDAY, OCTOBER 14

7:30 am - 8:30 am — BREAKFAST - Buffet — GRANHALL

8:30 am - 10:00 am — FIRST MORNING SESSION (COMBINED) — BAY ROOM

Air Quality Impacts Program - Emission Reduction Strategies

Ron Ritschard (LBL)	Energy Efficiency and Air Quality in the South Coast Air Basin
Arthur Winer (UCLA)	Energy Efficiency and Air Quality: The Role of Vegetation in the South Coast Air Basin
Haider Taha (LBL)	Analysis of Energy Efficiency and Air Quality: Albedo, Soil Moisture, and Surface Roughness in the South Coast Air Basin
Dave Sailor (LBL)	Analysis of Energy Efficiency and Air Quality: Meteorological Modeling

10:00 am - 10:30 am — BREAK — PRE-FUNCTION AREA OR MOUNTAIN DECK

10:30 am - 12:00 noon — SECOND MORNING SESSIONS (CONCURRENT)

Session A: End-Use Resource Planning Program — COURTVIEW

Alan Meier (LBL)	California Utility Database on Monitored Performance of Efficient End-Use Technologies
Joe Eto (LBL)	Residential Sector Space-Conditioning Load Data Analysis
Hashem Akbari (LBL)	Commercial Sector End-Use Load Shape and Energy Utilization Intensity Data

Session B: Building Energy Efficiency Program — BAY ROOM

Halil Guven (SDSU)	Thermal Energy Storage Commissioning
Steve Selkowitz (LBL)	Envelope and Lighting Technology to Reduce Electric Demand

WEDNESDAY, OCTOBER 14 (continued)

12:15 pm - 1:15 pm LUNCH - Buffet SOLARIUM/GRANHALL

1:45 pm - 3:15 pm POSTER SESSION (PRESENTATIONS) BAY ROOM

Richard Bourne (Davis Energy Group)	Cool Storage Roof Demonstration Project Monitoring
Laura Demsetz (UCB)	Commissioning of Building Control Systems
Helmut Feustel (LBL)	Peak Power Reduction Potential of Radiant Cooling Systems
Bill Fisk (LBL)	Design of a Follow-up Study of Sick Building Syndrome
Ashok Gadgil (LBL)	Improved Energy Efficiency and Reduction of Worker Exposure in Industrial Fume Hoods Using an Airvest
Joe Huang (LBL)	An Assessment of the Energy Performance of a Russian/German Industrialized Housing System
Sukhbir Mahajan (CSU Sacramento)	Optimizing the Use of EMCS Technologies to Reduce Peak Loads and Energy Consumption in Nonresidential Buildings
Mark Modera (LBL)	Indoor Ozone Exposures and Energy Efficiency Technologies
Jim O'Bannon (CSU Chico)	Mobile Home Project
Bailey Green (UCB)	Methane Recovery in Advanced Integrated Ponding Systems
Mike Rubin (LBL)	Spectrally Selective Glazings for Residential Retrofits
Dale Seborg (UCSB)	Improved Energy Efficiency for HVAC Systems via Advanced Process Control
Paul Singh (UCD)	Reducing Environmental Impact and Energy Use Through Water Recycling and By-Product Recovery in Food Processing
David Soane (UCB)	Preparation of High-Strength, Low-Density Polymeric Insulation Material with Environmentally Sound Foaming Agent
Hofu Wu (Cal Poly Pomona)	Comfort-Based Control Logics for Low-Energy Cooling Systems in California Residences

3:15 pm - 4:45 pm POSTER SESSION (POSTERS) LAKE ROOM

FREE EVENING

THURSDAY, OCTOBER 15

7:30 am - 8:30 am	**BREAKFAST- Buffet**		GRANHALL
8:30 am - 10:00 am	**FIRST MORNING SESSIONS (CONCURRENT)**		
	Session A: Air Quality Impacts Program - Gas Combustion Systems I		COURTVIEW
	Scott Samuelsen (UCI)	Formation of Nitrogen Oxides in Industrial Natural-Gas Burners	
	Session B: Building Energy Efficiency Program - HVAC Distribution Systems		BAY ROOM
	Eric Matthys (UCSB)	Reducing Losses in Hydronic Distribution Systems with Fluid Additives	
	Fred Bauman (UCB)	Localized Thermal Distribution Systems for Office Buildings	
	Ashok Gadgil (LBL)	Cold-Air Distribution for Office Buildings	
10:00 am - 10:30 am (check out)	**BREAK**		PRE-FUNCTION AREA OR MOUNTAIN DECK
10:30 am - 12:00 noon	**SECOND MORNING SESSIONS (CONCURRENT)**		
	Session A: Air Quality Impacts Program - Alternative Transportation Systems		COURTVIEW
	Dan Sperling (UCD)	Consumer Demand for Natural-Gas and Electric Vehicles	
	Catherine Kling (UCD)	Economic Incentives for the Introduction of Electric and Natural-Gas Vehicles	
	Andy Ford (USC)	The Impact of Electric Vehicles on the Southern California Edison System	
	Session B: Scoping Activities and Upcoming Projects		BAY ROOM
	Mark Modera (LBL)	Efficient Thermal Energy Distribution in Commercial Buildings	
	Mark Modera (LBL)	Peak-Demand Impacts of Residential Cooling	
	Karl Brown (CIEE)	Development of a Research Agenda for Commercial Cooling Systems	
	Jim Cole (CIEE)	Performance Measurement and Operational Control of Buildings and Systems	
12:15 pm - 1:45 pm	**LUNCH - Buffet** (12:15 pm - 1:15 pm)		SOLARIUM/GRANHALL
	Lunch Speaker:		
	Jim Cole (CIEE)	Future Directions for CIEE	

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THURSDAY, OCTOBER 15 (continued)

1:45 pm - 3:15 pm AFTERNOON SESSIONS (CONCURRENT)

Session A: Air Quality Impacts Program - Gas Combustion Systems II — COURTVIEW

Bob Dibble (UCB)	Energy Efficient, Low-NO_x and -CO Burners for Residential, Small Industrial, and Commercial Gas Appliances: Diode Laser Diagnostics
Nancy Brown (LBL)	Energy Efficient, Low-NO_x and -CO Burners for Residential, Small Industrial, and Commercial Gas Appliances: Combustion Modeling
Catherine Koshland (UCB)	Energy Efficient, Low-NO_x and -CO Burners for Residential, Small Industrial, and Commercial Gas Appliances: Experimental Burners
Greg Traynor (LBL)	Energy Efficient, Low-NO_x and -CO Burners for Residential, Small Industrial, and Commercial Gas Appliances: Residential Emission Modeling and Forecasting

Session B: Building Energy Efficiency Program - Residential Systems — BAY ROOM

Mark Modera (LBL)	Improving the Energy Efficiency of Residential Air Distribution Systems in California
Hashem Akbari (LBL)	Measured Savings in Air Conditioning from Shade Trees and White Surfaces
Joe Huang (LBL)	Alternatives to Compressor Cooling in California Transition Climates

PROJECT SUMMARIES

ENERGY EFFICIENCY AND AIR QUALITY IN THE SOUTH COAST AIR BASIN

RONALD L. RITSCHARD
STAFF SCIENTIST, ENERGY ANALYSIS PROGRAM
LAWRENCE BERKELEY LABORATORY

This multiyear project was launched last year as part of CIEE's Emission Reduction Strategies topic, the goal of which is to investigate the direct and indirect effects of end-use efficiency on the reduction of photochemical smog. This project addresses two aspects of that broad research area, focusing on the South Coast Air Basin (SoCAB):

- Reducing emissions from the buildings sector and improving existing emissions-calculation procedures to incorporate energy-efficiency considerations.
- The effects of variations in surface characteristics (such as trees, surface albedo, and soil moisture) on meteorological conditions, including surface heat balance, temperature, and air flows.

Three interrelated project efforts conducted by an interdisciplinary research team were funded during the first phase to establish the critical technical links between energy end-use efficiency and air quality: emissions studies (at Lawrence Berkeley Laboratory and the University of California, Los Angeles) to develop data on fuel-combustion sources and on trees that can directly affect the production of smog; surface characterization of the SoCAB (at LBL and UCLA) to compile information about surface roughness, albedo, and surface moisture; and meteorological studies (at LBL and Systems Applications International) to assess the effects of various surface modifications on meteorological conditio

The l el of photochemical smog production will be studied in future phases, using as inputs to the Urban Airshed Model (UAM) the emissions profiles and "new" meteorological conditions that result from the surface modifications. The goal of this project is to develop improved quantitative models and data for assessing the relationships among end-use energy efficiency and pollutant emissions and resultant air quality.

This multiyear study is expected to help define the causality between urban temperature reduction and smog formation in the SoCAB and to develop data and model enhancements that can be incorporated into future air-quality assessments.

PROGRESS TO DATE

The emissions studies will estimate both end-use emissions from the buildings sector and biogenic emissions of reactive organic gases (ROG) from trees in the SoCAB.

In the first phase of the project, the LBL team looked at how the South Coast Air Quality Management District (SCAQMD) and the California Air Resources Board calculate end-use emissions. The review concluded that the existing methods need to be revised so that the effects of energy efficiency on areawide emissions can be included. A preliminary "new" model was devised and used to calculate NO_x emissions from fuel combustion in residential and commercial buildings in the SoCAB. These preliminary results correlated well with the 1987 base-case emissions reported in the 1991 Air Quality Management Plan developed by the SCAQMD. This model is being revised even further to incorporate the effects of energy-efficiency improvements and to estimate end-use emissions for the buildings sector.

Also during the first phase, the UCLA research team estimated emissions from trees in the SoCAB. In a further analysis of these biogenic emissions, they investigated the crucial factors in determining total regional ROG from plants that can be used for air-quality modeling. The three most important factors are gridded estimates of the total biomass of the region, vegetative ROG emissions from these plants, and environmental factors (such as temperature) that affect emissions. The final product of this effort will be a gridded estimate of biogenic emissions in the Basin.

Surface conditions in the SoCAB need to be characterized before we can develop credible information about several variables to be modified and evaluated using prognostic meteorological models. The variables considered during Phase I include surface roughness, defined by vegetative cover (canopy cover); surface albedo; and surface moisture. The biomass inventory, developed by UCLA, is based on both the methods developed previously by Winer et al. and on other studies funded by the SCAQMD. To date, we have completed:

- An inventory of the surface data available within the SoCAB and proposed characterization methods.
- A preliminary vegetation biomass inventory of the Basin.
- A preliminary database on albedo, surface moisture, and surface roughness using existing data and available approaches.

Both the biomass inventory and the database on other surface conditions will be modified in the next phase using more advanced methods (such as satellite and aircraft data) and on-site measurements. Meteorological modeling is important in determining to what extent modifications of the urban surface (resulting from increased tree planting or increased albedo) affect the many meteorological variables. Since the causality between reducing urban temperature and decreasing or delaying photochemical smog episodes has to be demonstrated conclusively, this task provides data critical to the overall project goals.

To date, LBL (in cooperation with Systems Applications International) has conducted sensitivity tests and preliminary two-dimensional simulations of the mesoscale conditions resulting from changes in albedo, surface moisture, and surface roughness. During the remainder of the first phase, we will analyze initial three-dimensional simulations under at least four modeling scenarios: base case (existing SoCAB conditions), extensive tree planting, changes in surface albedo, and a combination of tree planting and albedo changes. The results of these meteorological simulations will serve as inputs to the air-pollution models (such as the UAM).

FUTURE OBJECTIVES

In future phases of this project, we will:

- Refine emissions and surface-characteristic databases and develop a geographic information system on the SoCAB.
- Assess spatial, physical, and other constraints (such as water use and fire hazards) on tree planting in the SoCAB.
- Refine the meteorological input and model development required for urban airshed modeling of photochemical smog formation.

ENERGY EFFICIENCY AND AIR QUALITY: THE ROLE OF VEGETATION IN THE SOUTH COAST AIR BASIN

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UNIVERSITY OF CALIFORNIA, LOS ANGELES

The goal of this three-year project is to address the direct and indirect effects of end-use energy efficiency on the reduction of photochemical smog in California's South Coast Air Basin (SoCAB). This study involves proposed modifications to the surface characteristics of the SoCAB, primarily an increase in the surface albedo and a massive tree-planting program. These changes in surface characteristics are designed to moderate the urban heat-island effect and reduce the air temperature of the SoCAB during the summer months. An overall decrease in temperature would likely lead to reduced energy use, with an associated decline in emissions of NO_x from electric power plants and lower evaporative emission of reactive organic gases from a variety of mobile and stationary sources. Reducing these photochemical smog precursors would improve air quality without imposing additional emissions regulations.

The effects of a massive tree-planting program, however, may not be entirely beneficial. While many trees have been shown to remove airborne pollutants, they also emit volatile hydrocarbons—primarily isoprene and various monoterpenes—that contribute to photochemical smog formation in both rural and urban areas. Volatile hydrocarbons emitted from vegetation generally have a substantially greater photochemical reactivity in the atmosphere than a typical urban mix of anthropogenic hydrocarbons. The addition of large numbers of trees could therefore increase both the total hydrocarbon emissions inventory for the SoCAB and the reactivity of the atmosphere. The specific focus of the University of California, Los Angeles, in this collaborative study is to examine the effects of massive tree-planting programs proposed for the SoCAB and the vegetation's ability to act as both a source of and a sink for air pollution.

To determine the effects of additional trees on the air quality of the SoCAB, we developed a baseline vegetative emissions inventory. First, we obtained an estimate of the total vegetative biomass from a previous survey. The biomass database included a species-specific, gridded inventory of green-leaf biomass within the entire SoCAB. Next, we developed hydrocarbon emission rates for all identified plant species in the SoCAB through an exhaustive literature search. Any plant without a specific emission rate was assigned one based on phylogenetic relationships to measured, species-specific emission rates.

The third phase of the study evaluated the effects of environmental conditions (temperature, light intensity, and humidity) on vegetative hydrocarbon emission rates. We selected a specific environmental correction algorithm based on recent plant physiological data to model the effects of changes in those conditions on vegetative hydrocarbon emissions from plants in the SoCAB. The total biomass, emission rates, and environmental algorithm were used to develop a gridded vegetative hydrocarbon emission inventory for the Basin. This inventory provides hourly estimates of vegetative emissions for each 5 km by 5 km grid square for an entire year; it will be included in the Urban Airshed Model to predict the impact of vegetative hydrocarbon emissions on the air quality of the SoCAB.

The final portion of this study focuses on estimating vegetation's pollutant-trapping ability.

The current estimated summer vegetative hydrocarbon emission inventory in the SoCAB—approximately 130 tons per day (115 metric TPD)—appears to be dominated by the estimated anthropogenic hydrocarbon emission inventory of approximately 2,000 TPD (1,800 MTPD). A massive tree-planting effort, assumed for calculation purposes to be a maximum of 10 million trees, is estimated to add approximately 40 TPD (35 MTPD) of vegetative hydrocarbons to the total inventory of the SoCAB. The 10 most numerous tree species now found in the SoCAB, excluding eucalyptus, were chosen for this first estimation. The species included high, medium, and low hydrocarbon emitters.

A detailed strategy for massive tree planting in Southern California would also require assessment of the drought resistance, fire potential, pollutant trapping and resistance, space requirements, hydrocarbon emissions, and location of trees to be planted in the SoCAB.

As noted earlier, the ultimate goal of the program is to reduce temperatures by suppressing the urban heat-island effect. Due to the logarithmic dependence of vegetative hydrocarbon emissions on temperature, we estimate that if changes in surface characteristics reduced temperatures by 4 to 7°F (2 to 3°C), the reduced vegetative emission rates resulting from lower summer temperatures would offset the additional vegetative emissions resulting from the tree-planting program.

At present, hydrocarbon emissions from vegetation do not appear to contribute substantially to the air-pollution problems in the SoCAB. However, as anthropogenic emissions decline with future control programs, vegetative emissions may define a lower limit on hydrocarbon emissions for the Basin. In the future, we may need to place greater emphasis on NO_x emission-control strategies to reduce ozone and other photochemical oxidants formed from hydrocarbons and NO_x precursors. Investigation of vegetative hydrocarbon emissions will become more important as mandated emission-control strategies reduce overall inventories of anthropogenic hydrocarbons.

ANALYSIS OF ENERGY EFFICIENCY AND AIR QUALITY: ALBEDO, SOIL MOISTURE, AND SURFACE ROUGHNESS IN THE SOUTH COAST AIR BASIN

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LAWRENCE BERKELEY LABORATORY

A major task of this project, which relates energy efficiency to air quality in the South Coast Air Basin (SoCAB), is to develop input data for simulating meteorology and air quality in that area. Generally, the input to meteorological models falls into three categories: atmospheric variable fields, subsurface variable fields, and surface characteristics. The latter is the primary force in the breakdown and transport of heat, momentum, and moisture toward or away from the surface.

Additionally, this project entails studying the meteorological and air-quality consequences of surface albedo and vegetation modifications. The ability to characterize the surface in the SoCAB, particularly in terms of albedo and vegetation cover, will allow us to estimate the potential to modify these parameters. Thus, surface characterization is an important factor that will evolve into a more specific task during the second phase of this project.

During the first phase, three variables—albedo, roughness length, and soil moisture—in the simulation domain of the SoCAB were characterized. We used a "first order" approach, whereby the effective values for each 5-by-5-km cell were estimated from previous measurements and published data. Although these values were not obtained from or measured in the SoCAB, they were sufficient for performing sensitivity simulations as well as preliminary two- and three-dimensional meteorological studies in Phase I.

Surface characterization will be refined in the second phase, during which the three-dimensional meteorological simulations will be finalized and coupled to photochemical smog simulations with the Urban Airshed Model. The reason, as mentioned earlier, is that the values obtained using the first-order approach were not site-specific to the SoCAB. For the simulations to reproduce local conditions, surface characterization must be made site-specific.

The first variable, albedo, will be characterized more specifically using three methods. First, surface-based measurements (~2 m above the surface) will be performed over uniform and homogeneous ground covers, such as large vegetated areas, water surfaces, and large paved surfaces. The purpose is to calibrate the albedo values derived from the following two methods.

The second method uses a low-altitude aircraft for directly measuring the effective albedo of 5-by-5-km cells over the SoCAB. Pyranometers will be carried aboard the aircraft at an altitude of ~500 m. North-south and east-west flight transects will be used to scan a variety of land covers, topographies, and land uses.

Advanced, very-high-resolution radiometer satellite data will then be used to extrapolate measurements from these two methods into a broader scale covering the entire SoCAB.

The second variable, roughness length, will be made more site-specific by direct measurements of wind speed or indirect characterization of roughness elements. In the first approach, multilevel measurements of wind speed must be performed for a variety of land uses and covers to characterize the logarithmic wind-speed profile within the urban boundary layer and determine the roughness length. Although this method is the most accurate, it is the most inconvenient to perform: A tall tower (~30 m) needs to be moved from one site to another as needed. Also, the tower will require at least four sets of wind vanes and anemometers. In the second approach, roughness length can be determined indirectly from geometrical characterization of roughness elements. This method is easier to perform but is tedious and may yield general values of roughness that do not represent specific cells.

In another method, roughness length is determined from sounding data (geostrophic and surface-wind measurements); surface winds at 2 m will be correlated to the geostrophic winds at the 925-millibar level and the friction velocity term to determine roughness. This approach may be the easiest but may be too general for a cell-by-cell characterization. At this time, however, it is the most appropriate for the second-phase task. If necessary, limited characterization with the first or second method will be performed for comparison or calibration purposes.

The last variable, soil moisture, can be characterized with rather easy sampling. We will obtain a soil sample from each representative (major) land cover or land use, such as cropped areas, forests, bare soil, and paved areas. Samples will be sealed in vapor-proof membranes and either sun- or oven-dried to determine the moisture content. More sophisticated, sensor-based measurements will not be performed; the goal is to get general estimates rather than spot-specific soil moisture profiles. The approach we propose will yield only general moisture values, as this parameter is known to fluctuate on both diurnal and seasonal scales.

The extensive database that will be developed during the second phase will be entered into a geographical information system designed for easy access and management of highly site-specific information. Since the data will be multilayered (such as surface, aircraft, and satellite), this system may be very useful in correlating data from various levels and comparing it to the land-use category database.

ANALYSIS OF ENERGY EFFICIENCY AND AIR QUALITY: METEOROLOGICAL MODELING

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Numerical modeling efforts in support of this project are divided into three phases. In the first phase, a series of two-dimensional simulations was conducted to determine the meteorological model's sensitivity to varying surface conditions. In the second (current) phase, full three-dimensional numerical simulations for the Southern California Air Basin (SoCAB) are being conducted. A modified version of Colorado State University's Mesoscale Model is being used for both the two- and three-dimensional meteorological simulations. The three-dimensional simulations will use detailed surface characteristics to model the existing meteorological conditions in the Basin. In addition, we will be simulating the effects of six heat-island mitigation scenarios.

In the third phase of modeling, we will apply the Urban Airshed Model (UAM) to the SoCAB using the results of our meteorological simulations as input. The results of this phase of modeling will indicate the extent to which surface characteristics can affect urban air quality.

TWO-DIMENSIONAL SIMULATION RESULTS

The two-dimensional meteorological simulations consisted of a series of 22 cases in which the surface characteristics were varied both on a domainwide scale and in specific, localized regions. The 320-km-long simulation domain included 80 km of ocean on the western end to incorporate the effects of a developing sea breeze. Thus, the results of these two-dimensional simulations provide useful insight into the role of surface characteristics in the meteorology of the SoCAB.

The surface characteristics we investigated were albedo, roughness, moisture availability, and soil thermal properties. We found that the albedo and moisture availability were the most important surface characteristics in terms of effect on the local meteorology. Both characteristics were found to have positive and negative air-quality impacts. For example, a 10-km-long patch of high-albedo land resulted in a significant depression of the planetary boundary layer. In general, this would be likely to have a negative impact on air quality due to the decreased levels of atmospheric mixing. On the other hand, this same patch of high-albedo land resulted in decreased surface and air temperatures, which would in turn result in lower photochemical smog rate constants. We concluded that the best way to determine the net effect of surface-characterization modifications is to conduct a detailed series of sensitivity studies with the UAM.

THREE-DIMENSIONAL SIMULATION

The meteorological model that was used in the two-dimensional studies is also being used to simulate the three-dimensional meteorology of the SoCAB. We made significant modifications to the model to make it useful in this study; arrays of surface characteristics were added to the source code so they could be allowed to vary across the domain, and a forcing term was added to the energy balance to account for anthropogenic heating of the near-surface air.

The modeling domain has 22 vertical levels, 65 east-west grid cells, and 40 north-south grid cells. The horizontal grid spacing is 5 km, and the vertical spacing varies from 25 m to 1,000 m. This domain is consistent with that used by previous researchers except that it extends 20 km further north.

Surface Characterization. Initially, the meteorological model used simple, domainwide average values of the surface characteristics. Preliminary three-dimensional simulations demonstrated that such approximations resulted in significant errors in the simulated temperature and wind fields. After modifying the model to accommodate variable surface characteristics, we identified two methods for determining the appropriate values of each surface characteristic. An urban terrain zone database was used to determine the composition of each grid cell (such as percentage urban core, parkland, and low-density residential housing). Each cell consisted of various percentages of each of 23 terrain types. We determined reference values of each surface characteristic for each terrain type, then used simple area-averaged values of these characteristics.

Satellite image data provides an improved method of determining surface albedo and vegetative cover. We will incorporate this type of data into future simulations.

Mitigation Schemes. This study is investigating two heat-island mitigation schemes. First, increasing the albedo of urbanized areas results in cooler surface temperatures, which in turn cool the air. The second approach is to plant additional urban vegetation, which will cool the air through evapotranspiration. We started by identifying potential areas in the SoCAB that would benefit from one of these mitigation schemes, then defined six scenarios to be modeled. These scenarios consisted of moderate albedo modifications, moderate vegetative modifications, moderate combined albedo and vegetative modifications, high albedo modifications, heavy vegetative modifications, and high albedo and heavy vegetative modifications.

The computational domain consists of 2,600 (65 by 40) surface grid cells. The first step in developing the mitigation scenarios was to define the regions of the domain that could be modified. These regions essentially corresponded to the developed areas. After applying this filter, we were left with roughly 300 grid cells. (Of course, some of these cells already have high albedos or significant vegetative cover.) We will be using satellite data to further limit our choice of grid cells for modification. In the end, we expect that about 150 grid cells will be modified in the various mitigation schemes. Although this is a small fraction of the total number of grid cells in the domain, the impact should be significant since most of the cells are concentrated in the western end of the land domain (near downtown Los Angeles).

CALIFORNIA UTILITY DATABASE ON MONITORED PERFORMANCE OF EFFICIENT END-USE TECHNOLOGIES

ALAN MEIER
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LAWRENCE BERKELEY LABORATORY

Utilities have monitored building and equipment performance as a regular part of their research, development, and customer-service activities. These investigations range from field measurements of agricultural pump tune-ups to the performance of new thermal storage systems in office buildings. In the laboratory, investigators have measured the energy use of everything from water-heater retrofits to Wanless motor retrofits. In most cases, an internal technical report or memo was written. These reports typically include a detailed description of the technology, the data collected, and an analysis of the results. (The California Energy Commission and other state agencies have also undertaken informal research and monitoring projects, but on a much smaller scale.)

These internal reports document savings from the use of new technologies and are a potentially valuable source of baseline energy data. They could provide an early benchmark for assessing the effectiveness of conservation activities now under way for the California Collaborative. Unfortunately, the projects are rarely coordinated, and few internal reports are archived. Indeed, few people outside the originating department in the utility are even aware of the reports. They are typically filed in one of several departments, depending on the motivation for the study and the author's affiliation. Thus, this information is virtually lost to the utility and others seeking measured data on new conservation technologies.

RESEARCH OBJECTIVES

The principal objective of this study is to assess the availability, quality, and value of previously collected monitored data for utility demand-side management programs. An immediate potential benefit of the monitored data will be documentation of the energy savings achieved through utility conservation programs. Later, reviews of the compiled information will help researchers target the most promising efficiency opportunities in California and apply the experience gained from past monitoring projects to improve the cost-effectiveness of future efforts. As the assessment proceeds, the program planners and forecasters will be surveyed to determine their needs for monitored data.

PROJECT DESCRIPTION

This project will locate and survey the internal technical reports recently written by various divisions within the California utilities and regulatory agencies. This will involve visits to the customer-services, engineering-services, marketing, and research divisions of several of those organizations. Since the current contributors are also anticipated to be the largest future users of the information, we will informally survey potential users of this information. The objective is to determine their specific needs regarding monitored data in hopes of better exploiting that data.

Once we have located the reports, we will review them for the range of topics investigated, technical quality, and extent and relevance of monitored data. We do not anticipate locating and reviewing every report; indeed, an important question is the ease with which we can find the reports.

In addition to assessing the reports' technical quality, we will evaluate the value of their monitored data. A database containing the results of these studies will be created to help utility planners and evaluators design new programs.

PRODUCTS

In the first phase, we will visit every major utility and CIEE sponsor to identify and collect examples of the gray literature. This activity is under way.

Our attempts to identify repositories of reports and technical memos have met with limited success. In some cases, the organizations already have databases of some reports but have not updated them in several years. In other cases, the reports are in closets and back rooms, often forgotten by staff. (None of the reports have been officially cleared by the utilities, so their exact nature cannot be discussed here.) Some reports have already stimulated considerable discussion within the CIEE community; for example, one internal Pacific Gas and Electric report on the performance of a photovoltaic-powered home identified the electric starter on a gas oven as a significant electricity consumer. As a result of this revelation, Southern California Gas has looked into establishing a special rebate to discourage this inefficient ignition device. The Los Angeles Department of Water and Power may revise its conservation programs and brochures to reflect the results of a Sacramento Municipal Utility District study indicating little or no significant electricity savings from refrigerator-repair measures.

After completing the site visits, we will write a report assessing the state of the internal reports and their value as a source of monitored data for the Collaborative. The report will describe ease of access to the utility reports and memos, the range of topics investigated, and the technical quality of the reports. It will also recommend any procedures that would improve the effectiveness or value of the reports.

In the process of surveying the utilities, we have begun to develop a modest database. Its initial use will be to store key information about each report reviewed; at the same time, the database will be demonstrated to utility planners and evaluators. (If it proves popular, it will be expanded in the next phase of the project.)

The third product is a workshop to discuss the value of the technical reports and the monitored-data needs of utility planners and field personnel. Both utility and regulatory staff will be invited.

RESIDENTIAL SECTOR SPACE-CONDITIONING LOAD DATA ANALYSIS

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The annual energy demand forecasting models used by California utilities and the California Energy Commission (CEC) rely on an explicit representation of the end-use structure of energy demand. To forecast peak electricity demand and load shapes, we need additional disaggregation of annual forecasts over the hours of the year. This disaggregation is appropriate because policy interventions to improve energy efficiency can only be captured by forecasting tools that incorporate end-use and load-shape detail.

Lack of high-quality end-use data to support these modeling activities has been cited as the most important factor limiting forecasting improvements. Moreover, collecting this data is often very expensive. California is fortunate because its utilities have begun collecting end-use metered data; however, analysis of the data for forecasting purposes has been limited.

The objective of this project is to analyze end-use metered data on residential space cooling to develop a common set of inputs for the end-use forecasting models used by the CEC and Pacific Gas and Electric (PG&E).

APPROACH

PG&E's load research group has been collecting end-use metered data from more than 700 residential customers since 1985. Lawrence Berkeley Laboratory (LBL) obtained this data, along with corollary weather data and statistical weighting factors, in a previous CIEE-sponsored project (subproject A of the Integrated Estimation of Load Shapes and End-Use Energy Intensities in Commercial and Residential Buildings project).

Both PG&E and the CEC will use HELM, a load-shape forecasting model developed by the Electric Power Research Institute, to forecast electricity demand. PG&E and the CEC, however, use different conventions for defining end uses within HELM.

Working within existing PG&E and CEC conventions, LBL will develop HELM input files and apply consistent data-analysis procedures to a common set of data. Three types of inputs will be developed:

- A weather response function that allocates a forecast of annual energy use to the days of the year.
- Sets of 24-hour load shapes correlated with measures of daily climatic severity.
- Direct estimation of 24 hourly values (in a parallel task that will explore an alternative to the second task).

CURRENT STATUS AND FINDINGS

LBL has obtained all required data from PG&E and the CEC, which are reviewing a work plan to finalize project activities. Input files are expected to be delivered to those organizations in November, coinciding with their preparations for the next forecasting cycle.

FUTURE WORK

All load-shape models currently act as post-processors to annual energy demand forecasting models. In the future, we would like to investigate methods for relating observed hourly end-use electricity consumption directly to physical and other characteristics of metered households. We are also interested in determining how best to leverage expensive end-use metered data with nonmetered data to develop reliable data for forecasts and demand-side management program evaluation.

COMMERCIAL SECTOR END-USE LOAD SHAPE AND ENERGY UTILIZATION INTENSITY DATA

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One of the weakest empirical links in the end-use forecasting arena is the absence of reliable data on electricity end uses in the commercial sector. For several years, we have been investigating ways to estimate end-use load shapes and energy utilization intensities (EUIs) using a variety of available data, including whole-building and end-use metered load, on-site survey of building and equipment characteristics, and mail survey. This project has focused on obtaining end-use load shapes and EUIs that can be applied to the Pacific Gas and Electric Company (PG&E) service area.

The overall objectives of this multiyear project are to:

- Analyze measured, end-use load data in commercial buildings collected by California utilities (such as PG&E and Southern California Edison) to validate an end-use load-shape estimation model developed at Lawrence Berkeley Laboratory (LBL).
- Apply the validated model to develop a common set of reconciled hourly end-use load shapes and annual EUIs in commercial buildings by building type, vintage, and climate region. The results will be compatible with energy and peak-demand forecasting models of both PG&E and the California Energy Commission (CEC). Of special interest are load shapes for typical weekdays, weekend days, and peak days, by month or by season.
- Evaluate the adequacy of the estimated load shapes and EUIs in the PG&E and CEC energy and peak-demand forecasting models.

The specific goals of the first phase were to apply LBL's end-use load-shape estimation model to obtain a common set of reconciled hourly end-use load shapes and annual EUIs for four commercial buildings types and to initiate work with PG&E and the CEC to resolve issues related to data transfer for application in forecasting models.

RESULTS

To apply the LBL model, we first developed preliminary prototypical EUIs and load shapes for the premises of interest using the on-site survey data and the DOE-2 building energy analysis program. Second, using the load research data and monthly billing data from the on-site surveys, we built average whole-building hourly load shapes for each premise type. Third, using the initial building loads by end use from the first step and the average hourly loads from the second step, we applied the LBL End-use Disaggregation Algorithm to obtain adjusted, reconciled end-use load profiles for all building types. The corresponding EUIs are simply the integration of the hourly profiles for the entire year.

During the first year, we obtained end-use load-shape and EUI data for four building types (large office, small office, large retail, and small retail) and up to 10 end uses for both coastal and inland climates of the PG&E service territory. In general, reconciled EUIs are significantly different from simulations, particularly for a large office. The differences appear in both the nighttime and daytime EUIs. Without reconciliations, errors from engineering estimates (simulations) would go unchecked.

THERMAL ENERGY STORAGE SYSTEM COMMISSIONING

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Properly designed, equipped, and installed, thermal energy storage (TES) systems can shift a significant portion of the daytime facility cooling loads to off-peak, reducing the need to use less efficient and more polluting power-generation equipment or build costly power plants to meet these loads. Applying this technology is mutually beneficial to facility owners, the general public, and electric utilities.

Some installed TES systems, however, are not meeting their design intent. Their failure to deliver the expected load shift is of concern to facility owners, the TES industry, and, in particular, the electric utilities, which have used ratepayer funds for incentives to install these systems.

For those TES systems studied that were not meeting the expected load shift, effective commissioning procedures had not been implemented. Such procedures would have significantly improved the performance of these failed systems. Commissioning guidelines are recommended for all new TES installations and are believed to enhance the image of TES as an effective, reliable energy-efficiency technology. It is anticipated that development of comprehensive and proven commissioning guidelines—and possible future adoption of these codes by utilities for new installations—will greatly enhance the field-performance characteristics and reliability of TES systems.

One of the subtasks of Phase I of this multiyear project was to design commissioning guidelines for TES systems. During that phase, we developed a generic, usable commissioning process for TES systems. We designed this process after studying commissioning literature and incorporating feedback obtained during a 1991 TES Commissioning Workshop conducted by the San Diego State University research team. (Of all the commissioning literature studied during Phase I, we found the British Commissioning Codes for water distribution, air distribution, and refrigeration systems to be the most relevant and useful references for this effort.)

The most important goal of Phase II is to produce a fully critiqued, field-tested commissioning process that is viewed by the TES industry as a usable, cost-effective tool. The TES commissioning process has been further developed and refined, and pilot field testing has been undertaken to document the guidelines' applicability, usability, relevance, costs, and benefits.

ENVELOPE AND LIGHTING TECHNOLOGY TO REDUCE ELECTRIC DEMAND

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Fenestration and lighting systems are major contributors to peak electric demand and peak cooling loads in commercial buildings and thus to annual energy use and mechanical system costs. These loads can be reduced significantly through proper fenestration and lighting design and the use of daylighting strategies. However, the lack of documented applications of highly efficient daylighted buildings suggests that significant obstacles to efficient fenestration and lighting design and use still exist. Integrated lighting/daylighting/fenestration design solutions that provide maximum energy efficiency will not be widely implemented until buildings are designed as integrated systems.

Moving beyond the current practice of piecemeal adoption of individual efficient components, we attempt to integrate existing and emerging component technologies into functional systems. The goal is to optimize the relevant building energy performance parameters with improved occupant comfort and satisfaction. Because new hardware systems alone will not ensure optimal building performance, we study obstacles to innovation within the design community and propose strategies.

The objective of this project is to give designers cost-effective demand-reduction technologies and to demonstrate their use in built projects, targeting peak-load reductions of 15 to 40%.

PHASE I RESULTS

Establish goals, framework, constraints, and methods. We began by completing a utility impact assessment of new and emerging window and lighting technologies in office buildings. We analyzed the energy performance potential of these technologies to establish preliminary "targets," or building performance goals. These targets were compared to a selection of measured and simulated building performance data, and to California energy code requirements as a benchmark, to illustrate the uncaptured potential of these technologies in statewide energy use and peak-demand reductions. Glazing luminous efficacy, lighting power density (W/ft^2), and use of daylighting controls emerged as the key lighting and envelope parameters that most significantly affect energy performance. We projected potential lighting and cooling reductions of 38% by 1995 and 73% by 2005, with peak-demand reductions of 22% by 1995 and 40% by 2005.

Having established potential performance, we examined the efficiency options currently specified in building design. To establish a working base of technologies for analysis throughout the project, we reviewed existing, emerging, and future technology options in several categories of envelope and lighting hardware. Similarly, we examined market, industry, and design concerns by interviewing key individuals in design and construction regarding technical innovation and envelope design.

These tasks yielded several findings. The construction industry is fragmented into specialized and diverse trades that are highly localized. These characteristics, combined with the uniqueness of each building project, make mass production of integrated technologies difficult. The consequences of a new technology's failure in the building sector are serious, leading to caution regarding adoption of new technologies. Partially due to this conservatism, innovation in the building industry often requires implementation assistance beyond natural market forces (such as subsidies or legislation).

Building energy performance remains a relatively low-priority issue in building design, indicating a need for profound shifts in design priorities before new, efficient technologies are adopted.

Design, analyze, and evaluate candidate integrated systems. We developed several initial design concepts for the integrated envelope and lighting systems, drawing on our technology base overview. We also developed DOE-2 input descriptions for commercial building prototypes with two different building skins, each representative of typical California design, construction, and operation.

The integrated envelope and lighting systems we are designing cannot be simulated using existing analysis tools because of their dynamic capabilities and unique optical properties. Therefore, we developed a method for modeling the thermal and luminous performance of complex optical systems through a combination of physical-model photometry and DOE-2 software modification. We also developed analysis methods to evaluate the performance of dynamic envelope and lighting designs.

Demonstrate integrated systems in scale models, field tests, and buildings. Although our integrated design solutions will not be completed until Phase II, we pursued earlier opportunities to field-test and monitor key elements of our integrated systems and to demonstrate their potential and feasibility to others. We initiated two simultaneous paths: partial or small-scale demonstrations of advanced prototype systems prior to commercialization, and full-scale demonstrations in real construction projects of interim integrated systems.

We selected two potential short-term, utility-sponsored projects and worked directly with their design teams. These projects have helped us develop an initial method of interaction with design teams that are exploring new technologies. The lessons emerging from these efforts should prove highly useful, both for our Phase III demonstrations and for utility design assistance programs.

First, demonstrations are important, but they are difficult and expensive to carry out. Issues of schedule, budget, and risk often conflict with requirements for the demonstration. Good candidates for demonstration are those projects in the pre-schematic phase with time allotted for exploration and research. As this is atypical due to project budget constraints, we will need to find alternate methods to expedite evaluation of design alternatives.

Second, design assistance will need to be tackled from three fronts: provide experts for direct consulting at the beginning of the project, provide a database of case study "models of success," and provide continuing education to enable repeat performances without assistance. This last issue should ultimately be addressed with the development of a new generation of more powerful, sophisticated, user-friendly design tools. We plan to develop prototypes of such tools for use in later phases of this project.

PHASE II PLANS

Having established project performance, targets, and methodologies in Phase I, we will focus in Phase II on developing specific prototype integrated envelope/lighting systems. Two prototype designs will be developed, one suitable for conventional planar curtain wall facades typical of most commercial construction and a second based on a more articulated facade found in some designs today. Each incorporates such key components as spectrally selective glazings, operable shading, dimmable ambient lighting systems, efficient task lighting, and daylight controls.

The primary research thrust will be on developing smart-control strategies that will optimize energy efficiency and occupant satisfaction given the dynamic conditions of daylight, climate, and task occupancy. These will be developed through an iterative sequence of conceptualizing alternative designs to meet performance criteria, then fully analyzing performance through simulation models. Extensive tests using reduced-scale model prototypes under real-time weather conditions will gauge the operational performance of the lighting control strategies. We will also directly measure peak day cooling system impacts in a full-scale prototype using the Mobile Window Thermal Test Unit. This development sequence will involve the participation of key industry firms in each technology area to provide materials, supplies, and in-kind support and to help estimate commercial application costs for the prototype systems.

The second task will continue the Phase I effort to more thoroughly address the obstacles to commercial development and market penetration of our selected integrated systems, leading to a series of demonstration projects. We will plan two demonstration paths: The complete, integrated prototype systems will be demonstrated on a small scale in existing buildings and with industry collaboration, and elements of these integrated systems will be demonstrated on a whole-building scale. Full implementation of these demonstration projects will begin at the start of Phase III.

COOL STORAGE ROOF DEMONSTRATION PROJECT MONITORING

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The Cool Storage Roof (CSR) demonstration project was conducted at the California Office of State Printing (OSP) in Sacramento. The CSR system was developed with assistance from the California Energy Commission's Energy Technologies Advancement Program. This project was completed in June 1992. Predemonstration project activities included system development, prototype testing, hourly computer simulation development, and market studies; subsequent tasks included economic studies and overall project reporting.

The CSR is a water-ballasted, protected-membrane roof system in which rigid, interlocking insulation panels float on the ballast water. (Ballast is weight securing the membrane.) Both water and panels protect the membrane from outdoor conditions. In the cooling season, ballast water is sprayed above insulation panels at night for evaporative and radiative cooling. The cooled water drains back through panel joints and is used to reduce subsequent daytime cooling loads. Automatic refill and a filter with automatic backwash maintain water level and quality. The system is primarily directed at large, nonresidential new-building markets.

Key objectives of the CSR monitoring project were to:

- Measure the night heat rejection rate from the CSR.
- Measure cooling delivery from the CSR to occupied space.
- Assess CSR efficiency as a cooling system.
- Assess CSR water use and water quality.
- Evaluate CSR service and maintenance requirements.

The 6,500-ft^2 (604-m^2) demonstration CSR was placed at the south end of an existing 40,000-ft^2 (3,716-m^2), one-story book-storage warehouse at the OSP. The south end has 20 occupants from 7 a.m. through 4 p.m. on weekdays only. The sole existing cooling system was a two-ton rooftop unit for a small office. The demonstration CSR was placed atop the existing roof, with primary cooling delivery via fan coil loop to the occupied space below. The CSR contains 14,300 gallons (54,130 liters) when filled to the specified depth of 3.5 in. (8.9 cm). The 3-in.-thick (7.6 cm) interlocking insulation panels cover the water surface. Installation began on August 15 and was completed on August 30, 1991. Spray cooling operation (on a 9 p.m.–7 a.m. cycle) began September 6 and was completed October 24. Weather during the period was much warmer than normal; temperature monitoring continued through December 31.

METHODOLOGIES

Comfort impact was measured by before-and-after indoor temperature monitoring. Night cooling rate was determined by measuring the water-flow rate and average temperature drop between the pump suction and the water returning through the panel surface. Ceiling heat flows were estimated based on roof and ceiling surface-temperature sensors and known thermal characteristics of the roof system.

Using data from a representative weather period, we calibrated an hourly CSR performance algorithm for subsequent use in full-year hourly simulations. We determined the fan-coil cooling delivery rate by subtracting estimated hourly water-to-air roof transfers from the cooling rate based on the CSR water temperature drop. Cooling efficiencies were computed for the spray cooling cycle alone and for delivered cooling, including fan-coil parasitic energy.

A water-flow meter on the CSR's automatic-refill line measured system water use. We analyzed the water quality for pH, dissolved solids, and bacterial growth; potential service and maintenance problems were evaluated during frequent site visits.

RESULTS AND CONCLUSIONS

During typically warm summer weather, pre-CSR indoor air reached 86 to 88°F (30.0 to 31.1°C) by mid-afternoon; ceiling temperatures reached 97°F (36.1°C) and stayed above 85°F (29.4°C) through the night. With similar highs (but shorter days) after CSR installation, indoor and ceiling temperatures stayed below 80°F (26.7°C) and 75°F (23.9°C), respectively. Occupants expressed satisfaction with cooling comfort.

The spray cooling cycle was effective, typically cooling CSR water to between 5 and 9°F (2.8 to 5.0°C) below the night low air temperature and often below the night average wet-bulb temperature. Cooling benefits averaged more than 300 Btu/ft^2-night (29.4 kJ/m^2-night) under high cooling-load conditions, with daytime highs averaging 95°F (35.0°C). Performance was significantly better than original project expectations due to improved panel and water-flow design. The CSR system also added valuable roof-assembly thermal resistance under winter heating conditions.

The fan-coil heat-transfer rate was lower than projected but still delivered cooling at a rate comparable to a plywood roof deck "direct-contact" CSR configuration (direct heat transfer through the deck without a fan coil). Spray cycle energy efficiency ratios[1] (EERs) ranged from 50 to 100; overall cooling EERs (including benefits from reversing ceiling heat flow) exceeding 50 can be expected when a low pressure drop fan-coil pump is substituted for the spray/filter pump used in both flow loops for the warehouse project. Substantial future efficiency improvements are expected from modifications in spray, filter, motor, and control components. Most CSR electrical energy use is off-peak.

Water-use data was inconclusive. Overspray caused water loss around the perimeter until inward-directed perimeter spray heads were substituted on October 7; water use prior to that was slightly higher than for equivalent cooling from a direct evaporative cooling system. Insufficient data was available to determine water use after the heads were changed. The filter maintained excellent water clarity; although several bacterial colonies were found in both tap and CSR water samples at the site, none were considered dangerous and no Legionella organisms were found. The pH became slightly acidic in winter but not enough to endanger the copper cooling coils, the only metallic system components.

The overall goal of minimizing CSR service requirements appears achievable based on demonstration project monitoring. The roof surface is self-cleaning, drains cannot clog, and the permanent sand filter has an automatic backwash cycle. The system performed reliably throughout the monitoring period, though several minor problems justify panel improvements to prevent damage from birds and breakage.

RECOMMENDATIONS

Continuing CSR research and development activities are recommended to demonstrate other CSR configurations, develop more advanced controls, optimize spray-system design, toughen the panel-surface coating, complete water-use monitoring, and investigate water-treatment alternatives. Evaluation activities are also recommended to compare performance and economics for the CSR and other commercial building energy-efficiency measures.

[1]Energy efficiency ratio is defined as $\frac{\text{kBtu cooling}}{\text{kW energy}}$.

COMMISSIONING OF BUILDING CONTROL SYSTEMS

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When properly designed, installed, operated, and maintained, energy management and control systems can significantly reduce energy consumption. However, anecdotal evidence of malfunctioning building control systems abounds ("For months, the heating and cooling plants had been working simultaneously and at full blast, the boilers producing their full output and the cooling plant fighting to chuck it all out at the roof"[1]). Buildings in which the control systems are not working properly can be uncomfortable and extremely inefficient. In addition, poor performance of systems that have been touted as energy-efficient may leave building owners reluctant to invest further in energy-efficient technology.

The factors that affect building control system performance span the building life cycle. Performance depends on design, construction, operation, maintenance, and the interfaces between these functions. Possible problems during the design phase include inaccurate predictions of level of use and inadequate modeling. During construction, problems such as substitution of components not truly equivalent to those specified or of poor quality (for example, incorrect installation of components or failure to complete electrical connections) can lead to poor performance.

Operation and maintenance also affect performance. Operational errors are thought to have played a large role in a recent high-rise fire; an employee reset a fire alarm several times before realizing that the alarm was not malfunctioning. Similar errors can increase energy consumption on a daily basis. Inadequate maintenance can result in components that work inefficiently or not at all.

Finally, it is important that intent be communicated from the design phase to the construction, operation, and maintenance phases. For example, a sensor intended to detect lighting levels must not be obstructed by equipment or furniture.

[1]Reid, E. *Understanding Buildings*. Cambridge, Mass.: MIT Press, 1984.

The appropriate means of improving building control system performance depends on the prevalence of each type of problem. For example, if poor performance is primarily due to maintenance problems, it would be reasonable to investigate the incorporation of additional self-checking functions in building control systems. If the problem is in construction, increased emphasis on quality control might be in order. If the problem lies in communication between design and construction, one solution might be to modify the design and construction processes to allow greater partial testing of systems during construction.

An important first step in improving the performance of building control systems is to document the extent of performance problems—verifying or refuting anecdotal accounts of poor performance—and understand their origins. This project provides initial research in this direction. We are documenting performance problems and investigating their origins through a review of the literature; a survey of local building managers; discussions with building owners, designers, contractors, maintenance personnel, and control system manufacturers; and site visits to selected buildings.

The results of this project will be threefold:

- A well-documented assessment of the extent to which poor performance of building control systems is a problem.
- An improved understanding of the causes of poor building-control performance and an assessment of their relative frequency.
- Suggested improvements for common causes of poor performance.

These results should help CIEE determine the need for and establish the direction of further research on building control system commissioning and performance.

PEAK POWER REDUCTION POTENTIAL OF RADIANT COOLING SYSTEMS

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Cooling nonresidential buildings in California contributes significantly to electrical power consumption (in 1985, about 9,000 GWh) and peak power demand (approximately 6.5 GW in 1989). Much of the electrical energy used to cool buildings is drawn by fans that transport cool air through ducts. Some of that electricity, because it is heating the conditioned air, is part of the internal thermal cooling peak load. Of the typical thermal cooling peak load for California office buildings, 31% is for lighting, 13% is for people, 14% is for air transport, and 6% is for equipment; external loads account for only 36% of the peak load.

DOE-2 simulations for different California climates using the California Energy Commission base-case office building show that at peak load, only 10 to 20% of the supply air is from the outside. This is the fraction of supply air necessary to maintain a high level of indoor air quality in buildings.

HVAC systems are designed to maintain indoor air quality by removing pollutants from sources inside the building and to provide thermal space conditioning. Traditionally, HVAC systems are designed as *all-air systems*; in other words, air is used for both tasks. For conventional HVAC systems, the difference in volume between supply air and outside air is made up by recirculated air. The recirculated air is necessary to keep the temperature difference between supply and room air in the comfort range. The additional supply air, however, often causes drafts and indoor air-quality problems by distributing pollutants equally throughout the building.

Air-and-water systems separate the tasks of ventilation and thermal space conditioning by using a primary air-distribution system to fulfill the ventilation requirements and a secondary water-distribution system for thermal conditioning. These systems reduce the amount of air transported through buildings by 80 to 90%; the cooling is provided primarily by radiation, using water as the transport medium (the systems are hydronic). Ventilation is provided by a separate outdoor air system without recirculating air. Besides improving comfort conditions, this improves indoor air quality and the control and zoning of the system. Due to the physical properties of water, hydronic cooling systems can remove a given amount of thermal energy using less than 5% of the fan energy that would otherwise be necessary.

Since large surfaces are used for heat exchange in radiant cooling systems (ceilings are most often used), the coolant temperature is only slightly lower than the room temperature. This difference allows the use of chillers with high Coefficient of Performance values or direct use of a cooling tower to further reduce the electrical power requirements. Additionally, radiant cooling systems reduce the problems caused by duct leakage; that's because the supply-air volume is decreased and is conditioned to meet room-temperature rather than cooling-air-temperature conditions. Furthermore, space needs for ventilation systems and their ductwork are reduced by about 80%.

Besides reducing the space requirements for the shafts that house the vertical air-distribution system, we can reduce floor-to-floor height and thereby offset the initial cost of the additional system. Integrating water-distribution lines for hydronic cooling systems and the sprinkler system would further reduce the initial cost.

The thermal storage capacity of the coolant also helps shift the peak to later hours. Because of the hydronic energy transport, the system has the potential to interact with thermal energy storage systems and looped heat-pump systems.

Most radiant cooling systems fall into three system-design categories. The one used most often is based on aluminum panels with metal tubes connected to the rear of the panels. A sandwich design allows the necessary flow between the panels, increasing the directly cooled panel surface and reducing the differences in surface temperature.

A system that provides even surface-temperature distribution consists of cooling registers made of small plastic tubes placed close together. The registers can be embedded in the plaster or mounted on ceiling panels. The flexibility of the plastic tubes makes this system perhaps the best choice for retrofit applications.

A third system uses cooling registers embedded in a concrete ceiling. This component cooling system uses the thermal mass to phase-shift the room's cooling requirements and remove the stored energy at times when ambient conditions allow more efficient heat removal. It is particularly well suited to operation during off-peak hours and is designed to be combined with alternative cooling strategies (such as night cooling).

Although radiant cooling has already been applied in the U.S., it has never become commonplace. In Europe, it was more or less abandoned after some applications in the 1930s and 1950s. However, user complaints about all-air systems changed designers' attitudes toward radiant cooling and led to new system designs with better temperature controls. These new developments have led to more common use in Europe.

Together with efficient ventilation systems and humidity control, radiant cooling systems provide several advantages over conventional HVAC systems: draft-free cooling, reduced space requirements, increased indoor air quality, reduced energy consumption for heating and cooling, and cost-effectiveness (if cooling loads are above 50 W/m^2).

DESIGN OF A FOLLOW-UP STUDY OF SICK BUILDING SYNDROME

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Sick building syndrome (SBS) is now widely recognized as a significant problem, particularly in office buildings. SBS is characterized by an unusually high prevalence of health symptoms and health complaints from the buildings' occupants, who generally believe their symptoms are caused by the indoor environment (especially air pollution). Increased ventilation, with associated increases in energy use and peak power, is one of the few options available to building operators seeking to prevent or reduce SBS problems; however, the efficacy of this common response to SBS has not been clearly demonstrated. To develop energy-efficient solutions to this problem, which impairs worker health and which may decrease productivity, we need an improved understanding of its causes.

In summer 1990, we completed a Phase I survey in 25 spaces within 12 San Francisco-area office buildings. Questionnaires were used to determine the prevalence of health symptoms and to collect information on the individuals, their jobs, and their workspaces; inspections and measurements were the basis for information on buildings and environmental conditions. The Phase I data indicated that occupants of air-conditioned and mechanically ventilated buildings had a higher occurrence of symptoms associated with SBS than occupants of naturally ventilated buildings.

Other factors associated with increased prevalence of one or several symptoms included high job stress (reported on the questionnaire), use of carbonless copies, new carpets (less than one year old), any carpet in the test space, and no window within 15 feet of the workstation. No measured environmental parameter was clearly associated with an increase in symptom prevalence.

SUMMARY OF STUDY DESIGN

The buildings that were studied in Phase I will be the subject of further research in Phases II and III. Phase II activities planned for fall 1992 are limited to inspections and low-cost measurements that yield information that can be used in conjunction with the Phase I symptom data; permit a more efficient and directed third phase; or provide valuable experience for future research. Phase III, scheduled for summer 1993, is intended to be a much more intensive investigation that includes substantial measurements and, similar to Phase I, administration of a questionnaire on health symptoms and personal characteristics.

The hypotheses tested in Phase III, however, are much more in depth than those tested in Phase I. We generated and selected for study 11 hypotheses, some with associated subhypotheses, about the causes of work-related symptoms. The following are brief statements of these hypotheses:

1. Ventilation systems emit volatile organic compounds (VOCs), microbial agents, and fibers that elicit symptoms.

2. Occupant exposure to pollutants that accumulate on indoor surfaces elicits symptoms.

3. New carpets (or components of carpet installations) emit VOCs that cause symptoms.

4. Inhalation of specific bioaerosols is a source of symptoms.

5. A decreased outside air ventilation rate is associated with increased symptom prevalence.

6. Formaldehyde and ozone cause sensory irritation and respiratory problems.

7. Elevated respiratory symptoms due to gaseous contaminants can be predicted by a mouse bioassay.

8. An increased noise level is associated with increased occurrence of symptoms.

9. Flicker from lighting is associated with headaches.

10. Toner particles emitted by photocopiers and chemicals on photocopies cause skin irritation.

11. Carbonless copy paper releases organic chemicals that cause respiratory problems.

Detailed research plans have been developed for evaluating each hypothesis. Phase II activities range from direct tests of hypotheses (collection and correlation of data to Phase I symptoms) to evaluation of proposed protocols for Phase III measurements and data collection. Planned Phase III activities include focused selection of study populations, extensive measurements, administration of a questionnaire, and regression analyses to evaluate the data.

IMPROVED ENERGY EFFICIENCY AND REDUCTION OF WORKER EXPOSURE IN INDUSTRIAL FUME HOODS USING AN AIRVEST

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Walk-in fume hoods (also called *spray booths*) are widely used in industry for removing airborne pollutants resulting from localized production activity, such as spray painting or welding. A typical fume hood consists of a rectangular enclosure with one open side; on the opposite side is a bank of filter pads, and beyond that is an exhaust fan.

Fume hoods remove pollutants quite effectively as long as no worker is standing in the open face, partially blocking the air flow. When that happens, however, an eddy develops in front of the worker. The eddy draws some of the pollutant, commonly generated near and in front of the worker, toward the worker's breathing zone. Increasing the face velocity of the fume hood increases the strength of the eddy almost proportionally, requiring large face velocities to reduce the worker's exposure to the pollutants.

AIRVEST OPERATION

The device (patent pending) developed in this project either eliminates the back-eddy downstream of the worker or ventilates the region of the eddy. It does this by positioning a small, portable manifold on the worker's back to draw air in and expel it from another small manifold, this one on the worker's chest. At high air-flow rates, the velocity of air exiting from the front manifold approximately equals the face velocity of the fume hood, essentially eliminating the eddy. Lower rates of air ejection from the front manifold do not eliminate the recirculating eddy, but ventilation of the region containing the eddy is greatly increased. Both modes of operation significantly reduce pollutant concentration in the worker's breathing zone.

The technique is also shown to be effective in the absence of a back manifold to draw in air; in this case, air is supplied to the front manifold from a stationary supply near the worker.

RESULTS OF THE EXPERIMENTS

Experiments were conducted to provide a proof-of-concept for operation of the airvest. These experiments used a heated, full-size mannequin and were conducted with a full-scale, walk-in fume hood. Sulfur hexafluoride, released at a slow, constant rate near and in front of the worker, was used to simulate pollutant generation in a work situation. The concentration of sulfur hexafluoride at several points near the worker was continuously sampled. Several experiments were conducted with different hood face velocities, various mass flow rates for air ejection from the front manifold, and with and without an intake manifold on the mannequin's back.

The experiments show a reduction in the breathing-zone concentration of the simulated pollutant by factors of 100 to 800. If such a large reduction in exposure is not warranted, the face velocity of the hood can be reduced—without increasing worker exposure—using this device. We calculate that in a Chicago-like climate, such a reduction would lead to annual energy savings (resulting from reduced energy use for conditioning make-up air) of about $1,200 per fume hood per shift.

AN ASSESSMENT OF THE ENERGY PERFORMANCE OF A RUSSIAN/GERMAN INDUSTRIALIZED HOUSING SYSTEM

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The aim of this project was to investigate the energy efficiency of a German/Russian modular housing system and determine whether it can improve on the energy-conservation abilities of conventional manufactured and site-built houses. This housing system uses an industrial technology originally developed by the Bison Company of Germany and since licensed to Energotechprom of Russia, formerly the Soviet Ministry of Power and Electrification.

Over the past three years, San Diego Gas and Electric Company (SDG&E) has shown an interest in the Bison/Energotechprom housing system as a way to produce low-cost, energy-efficient houses for low-income families. The housing system consists of prefabricated sandwich panels with wood-and-concrete boards on the outside and either insulation or wood on the inside. The roof, wall, and floor panels are identical except in thickness and exterior treatment and are reinforced by a lightweight steel frame (see Figure 1). The key components of the system are the composite wood-and-concrete boards, which are manufactured using an industrial process Bison developed more than 30 years ago.

In 1990, Bison shipped a sample building (built by Energotechprom) to the U.S. and exhibited it at the Responsible Energy Technology Symposium and International Exchange conference in San Diego. The building caught the attention of SDG&E as well as Secretary of Energy Watkins. Although attracted to this system as a potentially low-cost, energy-efficient alternative to conventional housing, SDG&E did not perform an engineering assessment of its energy performance or compare the Energotechprom house to conventional houses being built in California.

Building energy analysis for this project was done with the DOE-2 energy simulation program, using as inputs the manufacturer's specifications, blower-door test results, and measurements of a sample building. The simulated energy performance of the sample Energotechprom house was compared

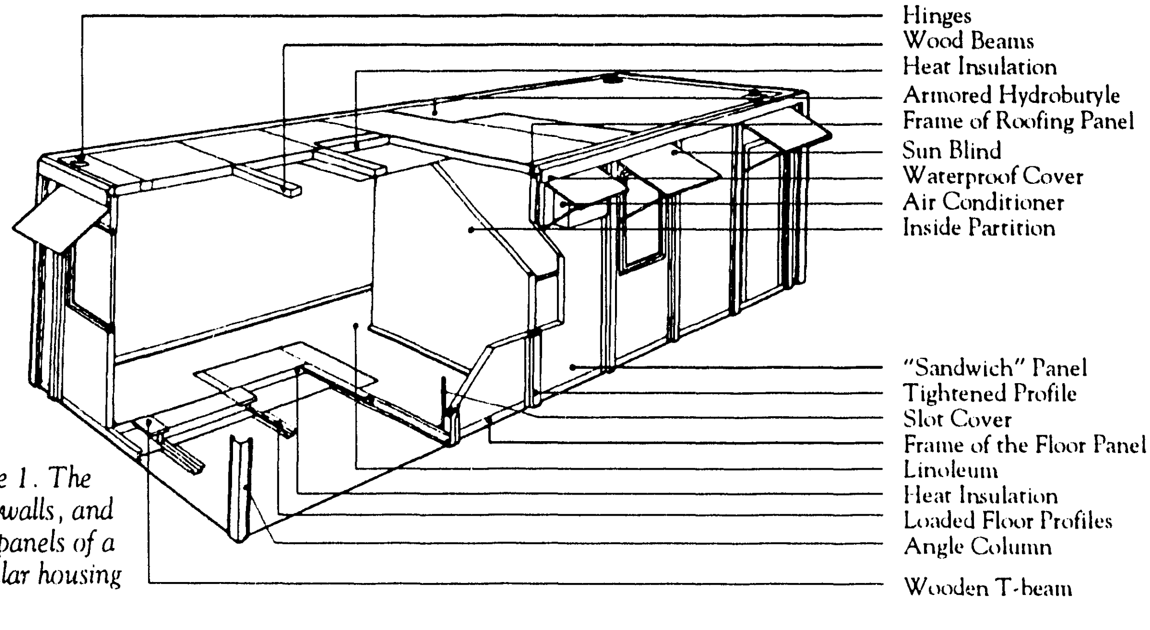

Figure 1. The roof, walls, and floor panels of a modular housing unit.

to that of conventional manufactured and site-built houses constructed according to current building energy standards in San Diego, Oakland, and Fresno.

Technical literature from Energotechprom indicates that this building's thermal integrity is substantially higher than that specified in the National Fire Protection Association (NFPA) energy standard for manufactured houses but somewhat lower than the Title 24 standard for site-built houses. (According to the California Energy Commission, manufactured housing is not subject to Title 24 building energy standards.) Blower-door tests showed that the sample building is fairly tight (0.60 air changes per hour), especially when considering its greater surface-to-volume ratio (570 ft^2).

Computer analysis shows that the Energotechprom house uses 23 to 45% less energy than the NFPA standard specifies. Compared to the Title 24 standard, however, the house uses the same amount of energy in San Diego, 42% more heating in Oakland, and 35% more heating and 13% more cooling energy in Fresno. The Energotechprom housing system performs relatively better in San Diego because the thermal mass of the wood-and-concrete boards allows the building to coast through many of the mild heating and cooling hours. Sensitivity studies suggest that the Energotechprom system can meet or exceed Title 24 standards with two simple improvements: increasing the roof insulation from R-12 to R-22 and adding exterior window shading to reduce summer solar heat gain (see Figure 2).

An economic evaluation of this housing system can only be made if we know the construction and shipping costs. These will vary greatly depending on whether the prefabricated panels are manufactured in Russia, the U.S., or Mexico (as SDG&E once contemplated). Cost considerations aside, the current Energotechprom house has a boxy, institutional appearance that reduces its marketability. However, nothing intrinsic in the panel system would prohibit the prefabricated walls and roofs from being assembled more aesthetically.

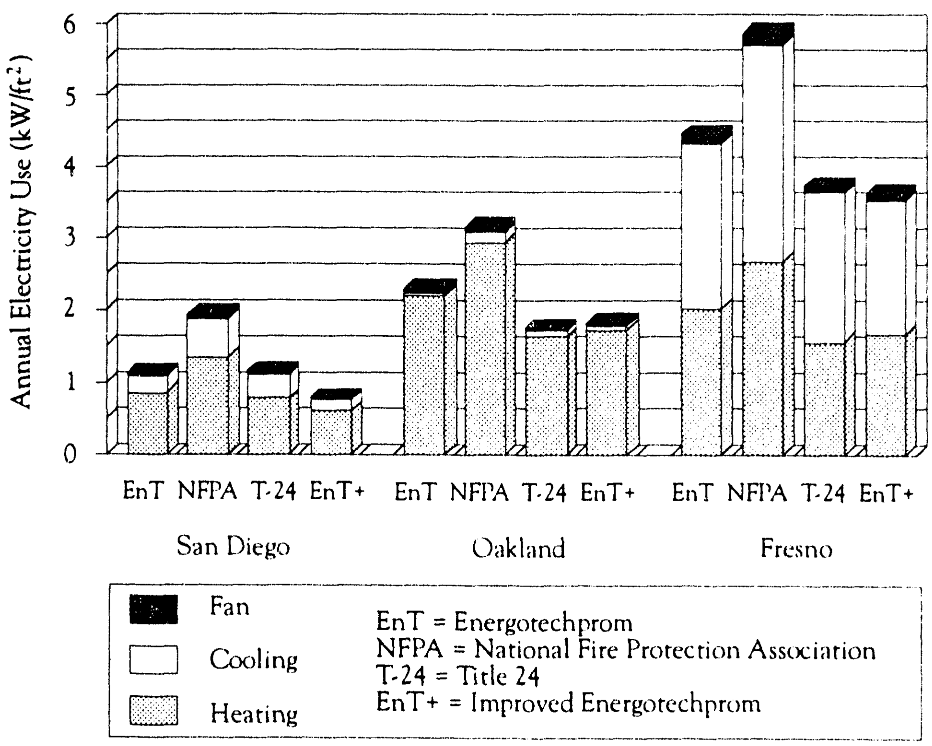

Figure 2. Annual electricity use of a 507-ft^2 house with a heat pump using three construction systems.

OPTIMIZING THE USE OF EMCS TECHNOLOGIES TO REDUCE PEAK LOADS AND ENERGY CONSUMPTION IN NONRESIDENTIAL BUILDINGS

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The overall goal of this project is to develop a methodology for using a concise simulation model in connection with an "intelligent" energy management and control system (EMCS) in nonresidential buildings to reduce peak load and total energy consumption. A new, large classroom building at California State University, Sacramento, was chosen as a site for developing and field-testing the procedures.

The anticipated EMCS will schedule heating and cooling not only in response to the current state of the building and to fixed schedules but also in response to a *prediction* of the building's response to expected driving forces for the near future (about 48 hours). This approach allows for the possibility of sophisticated preheating and precooling strategies. It also requires an energy simulation model small enough to fit into the EMCS computers, fast enough to get the job done without overburdening the system, and able to be fine-tuned to reflect the actual building and its systems. Such a model has been constructed as part of this study and is being tested.

TASKS

To accomplish the overall goal, we have carried out several intermediate tasks, some of which are significant studies in their own right. They fall naturally into four groups:

- The underlying simulation model and the procedure for fine-tuning it. The approach we have taken is patterned after the Building Element Vector Analysis and Primary and Secondary Terms Renormalization (PSTAR) techniques, though we devised new methods for handling solar loads. The model initially deals with the building at a level of detail similar to that of DOE-2, but it systematically and drastically reduces the number of parameters that are ultimately used in the simulation. The parameters are created based on the building specifications, and PSTAR-type techniques are used to fine-tune these parameters based on actual building performance.

- Using the building EMCS in a data-collection mode. Collecting the data necessary for development and field-testing of the process required significantly more sensors than were needed for control purposes. We also needed to develop a way to log and archive the data. Applying the techniques will require far fewer additional sensors than does this development effort.

- Using DOE-2.1D simulations to validate the underlying simulation model and predict building performance. Our approach to understanding the operation of a building such as this and developing an appropriate control strategy involves interplay between simulations and field data.

- Implementation of the concise simulation model in the building's own EMCS computers. If this methodology is ultimately to be useful, the necessary software should fit into actual commercial control systems and require little interaction with external computers.

ACCOMPLISHMENTS

The concise simulation code has been developed and tested against DOE-2, both on simple structures and on the actual building under test. The extra sensors have been installed in the test building and calibrated in place, and the EMCS is routinely sending data to our lab. The parameters of the model have been adjusted according to the results of a one-time thermal cycling test of the building. We don't have enough field data to state with assurance how well the simulation codes are predicting the actual performance of the building; however, a control strategy based on the results of the simulations has been devised (it has not yet been implemented in the building control system).

While the ultimate product is not yet complete, the pieces are in place and building data is routinely being received. The next step is to either fit the control process completely into the EMCS or devise a minimal interaction with an external PC that would actually carry out the algorithms.

INDOOR OZONE EXPOSURES AND ENERGY EFFICIENCY TECHNOLOGIES

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This exploratory project is investigating the effect of energy-efficient technologies for space conditioning on indoor ozone concentrations. The objectives of this research effort are to:

- Compile, review, and synthesize existing information on the relationship between building design and operation and indoor/outdoor ozone concentration ratios.
- Analytically investigate the importance and variability of selected key factors affecting indoor ozone concentrations.
- Provide the foundation for developing a cogent research agenda aimed at controlling human ozone exposure in California by modifying building design and operation.

BACKGROUND

Despite considerable efforts throughout the past two decades, most urban areas in California and the U.S. remain out of compliance with federal air-quality standards for ozone. For example, for the period 1986 through 1989, 10 areas in California exceeded the federal ozone standard. In Los Angeles, the standard was exceeded an average of 137 days per year during this period. When outdoor ozone levels are high, people are advised to remain indoors on the premise that indoor concentrations are lower than outdoor concentrations. Existing data indicates that the indoor/outdoor ozone concentration ratio varies from <0.1 to 0.8. Understanding this variability is critical to evaluating indoor ozone exposures.

Underscoring the importance of indoor ozone exposure is the fact that Americans spend as much as 90% of their time indoors and 50 to 90% of their time in residences. In addition, recent studies suggest that ozone exposures at concentrations below the federal standard may result in acute and chronic health problems. The following are the key issues associated with improving our understanding of indoor ozone exposure and its importance to California utilities.

Ozone Entry. The rate at which ozone enters from outdoors depends on the ventilation rate and on the degree of ozone scrubbing as air passes from outdoors to indoors. Air may enter buildings through a mechanical ventilation system, through leaks in the building envelope, and through leaks in the air-distribution network. However, the topic of ozone scrubbing efficiency in air-entry pathways has received negligible research attention.

Passive Ozone Removal. The two principal mechanisms of passive ozone removal are reaction with indoor surfaces and removal by indoor atmospheric chemistry. The removal rate at indoor surfaces depends on both near-surface air-flow patterns and material characteristics. Indoor atmospheric chemistry, although generally considered to be a less significant contributor to ozone removal, is complicated by the variability of the concentrations of other indoor air pollutants with which ozone reacts (such as nitric oxides and olefins), particularly in residences.

Active Ozone Removal. Indoor ozone concentrations may be reduced using active control devices.

The most common devices are activated-carbon filter beds, which have been used in some commercial buildings. The operational effectiveness, economics, and energy impacts of this control and other active control techniques, for both commercial and residential buildings, have received inadequate attention.

Energy Issues. Indoor ozone levels increase monotonically with ventilation rates, which in turn account for a significant fraction (approximately 15%) of the energy used in buildings. Although reductions in ventilation rates should lower ozone exposure as well as energy use, several issues complicate this relationship. Two of the more obvious issues are that most indoor pollutant concentrations are reduced by increased ventilation, leading to minimum ventilation standards, and that key energy-conserving cooling strategies (including natural ventilation and economizers) are associated with significantly increased ventilation.

Indoor ozone exposure limitations would discourage the use of natural ventilation and economizers, which could have important implications for energy use in California. Also, the use of active indoor ozone control systems would have clear energy implications, as well as peak electricity-demand ramifications, because ozone concentration peaks tend to occur at or near peak system demand.

RESULTS

The results of this project stem from our analysis of ozone scrubbing in building leaks and mechanical systems and our exposure analysis based on simulations of temporally varying ventilation and outdoor ozone concentrations. The ozone-scrubbing analysis showed that the principal determinant of the degree of scrubbing is the leak or duct surfaces' reactivity. More specifically, under typical flow conditions in leaks and ducts, most of the ozone would be removed if each collision with the surface resulted in removal; however, the probability of reaction varies between 10^{-4} and 10^{-7} for common materials, making the results extremely material-sensitive.

On the simulation side, our results clearly demonstrated the dramatic impact of natural ventilation, whole-house fans, and economizers on indoor ozone exposures in residences. It was clear that residential concentrations were basically determined by climatic conditions and ventilation practice. For example, indoor exposures in Riverside are a factor of five higher in June compared to July and August; that's because it is generally too hot to open windows in the later months. Similar results were obtained for a commercial office building in Los Angeles with an economizer.

MAJOR ACCOMPLISHMENTS

This effort has:

- Developed a computer code that simultaneously accounts for temporal variations in both ventilation rates and outdoor ozone concentrations. The code is used to compute peak and integrated indoor ozone exposures in residences and commercial buildings.

- Analyzed ozone scrubbing in residential building leaks, demonstrating the importance of the materials lining the infiltration pathways.

- Analyzed residential ozone exposures when natural ventilation is used to reduce cooling loads in different California climates, demonstrating the dramatic impacts of natural ventilation on indoor ozone exposures and the inadequacy of using average indoor/outdoor ratios to understand exposures.

- Analyzed the indoor ozone implications of economizers in Los Angeles.

MOBILE HOME PROJECT

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This project, which was completed in June 1992, combined the resources of government and private industry with the goal of developing and delivering state-of-the-art energy-conservation standards for mobile homes. Planning for this effort began in late 1989; sponsored jointly by CIEE, the Department of Energy (DOE), the California Department of Economic Opportunity, and California's four largest utilities, the project was designed to:

- Investigate and determine the best approach to weatherizing mobile homes, emphasizing the use of blower-door technology.
- Draft a set of material and installation standards for weatherization.
- Field-test the drafted standards.
- Produce finalized standards to be used as a model for weatherization programs.

The project employed seven contractors across the state to assess selected mobile homes and weatherize them using a blower-door methodology. The contractors learned to use this technology through a cooperative effort with Pacific Gas and Electric's state-of-the-art training facilities; they were also the first to field-test the mobile home weatherization standards. The standards are based on the nation's four regional residential building codes, the uniform mechanical codes, the DOE 1992 Weatherization and Material Standards, input from mobile home experts throughout the nation, and a plethora of mobile home specifications, reports, research, and standards.

A total of 450 mobile homes were assessed and weatherized during the project. Work was performed and data gathered on the following weatherization measures:

- Caulk bottom seam on double-wide units
- Install electrical outlet gaskets
- Install evaporative cooler vent covers
- Install furnace filters
- Replace return system
- Replace ducts
- Patch walls and floor
- Repair belly
- Seal boots
- Seal heater flue opening gaps
- Seal plumbing and electrical penetrations
- Seal registers to floor sheathing
- Seal water heater closet area
- Install storm windows
- Install sun screens
- Install weather-stripping
- Replace/repair windows.

Additional on-site testing was conducted on both occupied and unoccupied mobile homes in Chico, Willows, and San Diego, California. The goal of these coheat and cooling-load studies was to quantify the savings associated with various mobile home weatherization measures tested in a controlled environment. Both occupied and unoccupied mobile homes were retrofitted with data-acquisition equipment and used to monitor the energy reduction associated with specific weatherization measures.

FINDINGS

From a humanistic standpoint, the most important result of the study is that 450 homes of low-income occupants were weatherized; their energy bills will be lowered and their comfort levels increased. The other findings can be separated into three categories: material and installation standards, programmatic findings, and coheat and cooling-load analyses.

Material and Installation Standards. The major result of the project is a comprehensive, graphic-based Material and Installation Mobile Home Weatherization Standards Manual. The 250-page manual includes material and installation criteria for 15 weatherization measures.

Programmatic Findings. The second major accomplishment of the mobile home pilot is a measure-by-measure analysis of air infiltration and energy reduction. Contractors took blower-door readings before and after each weatherization measure was implemented, revealing the measure's effectiveness in reducing infiltration. In the process of recording this data, contractors also recorded the time and cost to implement each measure. This data, combined with results from the coheat and cooling-load studies and climatic profiles, resulted in a tabular ranking of each measure. The ranking is based on detailed labor and material costs, infiltration reductions, and calculated paybacks.

Combustion appliance data collected during the assessment portion of the project was sorted, analyzed, and tabulated into graphs that detail safety problems.

Producing the standards and preparing for field training allowed the development of detailed minimum ventilation standards and tables showing maximum allowable carbon monoxide levels. The tables are easy to read and specifically designed for field use.

Coheat and Cooling-Load Analyses. Findings from the coheat and cooling-load studies illustrate that the mobile home research by the Solar Energy Research Institute in Colorado applies somewhat to mild, arid climates. They also demonstrated that the Synertech MPR4 system and protocols can be used effectively for short-term monitoring but require modification and allowances for client interference. Another result is a demonstration that a working model of a coheat system can be assembled using off-the-shelf instrumentation equipment that mimics the MPR4 system with greater precision. The studies also showed that a coheat system can be modified to serve effectively as a cooling-load monitoring and measurement system.

The coheat and cooling-load analyses demonstrated the need to develop a small, inexpensive, accurate data-acquisition system using off-the-shelf equipment and new solid-state circuitry. This system could reproduce these studies in a variety of climates and provide data needed to determine the effects of specific weatherization measures.

METHANE RECOVERY IN ADVANCED INTEGRATED PONDING SYSTEMS

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The Advanced Integrated Ponding System (AIPS) is an efficient, low-cost wastewater treatment and reclamation method designed to exploit certain well-known—but rarely applied—physical, chemical, and microbiological processes. After two and a half decades of commercial use, AIPSs' energy savings and lower capital and operational costs are well-established. They accrue energy savings by completely converting settleable organic solids to methane, carbon dioxide, and stable residues, eliminating the energy expenditures associated with conventional sewage sludge digestion, handling, and disposal. Additional energy is saved in aeration: Using solar energy and microalgae grown in gently mixed, high-rate ponds, aeration in an AIPS has one-tenth the energy cost of mechanical aeration.

Previously built AIPSs have not recovered methane from their primary ponds; nor have they recovered the algal biomass that may be used for additional fermentation substrate to increase methane production by approximately 50%. Having added these elements to our intermediate-scale AIPS at the Richmond Field Station (see Figure 1), we are now seeking to further improve the energetics of the AIPS technology by recycling carbon and optimizing methane production, recovery, and conversion to electricity while minimizing greenhouse gas emissions.

Preliminary data gathered during the first few months of operation indicates a methane fermentation yield of 281 liters of methane per kilogram of

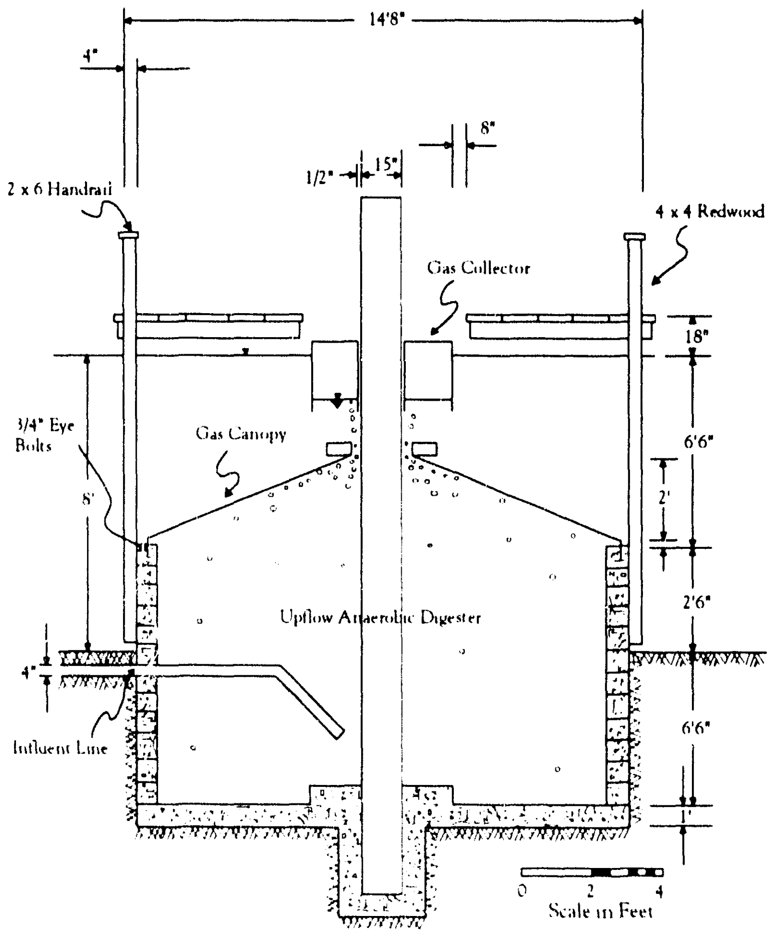


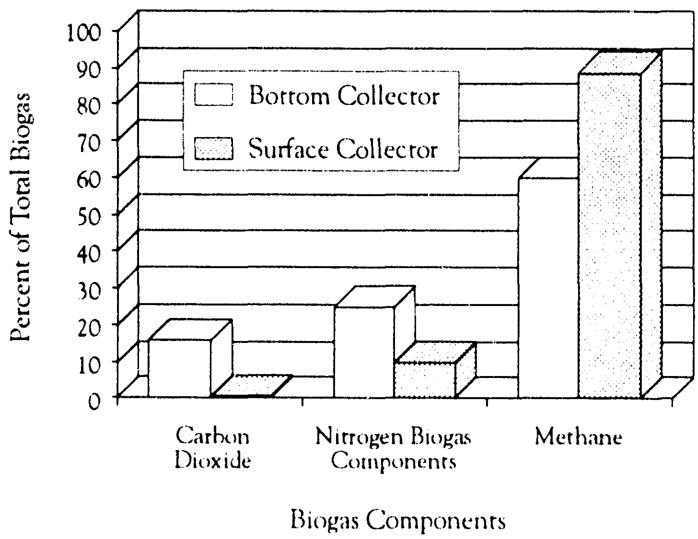
Figure 1. Cross section of an advanced facultative pond digester, gas collector, and sampling deck.

volatile solids introduced. Biogas produced in the in-pond digester is scrubbed as it rises through the overlying pond, increasing the methane component from 60% to 90% (see Figure 2). In terms of water reclamation, more than 90% of the soluble bio-chemical oxygen demand is removed, giving an effluent concentration of less than 10 mg/l; 95% of the ammonium and 60% of the soluble phosphorus are also removed. These values exceed the effluent quality of a typical activated sludge plant.

Successful demonstration of methane recovery, carbon dioxide recycling, and algae harvesting will further prove the energy advantages of treating sewage, animal wastes, and organic industrial wastes in AIPSs.

While not part of this CIEE-sponsored project, the data being collected over the next 18 months will more precisely quantify the advantages of AIPSs and promote the dissemination of this innovative technology for similar research efforts.

Figure 2. Changes in biogas as a result of scrubbing.



SPECTRALLY SELECTIVE GLAZINGS FOR RESIDENTIAL RETROFITS

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A large fraction of California's energy consumption and peak demand results from the need to cool residential buildings with high levels of solar heat gain transmitted through windows. Spectrally selective ("cool") glazings are a relatively new class of window products that admit a high proportion of visible daylight while excluding most of the heat gain arising from the solar infrared. The goal of this project is to determine the potential benefits of cool glazings and to explore methods for retrofitting existing clear, single-pane glass.

We have completed a parametric cost-effectiveness study of cool glazings in California climates using the DOE-2.1D program. The orientation of the glazing has the most significant impact on cool glazings' cost-effectiveness in a given climate, as shown in Figure 1. For the moderate California climates that have relatively high populations, such as Sacramento, Fresno, and Riverside, one can expect a total incremental energy savings of \$0.53 per square foot of glazing if all the existing windows (shading coefficient = 1.0) are retrofitted with a spectrally selective coating or film (SC = 0.5). For the hotter California climates that have a lower population, such as Red Bluff and Blythe, one can expect a larger total incremental energy savings of \$0.80 to \$1.38/ft^2-glazing.

We have completed a survey of existing commercial products and advanced materials under development. Ideally, the retrofit glazing should have a low SC and a high visible transmittance. Figure 2 shows the distribution of retrofit products in typical configurations as measured by these parameters.

Until recently, in the transmission range above 0.5, no laminate products were available with low SC because the edges of high-performance coatings in a retrofit installation are prone to corrosion. Manufacturers now perceive, however, that plastic laminates must catch up to their glass counterparts.

We have outlined a range of retrofit configurations. Replacing the entire window would be prohibitively expensive in most cases, although the new window would have the best available spectral selectivity, thermal conductance, and durability. Other options include adding a second pane with a spacer to create an unsealed insulated unit, gluing a coated plastic film to the existing glass, and replacing the existing glass with monolithic, coated, or laminated glass. Gluing a coated film to the existing glass is simple and inexpensive, but the durability of the films in this configuration is in question.

Based on the high proportion of existing residences built with clear, single glass and the results of our performance modeling, we conclude that retrofitted, spectrally selective glazings have

Figure 1. Incremental cooling electricity cost for a window of given shading coefficient relative to an unglazed wall in Fresno.

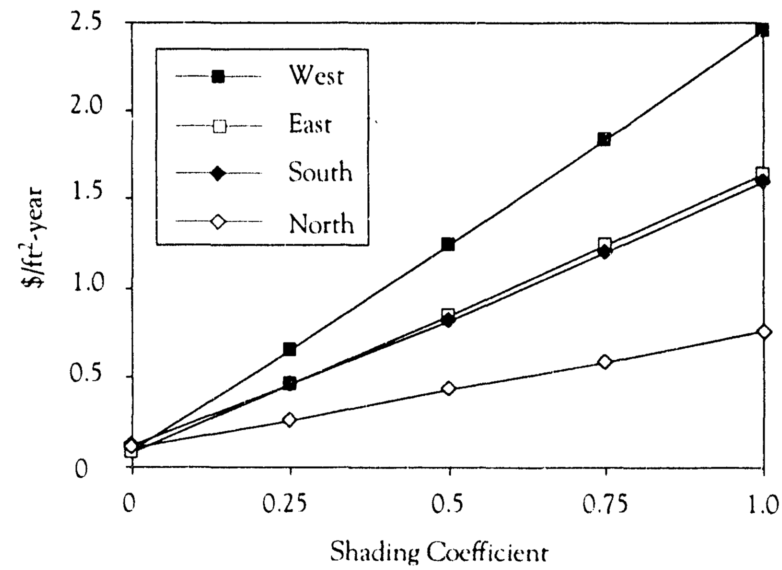
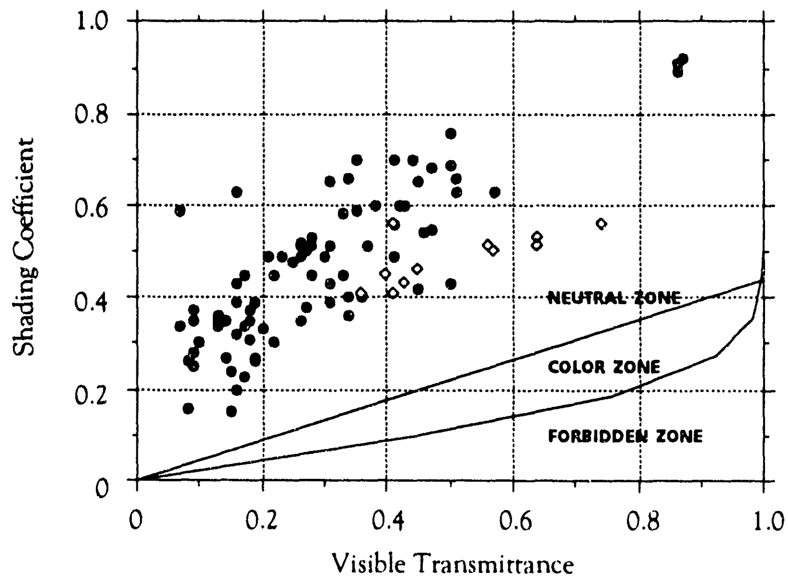


Figure 2. Spectral selectivity of coatings on plastic film that are laminated to clear or heat-absorbing glasses. Open symbols represent new products that have not been fully tested.



the potential to save energy in California. Incentive programs being considered by the public utilities would help make selective retrofits cost-effective. Some options can be used immediately, while others would require additional testing in the laboratory or in demonstration projects.

IMPROVED ENERGY EFFICIENCY FOR HVAC SYSTEMS VIA ADVANCED PROCESS CONTROL

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A significant portion of the nation's energy consumption is from HVAC systems for commercial and residential buildings. Traditional control systems for HVAC applications consist of simple, inexpensive sensors, actuators, and controllers. One of the disadvantages of such systems is that little information is available for evaluating the energy efficiency of buildings and HVAC systems. Although the traditional approach was adequate when energy was relatively inexpensive, it is no longer sufficient in view of the strong incentives for both demand-side management of energy consumption and peak-load reduction by utilities.

Contemporary HVAC control systems for large buildings include digital computers that can monitor large numbers of process variables and evaluate control-system performance. Recent publications have documented the energy-saving benefits of using computer-based energy management systems; more typical HVAC applications, however, perform only basic control calculations and simple diagnostic checks. Thus, the full potential of such computer-based control systems for energy management is not being met.

Dynamic analysis of HVAC data in real time can improve energy efficiency in several ways. First, the monitoring and real-time analysis of HVAC system data can be a powerful diagnostic tool for determining whether expected performance and actual performance are significantly different and for determining the reasons for such deviations. Many documented case studies show that potential energy savings were not realized due to equipment or sensors that were not operating properly. Second, modern fault-detection methods can be applied to determining a malfunction in the HVAC components; the energy costs associated with such malfunctions can be significant. A third benefit is that real-time monitoring and data analysis can facilitate the implementation of advanced strategies for process control and optimization, especially model-based control techniques in which the accuracy of the process model should be evaluated periodically.

In the proposed research, a novel strategy is being developed to improve control-system performance monitoring and fault detection of HVAC system components. This new approach integrates three types of information:

- Physically based knowledge, such as component characteristics and energy balances.
- Statistical quality-control charts.
- On-line updating of process models to reflect current conditions and equipment performance.

Modern fault-detection techniques based on statistical tests are being used to detect faults and identify significant changes in HVAC system performance. The expected benefits of such a strategy are decreased energy consumption, an improved building environment, and reduced operating and maintenance costs.

PROGRESS TO DATE

A preliminary screening of alternative fault-detection strategies has been performed to determine their suitability for HVAC applications. A representative HVAC system—a physical model of an air-duct/heating-coil system—has been selected as the simulation example. A MATLAB™ simulation of this system has been developed, and standard feedback controllers have been tuned. The closed-loop behavior of the coil, instrumentation, and control system has been evaluated for a wide range of operating conditions and faults.

These simulations provide the test data for the fault-detection techniques being developed and evaluated as the main focus of this study. Those techniques are simple, model-free signal processing (high, low, and rate-of-change alarm limits); a variety of statistical quality-control charts; and model-based fault-detection methods, including on-line parameter estimation via recursive least squares.

We are evaluating several levels of fault detection, depending on the type and amount of instrumentation available; that way, prospective users will be able to assess whether additional sensors would improve control and fault detection enough to warrant the additional cost. The results so far demonstrate that HVAC system faults and malfunctions can be detected during simulations of realistic operating conditions.

REDUCING ENVIRONMENTAL IMPACT AND ENERGY USE THROUGH WATER RECYCLING AND BY-PRODUCT RECOVERY IN FOOD PROCESSING

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The food industry uses a great deal of fresh water and generates a considerable amount of wastewater. The demands of urban areas and periodic droughts have driven up the cost of potable water as wastewater disposal regulations have become more strict; consequently, reducing the incoming and outgoing water in industrial operations has become increasingly important. Significant energy savings are also associated with decreased water use.

One way to reduce water use in a food processing plant is to recycle the water from one unit operation to another. Additional tanks control the flow rate, and an intermediate operation cleans the water. One such operation is membrane filtration, which offers the additional benefits of by-product recovery and energy conservation.

Before a new water-management scheme is implemented, it is helpful to develop a mathematical model of the system. This allows simulation of different schemes and a study of the system response under variable sets of conditions (involving the addition or elimination of lines, frequencies of breakdowns, cleaning schedules, and filtration methods). The most important factors in such simulations are the total water-flow rates and the final water quality for certain operating conditions.

A broader knowledge of the water management system, from the standpoints of both quality and quantity (flow rates) of the water, is necessary if the system is to be redesigned to reflect better management practices. As part of this study, three food processing plants—a peach cannery, a tomato cannery, and a pea-freezing plant—were monitored during 1991-1992 to measure the flow rates and quality of every unit operation's influent and effluent streams. In addition, water management in a food processing plant was simulated using actual data from the plant. The simulation was designed to develop strategies for in-plant recycling of water; other uses include critical-point control and shift schedules.

The water-management system was simulated using the EXTEND package on an Apple Macintosh computer. This model consists of nine blocks representing all unit operations, two blocks for the two intermediate tanks that control the flow between the unit operations, and one block to define the freshwater characteristics to be used.

The system was designed for a product flow rate of 1,100 lb/min (500 kg/min). In the simulation, this rate was maintained for the first two hours, then increased to 2,200 lb/min (1,000 kg/min) to observe the system's response. Two quality characteristics of the exiting water—COD and total solids—increased because solids accumulating in the tanks tended to contaminate the reused water.

The objective of this model was to simulate the global water inflow and outflow and the changing characteristics of water quality in the final outflow for different designs and conditions. This type of analysis is important when selecting the appropriate unit operations for the recycling system. Indirect uses include establishing the cleaning and maintenance schedules, determining how often the pumps are running and the level of the intermediate tanks, and obtaining a quantitative understanding of the membrane system applications and other water treatments.

The water accounting data from the three plants and the simulation model developed in this project are useful in identifying water-intensive unit operations. The model is particularly helpful in minimizing water use, thus reducing the energy required to process food.

PREPARATION OF HIGH-STRENGTH, LOW-DENSITY POLYMERIC INSULATION MATERIAL WITH ENVIRONMENTALLY SOUND FOAMING AGENT

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Hollow polymer microspheres play a significant role in high-strength, low-density aerospace composite and general structural applications. Precise geometric shape gives these particles exceptional stress-bearing qualities, especially when they are used as fillers for high-temperature thermosetting matrices. The objective of this project is to develop a novel blowing process for this potential insulating material using CO_2. With a lower greenhouse potential than CFCs and no ozone depletion potential, CO_2 represents a promising alternative foaming agent for this process.

We used an improved apparatus in our attempts to make hollow polymer spheres from polymerorganic solvent CO_2 systems. With a view-window pressure cell located below a nozzle connected to a sample cylinder, we can adjust the pressure drop (DP) across the nozzle. We found that DP was the key to controlling formation of the droplets. A higher DP value allows CO_2 to be released suddenly from the wet particles, which then burst into pieces; therefore, it is important to limit DP to less than 100 psia for suitably shaped spheres to form on the nozzle.

Because this process must be carried out with a homogeneous starting solution, we need to know the critical CO_2 pressure at which the second phase appears in the system. We measured the temperature dependence of the critical pressure and the volume change of the polymer solution due to absorption of CO_2 at that pressure. For a fixed concentration of polymer, a higher temperature gives a higher critical pressure. This critical pressure was used as the upper limit in the sample cylinder to prevent the second phase from appearing. The volume change of the polymer solution declines with higher temperatures or higher polymer concentration.

The particle morphology can be varied with different CO_2 pressures in the sample cylinder at equilibrium with a solution of polymer in organic solvent. Two kinds of hollow particles were obtained by using different CO_2 pressures in the sample cylinder. When the pressure is 900 psia, the particle has a porous, nontransparent wall and a specific gravity of about 0.3. When the pressure is 600 psia, the particle has a dense, transparent wall and a specific gravity of about 0.4. The diameter of the particles is about 2.0 mm. Measurements using a scanning electron microscope show that the average thickness is about 200 microns for the nontransparent wall and 220 microns for the transparent wall.

COMFORT-BASED CONTROL LOGICS FOR LOW-ENERGY COOLING SYSTEMS IN CALIFORNIA RESIDENCES

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Low-energy cooling systems—such as natural ventilation, forced ventilation, direct evaporative cooling, and two-stage evaporative cooling—are well suited to the coastal and semiarid climates in California. They take advantage of outdoor air's cool temperature and low humidity to provide cooling for buildings. These systems need very little electrical energy (a fan and/or a pump) to operate, but they do require occupant involvement. The actual indoor comfort and energy savings from these low-energy cooling systems are highly dependent on the control and operation of the system. Based on their thermal mass, window orientation, and geometry, residential buildings may require different operating procedures to achieve optimum cooling-system performance.

The objective of this exploratory project is to evaluate potential problems in the operation and control of these low-energy cooling systems and to propose control logic for greater energy-effectiveness and indoor comfort. Three coastal and transitional climatic zones—Santa Rosa, Long Beach, and Riverside—are being investigated.

The project involves the following research activities:

- Identifying control problems in low-energy cooling systems.
- Surveying the existing control techniques for operating these systems.
- Analyzing the basic control strategies in an effort to overcome the problems identified in existing operation.
- Deriving a control logic for these systems based on indoor human comfort and energy-effectiveness.

The results of this project will help homeowners and industry eliminate undesirable conditions associated with improper operations.

PROBLEMS IN EXISTING CONTROLS

Existing controls for ventilation and evaporative cooling systems are either too simple or too complicated. A simple on-off switch control relies on manual operation by attentive, sophisticated, knowledgeable users, while a complex control may incorporate several components that are potentially confusing to users.

Simple sensing devices do not respond adequately to the ever-changing natural environment. Actually, low-energy cooling systems require information on both indoor and outdoor conditions to provide maximum comfort. The humidity of the outdoor air is a key factor in evaporative cooling system performance; without knowing the outdoor humidity and the indoor mean radiant temperature, occupants may turn on the cooling system at the wrong time. The result may be wasted energy and indoor discomfort. In addition, due to the elevated air motion created by these systems, occupants may be misled regarding the need to operate them.

RESEARCH PROGRESS AND RESULTS

This project uses the modified DOE-2.1D building energy simulation program to examine the energy benefits and indoor comfort conditions of low-energy cooling systems under various controls. The program includes the heat and mass transfer of evaporative cooling systems inside the DOE-2 RESYS module.

Natural Ventilation. The basic control for natural ventilation is to open a window when the outdoor air temperature is more than 3°F (-16°C) below the indoor air temperature and is within the comfort zone. The minimum indoor condition is set at 72°F

(22°C) to avoid excessive cooling, and the maximum indoor condition is set at 85°F (29°C) with elevated air flow around occupants.

Major concerns regarding the natural ventilation strategy are the unpredictable nature of wind speed and direction and the exterior humidity. This project uses a ventilation FUNCTION inside the DOE-2 simulation with a house prototype of four equal-size windows in four cardinal orientations. The result will be a demonstration of indoor air temperature under different control sequences. Plots will also be presented to illustrate indoor comfort performance.

Forced Ventilation. Natural ventilation cannot effectively use cool outdoor air due to the chaotic wind conditions. A forced ventilation system can optimize the outdoor cooling potential by using a small whole-house fan. The control logic for forced ventilation simulation is similar to that for a natural ventilation system: Whenever a three- to five-degree difference exists between indoor and outdoor air temperatures, a whole-house fan will be used to provide a constant air change. Since a control is in place, the indoor and outdoor temperatures can be closely monitored and controlled.

Direct Evaporative Cooling. The control for direct evaporative cooling systems is currently nothing more than an on-off switch. Increased outdoor wet-bulb temperatures degrade the performance (both cooling effectiveness and comfort condition) of such systems. Due to the adiabatic process of direct evaporative cooling, it can also be viewed as a simple humidifier. If the outdoor air is already humid, the wet-bulb depression is ineffective in supplying desirable air indoors. In a semiarid climate, however, a direct evaporative cooler can use the nighttime outdoor air to cool the building in a ventilation zone.

In this study, the outdoor air temperature and humidity are examined in the control sequences. Smart controls are used to determine whether or not the system should be turned on.

Two-Stage Evaporative Cooling. A two-stage evaporative cooling system can be used as a forced ventilation system, a direct evaporative cooler, or an indirect/direct evaporative cooler. The controls for these systems are currently either proprietary information seldom found in literature or merely a set of toggle switches. Most manufacturers suggest enthalpy control devices, but such controls are too expensive for a low-cost cooling system.

An appropriate control should be inexpensive but "smart" in switching between ventilation, direct evaporative cooling, and two-stage evaporative cooling. The outdoor conditions (both temperature and humidity) should be monitored if the system is to provide indoor comfort and energy-effectiveness.

FUTURE WORK

Comfort-based control logic of low-energy residential cooling systems should be simple to operate and enhance indoor comfort. Without a simple, appropriate control mechanism with which to operate these systems, the user may be easily frustrated. Further research in this topic should address the basic issues in controlling low-energy cooling systems and the potential for developing comfort-based controls to optimize performance. Another goal is to provide greater indoor comfort quality through appropriate control design. With microchip technology becoming commonplace, a smart control for energy savings and comfort isn't far away.

FORMATION OF NITROGEN OXIDES IN INDUSTRIAL NATURAL-GAS BURNERS

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In recent years, air-quality regulations have substantially reduced the emission of nitrogen oxides from industrial natural-gas-fired burners. Burner manufacturers and combustion-modification specialists have used empirical input/output methods to develop a varied population of low-NO_x burners; new demands to improve air quality even further have resulted in both a broadened population of industrial sources required to use low-NO_x burners and a requirement to develop ultra-low-NO_x burners.

RESEARCH CHALLENGE

The research challenge is to develop design criteria for ultra-low-NO_x industrial burners while maintaining or enhancing burner combustion efficiency and overall system energy efficiency. To develop an ultra-low-NO_x burner, we need more than just input/output methods; we need to understand and systematically control the process of NO_x formation in the burner. This requires that we:

- Gather detailed information regarding the velocity, temperature, and species-concentration fields and turbulent transport in the burner.
- Determine the sensitivity of these fields and mixing processes to system geometric features and operating conditions.
- Develop active control methodologies for maintaining ultra-low-NO_x performance during practical operation.

To meet this challenge, we have adopted a team approach. Joining researchers at the University of California, Irvine, Combustion Laboratory are investigators at Lawrence Livermore National Laboratory, Sandia National Laboratory, and Energy and Environmental Research Corp. (Irvine, Calif.).

The technical approach has the following goals:

- Design, build, install, and operate a 100,000 Btu/hr model industrial gas burner with full optical access for visualization and laser diagnostics.
- Modify an existing subscale (10,000 Btu/hr) test stand that will allow immediate measurements in support of experimental protocol development.
- Develop and apply a novel laser diagnostic for the in-situ measurement of NO and NO_2.
- Acquire in-situ measurements to reveal the burner's aerodynamics and thermal and chemical fields as well as the fields' sensitivity to parametric variation.
- Modify a comprehensive code to incorporate a mixing model and methane, thermal NO, prompt NO, NO_2, and N_2O kinetics.
- Apply the code for guidance in designing the experiment.
- Use the code in conjunction with the experimental results to develop needed insight into the formation and control of NO_x in practical burners.
- Identify the boundary and operating conditions that minimize NO_x formation while maintaining or improving energy efficiency.
- Develop and apply active control methodologies for attaining and maintaining

high-efficiency, ultra-low-NO_x performance in practical systems.

To assure the effective transfer of technology, the industry (including gas suppliers, burner manufacturers, and low-NO_x combustion specialists) is actively participating in the development of designs and experimental protocols.

ACCOMPLISHMENTS

This project, which is cofunded by CIEE and Southern California Gas, began in June 1991. The emphasis during the first phase has been to design, build, and bring on-line the 100,000 Btu/hr research burner and test stand; modify and operate the existing subscale 10,000 Btu/hr burner; apply and demonstrate comprehensive modeling for the research burner; and develop and demonstrate the adaptation of degenerate four-wave mixing for the in-situ measurement of NO and NO_2. Each of these objectives has been accomplished.

FINDINGS AND FUTURE DIRECTIONS

Early analyses suggest that one of the keys to achieving ultra-low-NO_x emissions lies in tailoring the mixing of natural gas with combustion air under overall lean conditions.

The second phase will focus on screening and parametric studies, while the third phase will be dedicated to optimization experiments and demonstration of active control.

REDUCING LOSSES IN HYDRONIC DISTRIBUTION SYSTEMS WITH FLUID ADDITIVES

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Our investigations are aimed at determining the optimum approach to saving energy through implementation of drag-reducing additives in hydronic systems. These additives greatly reduce the energy necessary to pump heating or cooling fluids in thermal distribution systems. The overall objectives are to conduct a feasibility study of the proposed approach, quantify the savings in various types of systems, identify the best technology and the best additives, answer the remaining technical questions on implementation of these additives, and transfer this information to industry and relevant agencies.

PHASE I: FEASIBILITY STUDY

A detailed feasibility study was completed during the first phase of this project. The results and conclusions were presented at the 1991 CIEE conference and are described more fully in the Phase I final report. The overall conclusion of this phase was that the use of surfactant additives would likely enable us to save large quantities of energy in hydronic systems, at little cost and with relatively little difficulty. A number of technical issues needing further investigation were also identified during this study.

CURRENT PHASE: EXPERIMENTAL INVESTIGATIONS

Objectives. The objectives of the current phase are to build an experimental facility that will allow investigation of the fluid's behavior and, in particular, to answer the following questions raised during Phase I:

- How long does the fluid take to recover its full drag-reducing potential after flowing through hydronic components (such as pumps, valves, and fittings)?
- How does the fluid influence the behavior of such components?
- How does the pipe diameter affect the fluid's drag-reducing characteristics?

Achievements and Findings. All the findings so far indicate that the proposed additives meet or exceed the requirements, as determined in the first phase, for their implementation in hydronic systems. This confirms that the surfactant-additive approach promises to save pumping energy in hydronic systems. Some of these achievements and findings are summarized in the following paragraphs.

We have designed and built an experimental installation to investigate the behavior of fluids in and downstream from hydronic components. A computerized system of tubing loops, pipes, pumps, tanks, and measurement devices for flow, pressure, temperature, and power has been constructed, tested, and used in our experimental work. A system to measure heat transfer is also under construction.

We have conducted preliminary experiments to investigate the effect of control valves on the fluid's effectiveness in reducing drag. This issue is of interest because previous studies of polymeric additives raised the concern that a valve could dramatically degrade the drag-reducing effectiveness of the surfactant solutions over long distances downstream from the valve. Our experiments showed, however, that the fluid recovers its full drag-reducing effectiveness shortly after the valve, even for pressure drops across the valve that are well beyond those typical of practical HVAC applications. This finding suggests that the fluid will not be significantly degraded by control valves in actual hydronic systems, thereby removing a major concern about the implementation of these additives. Some additional experiments have also been initiated to determine the effect of fluids on the valve flow and pressure drop. The preliminary results suggest that these characteristics are not affected by the additives, implying that major control-system redesign would be unnecessary when the additives are used in hydronic systems.

Several experiments have also been conducted to quantify the flow characteristics of the surfactant solutions downstream from pumps and therefore determine the effect of a centrifugal pump on the drag-reducing effectiveness of the fluid downstream from the pump. Conversely, we also investigated the additives' effect on the pump characteristics; we found that the fluid does not appear to be permanently degraded by long-term (several months') recirculation through centrifugal pumps. We also found that the fluid recovers its asymptotic drag-reducing effectiveness only 50 diameters (for Re = 25,000, where *Re* is the Reynolds number) to 150 diameters (at Re = 150,000) after a centrifugal pump. The flow curve of the centrifugal pumps was observed to be the same for water and for the surfactant solution, which would simplify the implementation of the additives in existing systems and the design of new systems intended for surfactant solutions.

The pumps' efficiency appears to be improved, in some cases, by the presence of the surfactant additives. The increase in efficiency measured for one pump is approximately 5%. This energy savings would increase the estimated frictional energy savings calculated in Phase I and further enhance the attractiveness of the proposed approach. The cavitation performance of the pumps was also found to be enhanced in some cases by the presence of the additives. In summary, we believe that centrifugal pumps would pose no problem in hydronic systems where proposed surfactant additives are used.

Recent preliminary experiments show that pipe diameter significantly affects the nonasymptotic drag-reducing regime for these additives; however, the results show no permanent degradation. Our measurements will enable us to quantify this diameter effect and, in particular, determine the optimal additive concentrations and critical shear stresses beyond which the solutions behave again as Newtonian fluids. We will also begin heat-transfer measurements.

CONCLUSIONS

Our experiments have shown that the assumptions made during the feasibility study were indeed appropriate, provided favorable answers to all the questions raised during that study that have been investigated so far, and eliminated the accompanying reservations and uncertainties. Additional savings and benefits beyond the expected friction reduction have also been observed.

In conclusion, all the results obtained so far have confirmed and even enhanced the attractiveness of the proposed drag-reducing fluids as energy-saving agents in hydronic systems.

LOCALIZED THERMAL DISTRIBUTION SYSTEMS FOR OFFICE BUILDINGS

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The goal of this project is to quantify and improve the effectiveness and energy efficiency of localized thermal distribution (LTD), or task conditioning, systems for office buildings. LTD systems have the potential to improve the energy efficiency of air distribution by distinguishing between the energy and comfort requirements of local workstation environments and those of less critical surrounding spaces. Poor design can, however, result in LTD systems that are substantially less energy-efficient than conventional systems.

In surveys, office workers report that LTD systems significantly improve environmental satisfaction; one might anticipate increased worker productivity as a result. Because of this, the technology is now spreading rapidly, driven more by interest in occupant satisfaction than by concern for LTD energy performance. California would benefit if it could increase worker productivity without paying an energy penalty over current practice.

CURRENT-PHASE ACTIVITIES

During the current (second) phase of this project, continuing laboratory experiments investigated the thermal and ventilation performance of two commercially available LTD systems: the Task Air Module (TAM), a through-floor supply fan and diffuser manufactured by Tate Access Floors; and the Personal Environmental Module (PEM), a desk-mounted unit manufactured by Johnson Controls, Inc. These units were tested for a range of realistic office configurations and operating conditions in the Controlled Environmental Chamber at the University of California, Berkeley (UCB). The tests were performed collaboratively by researchers at UCB and Lawrence Berkeley Laboratory (LBL); UCB studied the thermal performance (distributions of temperature, velocity, and computed comfort), while LBL studied the ventilative efficiency (air-flow patterns, age of air, and particulate transport) throughout the space.

One of the major findings of the laboratory experiments resulted from tests comparing the performance of the original small, desk-mounted PEM supply nozzles with that of supply nozzles with three times as much flow area. The larger nozzles were fabricated so that tests could be conducted at relatively higher supply-flow rates without requiring unacceptably high supply-air velocities.

Using tracer-gas techniques, LBL researchers found that the PEMs provide true "task ventilation" (increased ventilation at the location of the occupant). With the larger nozzles and high supply-flow rates, the age of air at the return duct (representative of average room conditions) was about 60% greater than that at the breathing level of the seated occupant. This is the largest age-of-air ratio we have measured for any task ventilation system, including the TAM. Thermal measurements by UCB researchers found that under the same test conditions, the larger nozzles generally provided more comfortable conditions than did the small PEM nozzles.

In addition, preliminary whole-building energy simulations using the DOE-2.1E computer program were performed at Humboldt State University to compare the energy performance and operating costs of a prototypical new office building in California having a floor-based task ventilation system to the same building with a conventional ceiling supply- and return-air distribution system. We configured the simulations to investigate the effects of zoning and stratification as measured in the Controlled Environmental Chamber under low supply-flow conditions from the TAMs. Using a San Bernardino weather file, DOE-2 predicted a 13.5% reduction in cooling load for the task-conditioning building compared to the conventional building. Electrical energy use for space cooling was reduced by about 11%, resulting in a 4.4% reduction in total energy use.

The results indicate the potential to save energy and operating costs with a task-conditioning system that can be controlled to take advantage of stratification and zoning. More extensive DOE-2 simulations planned for Phase III will investigate a full range of parameters affecting LTD system performance.

FUTURE WORK

During the summer of 1992, we will conduct an industry survey aimed at improving our understanding of energy issues with respect to the current state of practice of LTD systems. Our list of contacts will include consulting engineers, equipment manufacturers, researchers, and other users of LTD technology. By discussing important design considerations with these contacts, we hope to explore their current positions concerning:

- The energy performance of LTD systems.
- Comfort and air-quality implications.
- Productivity implications.
- How these systems can be controlled and integrated with central HVAC systems.
- LTD system costs.
- Other factors that either support or hinder potential users' willingness to consider LTD systems in their building designs.

Work planned for the third phase will focus on two field studies in buildings with operational LTD systems. We expect one field-test site to use the PEM system and the other to use the TAM system. During these tests, we will perform long-term measurements (up to one month) of the LTD units' energy-use patterns as well as average thermal conditions in the supply and return ducts of the buildings' air-distribution systems.

In addition, short-term (week-long) measurements at up to 100 workstations in the buildings will characterize local thermal conditions and obtain occupant survey data describing comfort, satisfaction, and LTD system use patterns. The data gathered from the field studies will help put the results of the laboratory experiments and building energy simulations into perspective with the current operation and performance of LTD systems.

COLD-AIR DISTRIBUTION FOR OFFICE BUILDINGS

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Potential cost and energy savings were motivating factors in the development of cold-air distribution (CoAD) technology in commercial buildings, particularly when combined with ice storage. By distributing lower-temperature air (40°F to 50°F [4 to 10°C]) throughout the building, a CoAD system can take greater advantage of the chilled water (typically 34°F to 36°F [1 to 2°C]) produced by the ice-storage system. The colder temperature reduces primary supply-air volumes compared to a conventional 55°F (13°C) supply-air design while satisfying the building's cooling load. Fans and ducts can then be downsized, reducing first costs and operating costs and often saving valuable floor area and vertical height. Because fan energy use is lowered primarily during peak hours, peak electricity demand is further reduced.

Last year's research focused on assessing CoAD in California and identifying key research needs for the continued development of this technology in the state, leading to widespread applications of successful designs in terms of both energy and cost savings. Two major efforts have been undertaken for this assessment:

- Consulting engineers, equipment manufacturers, researchers, utility representatives, and other users of CoAD technology were surveyed. We used the information gathered to assess the current state of practice in California by producing a list of current California projects involving CoAD and the factors influencing the future development of CoAD.

- Whole-building energy simulations using the DOE-2.1E computer program were performed to investigate the energy performance and operating costs of a prototypical office building using CoAD (42°F [6°C]). The results were compared to the same building with two different conventional 55°F (13°C) air-distribution systems. Simulations explored the energy use and operating costs for CoAD with different ice-storage capacities (compared to economizer use) for different fan-powered mixing box designs and operating strategies and for three utility rate structures. Most of the simulations were repeated for three California climates—San Jose, Fresno, and San Bernardino—representing areas of potentially rapid growth in new office construction.

INDUSTRY SURVEY

The industry survey demonstrated that CoAD (and ice-storage) systems are still not being used widely in California. The number of ongoing or completed projects was rather limited. The variety of ice-making equipment reported for the listed thermal energy storage/CoAD projects indicates that the market is still relatively wide open; practicing engineers have not developed a strong preference for a few brands of ice-makers. Although CoAD systems are most effectively matched with ice-storage installations, CoAD without ice storage is also a viable option, particularly as a retrofit in a building that has experienced a significant increase in heat loads.

In most California climates, space heating in commercial buildings is not a significant issue; there were no reports of heating problems with CoAD system designs. A recommended strategy for handling heating conditions is to install fan-powered mixing boxes in perimeter zones and operate them only during heating mode to increase mixing of the warm supply air with the room air. The relatively small amount of time these fan units must be operated in California climates produces an almost negligible increase in total fan energy use.

As more designers and building owners become familiar with using ice-storage systems for load management, largely in response to utility incentive programs, CoAD will also be considered more often.

In its current state of development, however, significant energy-saving features of CoAD technology are not being used effectively in installed systems. This situation stems from consulting engineers' lack of confidence in the ability of CoAD systems to provide acceptable room air distribution, in terms of both comfort and indoor air quality, without fan-powered mixing boxes. We recommend additional research to address the major needs of CoAD technology and to support the development of new products and energy-efficient designs for systems using ice storage with CoAD.

DOE-2 SIMULATIONS

The following are the major conclusions from the DOE-2 simulations:

- In all three climates, annual cooling energy use for the three cases involving CoAD was always greater than the base case. The most energy-intensive of the four cases studied was 42°F (6°C) without storage; annual cooling energy use more than doubled compared to the base case.
- Fan energy use for the three cases involving CoAD always decreased compared to the base case. These savings helped but did not completely offset the cooling energy increases.
- Compared to the system configuration using CoAD without storage, the combination of ice storage (half or full) with 42°F (6°C) supply air always reduced cooling and total building energy use.
- The base-case configuration always produced the lowest total building energy use. However, with the relatively efficient system designs used in this study, the largest increase in predicted total building annual energy use was only 5.6% over the base case for 42°F (6°C) without storage in San Jose; the largest increase in total building energy use for an ice-storage/CoAD system (also for San Jose) was only 4.3% over the base case for 42°F with full storage.
- The reduction in peak electrical demand for the two ice-storage/CoAD systems (approximately -15% for half storage and -30% for full storage) contributed to lower annual operating costs compared to the base case when a favorable utility rate structure was applied (-8% to -11% for half storage, -13% to -17% for full storage). Since CoAD without storage reduced peak demand minimally, if at all, operating costs were always highest for this energy-intensive configuration.
- Economizer use played an important role in energy savings, particularly in mild, marine-influenced California climates. In San Jose, failure to use an economizer with 55°F (13°C) supply air increased the total building annual electrical use by nearly 7% and operating costs by 5% to 6%. The economizer penalty was so severe that, if it was not included in the base-case 55°F supply-air system (a surprisingly common practice in California, as discovered in the survey), the comparative energy picture for thermal energy storage/CoAD systems improved significantly. A sample simulation found that operating without an economizer in San Bernardino using full storage and 42°F (6°C) supply air used essentially the same amount of energy annually (a 0.3% increase), compared to the 55°F supply-air case without storage and without an economizer.
- Use of fan-powered mixing boxes increased distribution energy consumption over a wide range (from 2% to 123%), depending on the type and mode of operation.

CONSUMER DEMAND FOR NATURAL-GAS AND ELECTRIC VEHICLES

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The goal of this project, being conducted at the University of California, Davis, Institute of Transportation Studies, is to examine consumer demand for electric and natural-gas vehicles (EVs/NGVs). The study is now in its second phase; during the first phase, the following research activities were completed:

- Developed a theoretical approach.
- Conducted a five-day test-drive workshop for electric, natural-gas, and methanol-fueled vehicles at the Rose Bowl in Pasadena. Also conducted meetings of 11 in-depth focus groups made up of test-drive participants.
- Developed a research method for evaluating consumer response to the limited range and long recharge times of EVs.
- Interviewed 103 EV owners.
- Published a report estimating the probable size of consumer demand for EVs based on census data.

THE TEST DRIVE

The results of the test drive suggest that, without product testing, stated-preference studies and other opinion research may systematically underestimate the market for EVs and NGVs. Test-drive participants found the EVs and NGVs better than consumer magazines and the general media had led them to expect. We also found that the general population is highly supportive of EVs as a solution to air pollution and energy-security problems and is therefore willing to consider adapting to EVs' limitations. The most receptive workshop participants own specialized vehicles, such as light-duty trucks and small commuter cars, and vehicles in the size range of the EVs used in the test; they are 45 to 55 years old and have strongly patterned travel habits, making recharging a minor concern. Focus groups indicated that a campaignlike program on the part of government and industry would greatly reduce consumer uncertainty about the future of EVs.

Responses to NGVs reflected greater uncertainty and lack of information about the product than did response to electric and methanol vehicles. While EVs enjoy popular support as a solution to urban air pollution, NGVs were not understood as a potential solution. NGVs were most commonly selected as a second choice to electric or methanol; they were chosen after EVs when a clean vehicle was desired but a larger car was needed, and second to methanol vehicles when uncertainty and economics were most important. Overall, responses to NGVs were not as consistent as responses to the other two vehicles—that is, consumers might at one point say they were afraid of compressed gas, then later voice a preference for NGVs.

PIREG INTERVIEWS

We developed an interview method called PIREG (Purchase Intentions and Range Evaluation Games) to investigate in detail the household responses to a limited-range vehicle with a long recharge time. The technique combines one-week driving diaries of all household vehicles with a gaming technique derived from household energy-conservation games developed by Martin Lee-Gosselin of Laval University, Quebec. These games are conducted with consumer households whose demographic, travel, and purchase patterns fit our initial profile of EV owners. That profile is derived from the range limitations of EVs, household requirements for recharging infrastructure, and income. We further selected households that had recently purchased a new vehicle of roughly the same size and expected model type as the first-generation EVs being planned for the '90s. The goal of the games is to test various purchase options, such as 100- or 150-mile-range vehicles, 30-minute or six-hour recharge time, opportunity and home recharging, and even fuel-cell technology. The options are examined in the context of households' recent purchase and driving behavior. A household can see in detail how a 100-mile range would work and review daily decisions about when and where to recharge and which car to use when the price of gasoline varies.

We have completed interviews with 12 households and plan to interview a total of 15 to 30. Our findings agree with those of the test drive: The more information and education consumers have about limited range, the more likely they are to consider EVs an option. We also found that two of the seven households were not candidates for long-recharge vehicles because the intended vehicle for substitution in both households needed to be available for emergency business outside the normal range, and swapping of vehicles was not an option. Therefore, previous constraint studies failed to identify all households limited by range needs. The other five households could be ranked from probable to certain purchase of an EV depending on price. In general, to predict demand we need more information about travel behavior than has been requested in previous studies.

Households have not previously used two types of fueling systems with such different costs. PIREG allows researchers to probe potential responses to this new situation. When the price of gasoline rose to $5 a gallon in a gaming situation, households were highly motivated to shift most of their vehicle use to EVs, suggesting that under such price conditions the high initial cost of EVs could be justified.

PIREG interviews will be completed during the summer and fall of 1992, and the findings—along with the results of the test drive, focus groups, and separately funded surveys of compressed-NGV owners in Canada and New Zealand—will be used to develop a comprehensive survey measuring consumer demand for EVs and NGVs in California. The survey will be conducted in the fall of 1992, with a sample population from the survey being recruited for a multiyear panel study to begin in 1993.

ECONOMIC INCENTIVES FOR THE INTRODUCTION OF ELECTRIC AND NATURAL-GAS VEHICLES

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This research project addresses the forms of government intervention that may be used to introduce electric and natural-gas vehicles (EVs/NGVs). The primary focus of the work is the cost savings from using a marketable permit system (MPS) compared to traditional regulatory approaches to meeting current and future emission-control standards. The project is divided into two parts: In the first, marketable permits for introducing alternative-fuel vehicles are examined; the second addresses a permit system for the adoption of alternative fuels.

To estimate the costs of emission control with an MPS, we collected data on such costs for gasoline-powered vehicles. Car dealers for 12 vehicle manufacturers in the Sacramento area were surveyed from January through July 1991. They were asked to provide cost information on emission-control parts for a variety of engine families. Combined with information on manufacturer and dealer markups and assembly costs to estimate the total cost of emission control per vehicle, this data suggests that, on average, vehicle manufacturers spend about $840 per vehicle on emission control. This number varies substantially among manufacturers, with American producers reporting the lowest emission-control costs and European manufacturers reporting the highest. Total emission-control costs for new cars sold in California in 1990 are estimated to be about $1.3 billion. Data on the emission characteristics of conventional vehicles was obtained from California Air Resources Board (CARB) certification data, which is an important baseline for establishing the economic competitiveness of EVs and compressed-NGVs.

Cost functions relating the total cost per vehicle to the emissions cost per vehicle were estimated using the data collected for conventional vehicles. Because these functions varied widely by manufacturer and vehicle class, we built a simulation model of manufacturers' behavior in which manufacturers are assumed to minimize the costs of emission control subject to meeting an emission standard. The effects of emission averaging and trading on the costs are also estimated in this framework.

In our simulation model, we used the current certification levels rather than the true standards so that emissions would not exceed current levels. The cost savings estimated by the model could then be attributed to the MPS rather than to a worsening of air quality.

The first series of simulations using this model estimated the cost savings of using a permit system for gasoline vehicles to meet 1990 hydrocarbon emission levels. In this system, manufacturers were allowed to average emissions by vehicle class (small, medium, and large cylinder) and to trade emissions across manufacturers. Preliminary results indicate cost savings attributable to the permit system of up to $170 per vehicle, depending upon assumptions regarding changes in vehicle sales and the form of the cost functions.

In the second series, we simulated a permit system similar to the CARB's low-emission-vehicle program and estimated the value of emission reductions from clean-fueled vehicles. These values are found to be largest for the vehicles with the lowest emissions. The values will increase over time as emission standards are tightened, as long as the vehicle meets the standards in that period.

THE IMPACT OF ELECTRIC VEHICLES ON THE SOUTHERN CALIFORNIA EDISON SYSTEM

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The objective of this project is to study the impact of electric vehicles (EVs) in Southern California. The initial research focuses on Southern California Edison Company (SCE), which serves the electric needs of about 60% of Southern California. The following summary of the first-phase results is organized around 10 questions of interest to planners in California.

WHAT ARE THE KEY FINDINGS FROM PREVIOUS STUDIES?

We reviewed the findings from previous EV studies, focusing on six that were conducted in Southern California. These studies indicate that power generation to supply EVs would come largely from natural-gas-fired units. The investigators concluded that EV demands would tend to improve the overall shape of the electricity demand and allow utilities to operate more efficiently.

While these studies show that EVs would significantly reduce emissions of important air pollutants, they also indicate that large numbers of EVs alone will not lead to significant reductions in the peak ozone concentration in Southern California. This CIEE study does not contradict the findings of these studies; rather, it confirms and extends those general findings.

HOW MANY EVs MIGHT APPEAR IN SCENARIOS FOR SCE?

We considered scenarios in which either 1 or 2 million EVs might appear in the SCE area by the year 2010. The first scenario is especially interesting because it happens to correspond closely to recent EV forecasts presented to the California Energy Commission. One million EVs in the SCE area would correspond to 1.7 million EVs in the South Coast, or roughly 17% of the vehicle population expected by the year 2010. The 2-million-EV scenario implies 3.3 million EVs in the South Coast—in other words, every third vehicle would be electric.

HOW WOULD EVs AFFECT THE PEAK ELECTRIC LOAD?

An important element of the initial study is a detailed analysis of EVs' impact on electricity demands for the eight scenarios shown in Table 1. The examples show little impact on peak demand, which is a logical consequence of the 250-mile range assumed for EVs with advanced batteries. The sole exception to this pattern is the scenario in which EVs have less advanced batteries with a daily range of 150 miles.

HOW WOULD EVs AFFECT THE OFF-PEAK ELECTRIC LOADS?

EV demands tend to fall in the late-evening hours, when nighttime charging is done at the convenience of the customer. Little of this demand would be in the deep valley between 1 a.m. and 5 a.m.; this pattern occurs because nighttime charging is limited to three hours or less. The short charging intervals, in turn, are the logical consequence of EVs with a 250-mile range and a daily use of 40 miles. Furthermore, simple financial incentives to shift nighttime charging demands may lead to a worsening of the demand shape.

COULD DIRECT-CONTROL SYSTEMS IMPROVE THE NIGHTTIME LOADS?

The initial investigation considered the impact of "blind control" and "smart control" of nighttime charging. Blind control implies one-way communication; the utility would send signals to start the EVs' nighttime charging cycle. But because the control system could not receive information on the status of the EVs, the utility would have to send the signals without knowing the duration of the charging cycle. This limitation would cripple the ability of a control system to improve the shape of the nighttime loads.

A smart control system involves two-way communication. The utility can send signals to start charging, and information on the status of the EV can be monitored at the control center. That way,

Table 1. Electric vehicle scenarios.

#	Number of EVs	Year	Nighttime Charging	Daytime Charging	Batteries, Range, and Small Car Efficiency
1	2 million	2010	Customer convenience	Minimal	Na/S, 250 miles 4.17 miles/kWh
2	2 million	2010	Customer incentive	Minimal	Na/S, 250 miles 4.17 miles/kWh
3	2 million	2010	Smart control	Minimal	Na/S, 250 miles 4.17 miles/kWh
4	2 million	2010	Customer convenience	Some	Ni/Fe and Pb/acid 150 miles 4.17 miles/kWh
5	1 million	2010	Customer convenience	Minimal	Na/S, 250 miles 4.17 miles/kWh
6	1 million	2010	Smart control	Minimal	Na/S, 250 miles 4.17 miles/kWh
7	50,000	2000	Customer convenience	More	Ni/Fe and Pb/acid 150 miles 4.17 miles/kWh
8	500,000	2000	Customer convenience	More	Ni/Fe and Pb/acid 150 miles 4.17 miles/kWh

the control center can begin charging the EVs later in the morning hours and obtain a better blending of the EV loads with SCE's regular loads. We found that relatively flat demand profiles could be obtained for typical days in both the summer and winter months.

HOW MANY EVs COULD THE EXISTING RESOURCE PLAN ACCOMMODATE?

Two million EVs could be accommodated within SCE's existing long-term plan, provided the vehicles are subject to smart control. The existing resource plan could accommodate 1 million EVs, regardless of whether their nighttime charging occurs at the customers' convenience or under smart control. These accommodation levels are surprisingly high compared to results from previous studies.

WHAT GENERATING RESOURCES WOULD SERVE THE EV LOAD?

This study confirms what previous investigators have found: Roughly 90% of the extra electric energy will come from burning natural gas, with the remaining 10% provided by a mix of coal-fired generation and economy purchases.

HOW WOULD EVs AFFECT THE UTILITY'S OPERATING COSTS?

Two million EVs would raise SCE's annual operating costs by around $1.9 billion, an increase of 22%. Payments for natural gas would account for the majority of this increase. Higher payments to qualifying facilities (QFs) are second to natural gas in accounting for the higher operating costs. Even though QFs are not projected to supply any of the energy needed for EVs, total payments increase because of marginal cost contracts. Marginal costs are driven upward in EV scenarios, particularly if smart control permits the utilities to "remove coal plants from the margin."

HOW WOULD EVS AFFECT THE AVERAGE ELECTRIC RATE?

The impact on SCE's average electric rate was estimated for each of the scenarios in which the EVs could be accommodated within the existing long-term plan. The calculation assumes that EVs do not affect SCE's fixed costs, and it ignores utility spending on infrastructure, distribution systems, and incentives. Two million EVs under smart control could lower SCE's long-term average electric rate by 2.9%; the average electric rate would be reduced by 1.2 to 1.5% in the scenarios with 1 million EVs. These reductions are well below previous estimates. We attribute the smaller rate reductions to the pivotal role of QFs.

WHAT ARE THE IMPORTANT QUESTIONS FOR FURTHER RESEARCH?

The next phase of research will consider additional scenarios to stretch the range of circumstances beyond the examples shown in Table 1. The new scenarios will consider hybrid EVs, EVs with a fast recharge, and EVs with higher daily travel.

As in the previous analysis, the new scenarios will be examined to learn the impact on SCE electric loads, on the likely operation of SCE's planned generating units, and on the need for additional generating capacity beyond the units specified in the resource plan. We will also examine the impacts on SCE's annual operating costs and the average electric rate.

The most important topic for further study involves utility incentives to promote the sale and use of EVs. Whereas the previous analysis assumes a given scenario will materialize without utility support, the next phase will analyze incentives to encourage EV use. Utility incentives might take the form of investment in supporting infrastructure, low electric rates, and direct financial incentives to lower the purchase price of an EV. The question at the center of the new research is whether the utility can finance these incentive programs through the improved operational efficiency that will result from significant market penetration of EVs.

EFFICIENT THERMAL ENERGY DISTRIBUTION IN COMMERCIAL BUILDINGS

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The overall goals of this project are to identify the largest energy savings opportunities in the thermal energy distribution (TED) systems used in commercial buildings in California and to perform the research needed to achieve those savings.

The objectives of the first-phase efforts are to:

- Identify the prevalence of each major type of thermal distribution system in existing and new commercial construction.
- Quantify the typical energy performance and peak-load impacts of those systems.
- Use available energy-analysis methods and performance data, along with a survey of design engineers, to identify the significant factors (inadequate design tools, construction practice, operating strategies, and so on) contributing to poor distribution system performance.
- Identify research or technology transfer needed to achieve the identified savings.

BACKGROUND

The first two phases of the multiyear research project Thermal Energy Distribution in Buildings consisted of four subprojects: one directed toward residential buildings and three toward commercial buildings. As the residential building population is relatively homogeneous, the only major difference being between single-family and multifamily, the appropriate direction for research has been relatively easy to define.

In the commercial sector, however, the variability in building types, system types, and operating characteristics is dramatic; thus, the prioritization of research topics has been less than systematic. Moreover, due to the large number of options for thermal distribution systems in commercial buildings, new ideas for savings opportunities continually arise. At this stage in the project, it seems appropriate to step back and look at the larger picture with the objective of identifying the largest and most cost-effective savings opportunities.

The term *thermal distribution system* refers to all equipment and pathways between the source of heating or cooling and the point of use (such as delivery of air to room or delivery of water to coil). Typical distribution media are air, water, steam, and refrigerant systems. Of these, air systems are by far the most popular and have the largest number of variations.

There are several reasons to evaluate these systems more systematically in commercial buildings:

- The issue of thermal distribution efficiency has not received adequate attention by the building energy research community.
- Anecdotal stories and case studies indicate that small commercial buildings suffer from many of the same inefficiencies that have been uncovered in residential systems.
- The potential for energy savings associated with increasing thermal energy transport efficiency is much larger in

commercial buildings. For example, approximately 35% of the energy consumption associated with a large air-distribution system is due to transport; a hydronic system transporting the same thermal energy would require less than 5% of the energy used to transport air.

- Many options are available for commercial building thermal distribution, and we need a way to identify and prioritize the energy savings opportunities.

PLANNED ACTIVITIES

During the first phase of this project, we will perform a scoping study to determine the most significant causes of energy inefficiencies in the commercial building TED systems found in California construction. Our technical approach will include a literature review, an industry survey, and energy analyses of a full range of thermal distribution systems in commercial buildings. This effort will lead to an assessment of the research and development opportunities for saving energy in the design and operation of commercial building TED systems.

Based on our current understanding of the situation, the technologies that we expect to examine in detail include:

- Various forms of hydronic distribution systems as replacements or supplements to air-distribution systems (such as flexible hydronic piping for localized thermal distribution systems, radiant-panel heating and cooling with hydronic distribution, and distributed water-to-air heat pumps tied to a hydronic distribution system).

- Retrofits of small commercial building distribution systems, including both thermal and transport-energy issues.

- More efficient fans, motors, and pumps as well as reduced frictional losses.

- Integration of design and energy simulation tools for large commercial buildings (for both air and water systems).

- Improved commissioning practices and controls for both air- and water-distribution systems.

In subsequent phases, we expect to carry out additional energy analyses and develop new approaches to improving the energy performance of commercial building thermal distribution systems, including design tools, construction practices, retrofit options, and operating strategies. Field measurements will be made to support our assessment of energy performance and to demonstrate the effectiveness of proposed energy-conserving measures. Research needs will be identified and pursued to achieve the potential energy savings identified. Energy-efficiency guidelines and other results and recommendations will be disseminated to the building industry, utility companies, and other users of thermal distribution technology.

PEAK-DEMAND IMPACTS OF RESIDENTIAL COOLING

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The goal of this project is to develop demand-side management (DSM) program strategies for residential cooling that address both peak-demand issues and energy issues. The specific objectives of this work are to:

- Modify existing detailed simulation tools to accommodate time- or load-dependent variations in the performance of DSM program options for residential cooling—for example, high Seasonal Energy Efficiency Ratio (SEER) air conditioners and duct-system retrofits.
- Use those tools to break down the loads and inefficiencies contributing to system and power-distribution peak electricity demand.
- Use laboratory and field-test data (including load research data) within the detailed simulation tools to analyze the electricity-demand implications of DSM program options addressing residential cooling.
- Use field studies to obtain primary data on the field performance of residential HVAC systems and envelopes, including peak-demand performance.
- Develop simplified analysis tools and standardized demand performance characterizations for residential HVAC system and envelope components.

BACKGROUND

The cost-effectiveness of utility DSM programs for residences is generally examined on the basis of energy savings and demand reduction. In fact, the cost to the utility and ratepayers of peak demand (both system and local transmission and distribution) is particularly dramatic for residences, for which air-conditioning electricity demand is large and occurs during only a few hours of the year.

Various groups have assessed the demand-side potential of residential technologies from the point of view of energy savings and demand savings; however, the degree of sophistication and understanding of the issues and the data needed to verify the field performance of cooling technologies and retrofits have not been available. In many instances, the peak-load impacts of many DSM measures are assumed to scale with their energy savings. This presumes that the measures have the same performance under average and peak conditions, when in fact the ratio of percentage peak-load impacts to percentage energy-consumption impacts can be significantly higher or lower than unity.

As an example, sealing duct leakage in single-family residences has been shown to save energy. However, the peak-demand impacts of that sealing remain unclear. Simulations indicate that duct leaks have disproportionately higher energy penalties under peak cooling or heating conditions, implying that the peak-demand benefits of sealing should be disproportionately higher than the average energy-savings benefits.

On the other hand, depending on the degree of oversizing of the air conditioner in the house in which the ducts are being sealed, the utility may realize only a fraction of the nominal peak-savings potential. In a house that was undercooled on peak days, the owner is likely to "take back" many of the duct-efficiency improvements in the form of improved comfort during the hours of peak cooling energy demand.

A related example is high-efficiency air conditioners, which are generally characterized in DSM programs by their SEER. The problem in this case is that although SEER might be a reasonable indicator of annual energy consumption, it is not necessarily a good indicator of peak-load performance. The peak-demand implications of these air conditioners depend on the measures taken by the manufacturer to improve SEER, some of which do not significantly improve the unit's performance under extreme temperature conditions.

These examples are by no means unique; the same issues are germane to most residential space-conditioning DSM measures in both new and existing construction.

In the long term, we need to evaluate the economic performance of utility DSM programs based on all of their energy-use and demand impacts. This includes their impact on local distribution peaks as well as on the system peak. To evaluate these impacts accurately, we need improved analysis tools and data.

PLANNED ACTIVITIES

The proposed effort is restricted to DSM technologies specifically targeted at reducing residential space-cooling consumption, focusing primarily on high-efficiency air-conditioner and duct-system issues. The approach comprises five principal activities: simulation, measurement, analysis, synthesis, and management. Specific activities include:

- Acquiring manufacturers' data on capacity and efficiency variations, with temperature, of standard and high-SEER central air conditioners.

- Using existing load-research data to characterize the oversizing and occupant-control scenarios of typical residential installations.

- Modifying and using the DOE-2 duct-simulation codes to examine average and peak-demand impacts of residential cooling technologies (including the use of heat-storm data to simulate peak-demand conditions).

- Developing and using a data acquisition and analysis protocol for a field study of air conditioner peak-load performance, analysis and synthesis of field measurement and simulation results, and development of standardized characterizations of the peak-load performance of residential cooling options.

DEVELOPMENT OF A RESEARCH AGENDA FOR COMMERCIAL COOLING SYSTEMS

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This effort was initiated as part of CIEE's topical research plan for Commercial Cooling Systems (CCS). Current CIEE research efforts in this Building Energy Efficiency program topic are focused on commissioning of Thermal Energy Storage (TES) systems. Phase I TES project findings concerning chiller performance formed part of the basis for this initiative to investigate the need for additional research in CCS. The CCS topic and the scope of this investigation are roughly defined as being concerned with chillers and other cooling equipment (as opposed to HVAC distribution systems, which form a distinct CIEE topic). Gray areas between these two topics include evaporative cooling systems, ventilative (free-cooling) systems, and package units.

A CIEE scoping study typically includes investigation into the state of the art, an assessment of the research needs of CIEE sponsors, an assessment of ongoing research by industry organizations, recommendations for general utility priorities, and specific recommendations for CIEE research.

In this investigation, input was first obtained from all CIEE sponsors through meetings with individual in-house experts identified through the CIEE Planning Committee. Current focus areas are the result of this input plus ongoing consultations with regulatory agencies and industry experts, as well as assessment of research plans of other industry organizations (including the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Air-Conditioning & Refrigeration Institute, Electric Power Research Institute, and Gas Research Institute).

DEVELOPMENT OF AN AGENDA

Initial investigations indicate that current research efforts or research plans of other industry organizations include significant work in the current focus areas mentioned below. For many of the subjects, CIEE efforts will be limited to tracking and advisory participation in other research efforts. Collaboration or coordination may be called for in special cases. Recommended areas for initiation of CIEE projects will include those not fully addressed by other research programs, those where CIEE's resources (academic institutions and national laboratories in California) can complement existing efforts, and those that involve issues of particular importance to California.

Development of an agenda is also affected by work in other CIEE topic areas. CIEE is considering general work on commissioning, operations, maintenance, improved HVAC controls, performance monitoring, and improved societal/resource tests. Certain of these subjects could be considered on a technology-specific basis or on a general basis.

INITIAL AREAS OF INTEREST

Sponsor utilities expressed interest in the following areas:

- Evaporative cooling
- CFC alternatives
- Part-load performance
- Small/packaged systems
- Thermally driven systems
- Instrumentation/controls/monitoring
- Process cooling systems
- Total resource/societal tests
- Condenser/cooling tower systems
- Electric utility peak episodes.

CURRENT FOCUS AREAS

Evaporative and Ventilative Cooling. More knowledge concerning acceptable thermal environmental conditions (both comfort- and health-related) is needed, particularly with respect to the use of evaporative and ventilative cooling strategies. Trade-offs between potential positive and negative air-quality effects are a particularly interesting aspect of these systems. In addition, there is an apparent need for effective designs that use conventional cooling systems to supplement evaporative systems (specifically, systems that include direct processes). For any evaporative system in California, water performance is particularly important.

Condenser/Cooling Tower Systems. Better design and upgrading of condenser/cooling tower systems could significantly improve system performance. Improved water treatment and maintenance may be critical in optimizing performance and allowing the use of the most efficient condenser-side equipment. In particular, industry research groups have indicated a need for greater knowledge concerning the process by which alternative water-treatment methods may inhibit corrosion and scale. Nighttime use of condenser/cooling tower systems (possibly designed to achieve significant radiative heat rejection) in conjunction with variations on TES systems may be an important application. Again, water performance is particularly important in California.

Desiccant Systems. Interesting aspects of desiccant technology include the potential to supplement evaporative systems under peak cooling-load conditions, indoor air-quality effects, and the potential for using solar energy for regeneration.

Integration of CFC/HCFC Phaseouts With Demand-Side Management Programs. The overall economics of chiller/cooling-system upgrades are affected by both CFC/HCFC phaseout and demand-side management programs. Considering these agendas together (as well as factors such as maintenance) may reveal opportunities for accelerating progress toward individual goals.

Instrumentation/Controls/Monitoring. Development, demonstration, and deployment of robust instrumentation, controls, and monitoring equipment are key to optimizing system peak performance, minimizing part-load energy use, and ensuring persistence of performance. Technologies of particular interest include lithium bromide concentration and humidity instrumentation, flow metering, and adjustable-speed drives.

Weather Data/Design Processes. Improvements in weather data addressing heat storms, electric utility peaks, and humidity would substantially assist development of optimized designs. Better design processes, including chiller sizing practices, could also significantly improve system performance.

ENERGY-EFFICIENT, LOW-NO_x AND -CO BURNERS FOR RESIDENTIAL, SMALL INDUSTRIAL, AND COMMERCIAL GAS APPLIANCES: DIODE LASER DIAGNOSTICS

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One of the goals of this project is to develop an understanding of the physical and chemical processes that control the formation and fate of nitrogen oxides and CO in premixed combustion as it occurs in residential, small industrial, and commercial gas appliances. Another goal is to evaluate the impact of new, low-polluting residential gas appliances on outdoor air-pollution levels. The flames in these appliances are distinct from the large furnace flames being investigated by other researchers; the flames of interest here occur in residential and small industrial appliances, are usually laminar as opposed to turbulent, are premixed as opposed to nonpremixed, and are in close contact with a heat-transfer surface rather than far from wall interactions.

While NO has been considered the primary air pollutant produced by natural-gas appliances, recent studies indicate that other oxides of nitrogen, including NO_2, N_2O, and HONO, may be produced in significant, sometimes dominant amounts. These compounds can be important contributors to both indoor and outdoor air pollution. Little is known about how or why these compounds are formed in gas appliances. Emissions of CO, a product of incomplete combustion, have also been found to be significant in existing appliances, indicating a loss of efficiency and an increase in pollutant emissions from these appliances.

We are carefully measuring these compounds under controlled combustion conditions, using new techniques that avoid the artifacts introduced by extractive sampling. Modeling studies complement the laboratory studies.

We are studying the convective flames using laser-based diagnostics as well as Fourier Transform Infrared (FTIR) spectroscopy. Laser Raman scattering will produce profiles of temperature and major species concentration. Infrared diode laser absorption spectroscopy will yield part-per-million measurements of the pollutant species CO, NO, and NO_2. The laser diagnostics will allow nonintrusive probing near the heat-transfer surfaces.

We are also evaluating the impact on outdoor air-pollutant levels of introducing low-polluting, high-efficiency combustion appliances in the residential market. This is done by evaluating pollutant emission rate data from existing and new combustion appliances and analyzing strategies to reduce pollutant emissions from the residential sector.

PROGRESS IN PHASE I

We have constructed and are operating a research burner. Profiles of major species concentrations and temperature are obtained using the FTIR and thermocouples. The laser diode is now operating on the wavelengths relevant for CO; because the burner is axisymmetric, several line-of-sight CO concentrations are used for tomographic reconstruction of the CO profiles. After the CO profiles are measured, the diode laser wavelength is changed to allow analogous reconstruction of the profiles of NO and NO_2. These initial measurements are being compared with the numerical calculations.

ENERGY-EFFICIENT, LOW-NO_x AND -CO BURNERS FOR RESIDENTIAL, SMALL INDUSTRIAL, AND COMMERCIAL GAS APPLIANCES: COMBUSTION MODELING

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The objective of this project is to develop a numerical model that contains the essential chemistry and physics necessary to understand the results of the experimental portion of this program. The experimental component is concerned with performing laboratory studies of combustion occurring in premixed laminar flames in contact with surfaces. The goal is to build a robust model that industry can use as a tool in designing high-efficiency gas appliances with low emissions of CO, NO_x, and other nitrogenous compounds.

A modeling team has been assembled, and the first phase of the modeling study—concerned with modeling and sensitivity analysis studies of premixed laminar flames over a range of equivalence ratios—has been completed. We used the results of Phase I as a starting point for the gas-phase chemistry, to determine limitations of approximations for NO_x estimates, and to guide experimental planning and measurements.

An initial chemical mechanism consisting of 50 species and 256 reactions was used with the CHEMKIN Thermodynamic Data of 1991 as input to the Sandia National Laboratory Fortran Program for Modeling Steady Laminar One-Dimensional Premixed Flames. Species and temperature profiles were computed as a function of height above the burner for methane/air flames of equivalence ratios from 0.85 to 1.30 at atmospheric pressure. We then determined sensitivity coefficients, which are the partial derivatives of the system solution with respect to the rate coefficients of the individual reactions. The flame profiles and sensitivity coefficients indicated the roles of the prompt-NO mechanism and the Zeldovich chemistry in the production of NO at different equivalence ratios. Concentration profiles indicated that CO was high in all flames with an equivalence ratio of 1.0 or greater.

A reduced mechanism was achieved by eliminating species that satisfied the following criteria:

- The concentration was always less than 1.0×10^{-7}.
- The species was not involved in important reaction paths for prompt NO.
- The species (according to the sensitivity analysis) was not involved in the 50 most important reactions for NO production and destruction.

The reduced mechanism resulted in the removal of 11 species and 71 reactions. Flame calculations run with this mechanism produced NO and CO profiles over the entire range of equivalence ratios. In addition, we considered approximations for predicting NO that consisted of using Zeldovich reactions for the nitrogen chemistry, decoupling the Zeldovich mechanism from the hydrocarbon oxidation chemistry, and calculating the equilibrium of NO. Concentrations of NO determined with these approximations deviated substantially from the flame calculations with the full and reduced mechanisms.

Two-point boundary values of a flame in contact with a cold quenching surface were calculated for a hydrogen/air flame. The goal was to guide experimental design by determining the magnitudes of concentration gradients in the vicinity of the surface. The conversion of NO to NO_2 as a result of thermal quenching due to the surface was also determined.

In current research, sensitivity analysis and chemistry describing methane/air oxidation and the production of nitrogenous pollutants and CO are being added to the two-point boundary-value problem codes. Efforts will then be directed toward determining the fate of pollutants generated from premixed laminar combustion in contact with a heat-extracting surface. In conjunction with the experimental effort, future research will quantify the effects of surface reactivity on pollutant formation and destruction.

ENERGY-EFFICIENT, LOW-NO_x AND -CO BURNERS FOR RESIDENTIAL, SMALL INDUSTRIAL, AND COMMERCIAL GAS APPLIANCES: EXPERIMENTAL BURNERS

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Natural-gas appliances—both existing ones and the new, higher-efficiency devices—are indoor sources of nitrogen oxides and other nitrogenous species. Such sources must be considered in light of their impact on human health as well as their contribution to overall ambient levels. The latter may be important for those regions not in compliance with federal or state standards for NO_x and ozone. Recently, the Bay Area Air Quality Management District issued a rule requiring reduced NO_x emissions for residential water heaters in the district; this rule is similar to requirements in the South Coast Air Quality Management District.

Developing and studying experimental models of natural-gas appliances and post-combustion processes will enable industry to develop improved systems that meet regulatory requirements. These laboratory models will allow control of flame cooling rates, mixing with entrained gases, and post-combustion cooling and mixing. While conditions will be chosen to simulate those found in actual appliances, optical access to the processes will be emphasized so that nonextractive analysis methods as well as extractive sampling can be used.

The investigation will range from the high-temperature flame regime, in which high-temperature nitrogen and hydrocarbon chemistry are important, to the lower-temperature regimes characteristic of cooling that occurs near a heat-transfer surface. Information on the physical and chemical mechanisms for the formation of NO_2 and other nitrogenous species will be sought. Of particular interest are the mechanisms by which such species form when the flame or the product gases come in contact with cool surfaces, such as those associated with cooking utensils or heat transfer.

BURNER DEVELOPMENT

In the first few months of this project, we designed and built two laboratory experimental burners. The first burner is for the combustion of premixed fuel and air. The burner assembly has a modular design, with a circular base that attaches through mating flanges to the burner. Several different burners may be used with this common base; to date, two premixed radiant burners have been constructed for use with the base. The circular shape allows for homogeneous measurements and provides a convenient geometry for modeling, while the flat burner surface allows optical access close to the surface. A rapid quench surface can be installed above the burner to simulate the close proximity of heat-transfer surfaces in appliance burners. Previous work suggests that NO_2 formation is enhanced with thermal quenching rates of 10^5 to 10^6 K/s. Such quenching may be expected in the boundary layer that arises from mixing with ambient air or contact with cool burner components or cool surfaces in the flame or product gases.

The second research burner has been designed and built for the combustion of nonpremixed fuels. Its surface is a symmetrical square matrix of fuel and air holes. The burner was designed for mass flow rates of typical appliance burners and can be used to represent conventional appliance burners.

These experimental burners are designed to allow both extractive and nonextractive sampling and analysis methods. Hence, while combustion conditions were selected to simulate those found in actual appliances, optical access was also considered in the experimental design.

Current work involves extractive probe sampling with Fourier Transform Infrared (FTIR) spectrometry to analyze the combustion and post-combustion gases. Initial efforts are focused on CO, NO, and NO_2. One possible extension is the in situ application of FTIR. In other work, we have successfully used in situ FTIR to detect chlorinated hydrocarbons in the post-flame region of a combustor; additional analysis involves temperature measurement using thermocouples and infrared absorption.

ENERGY-EFFICIENT, LOW-NO_x AND -CO BURNERS FOR RESIDENTIAL, SMALL INDUSTRIAL, AND COMMERCIAL GAS APPLIANCES: RESIDENTIAL EMISSION MODELING AND FORECASTING

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One goal of many local, state, and federal agencies is to reduce outdoor air-pollution levels in California's South Coast Air Basin and other urban airsheds. Developing gas-fired burners that produce low levels of NO_x and CO would help reduce outdoor air-pollution emissions from gas-fired appliances; measures that reduce the need for gas combustion (such as increased space- and water-heater efficiencies and house insulation) would also help decrease those emissions.

The goal of this project is to develop a quantitative model that can both predict outdoor pollution emission rates from residential natural-gas appliances and evaluate various pollutant-reducing strategies on a cost-benefit basis. The model will use detailed information on emission rates, usage rates, and market penetration for appliances. It will be used to evaluate the benefits of various pollutant-reducing strategies, rank the strategies, and compare them to similar measures proposed in other pollutant-producing sectors (such as large industrial and mobile sources).

APPROACH

Our approach has three basic components. We will develop a model that quantifies outdoor pollutant emissions from residential gas appliances, collect the data necessary to run the model, and run the model.

Besides the parameters mentioned earlier—gas appliance emission rates, usage rates, and market penetration—the model will include usage rates for particular gas appliances (such as space heaters) based on the need for those appliances. For example, residential space-heater usage depends on outdoor temperature, house insulation levels, house air exchange rates, and other energy-related parameters.

Data for the model will be collected from a wide variety of sources. Pollutant emission rate data will be collected from published journal articles and reports from research agencies, including the U.S. Environmental Protection Agency, state air-quality agencies, the Gas Research Institute, the American Gas Association, gas utilities, and gas appliance manufacturers. To date, we have found more than 80 papers that report pollutant emission rates from over 700 residential gas appliances. Appliance market penetration and residential housing stock characteristics will be collected primarily from local utility surveys; meteorological information will be obtained from the National Oceanographic and Atmospheric Administration. Information on appliance use will be modeled or obtained empirically from surveys.

After gathering the data and developing the model, we will run the model to compare its results to current aggregate pollutant emission estimates used by state and local air-quality districts. Large discrepancies between the results and the current aggregate estimates will be explored. We will also run the model to compare, on a cost-benefit basis, various strategies for reducing outdoor air-pollution emissions from residential gas appliances. Those strategies, including the development of burners that emit low amounts of NO_x and CO, cannot be evaluated quantitatively on a cost-benefit basis without a model incorporating all the factors that affect those emissions. Without such a model, we may overlook cost-effective strategies for reducing emissions and pursue inappropriate, costly strategies.

IMPROVING THE ENERGY EFFICIENCY OF RESIDENTIAL AIR-DISTRIBUTION SYSTEMS IN CALIFORNIA

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This multiyear research program, now in its second phase, is investigating ways to improve the efficiency of air-distribution systems in single-family, detached residences in California. The objectives of this effort are to:

- Obtain representative data on the implications of air-distribution systems for residential energy consumption, peak power demand, and ventilation in California.
- Develop, test, and evaluate the cost-effectiveness of alternative approaches to the problems with residential air-distribution systems in both new and existing buildings (including duct installation standards, sealing technologies, and non-air-distribution systems).
- Deliver a field-tested retrofit package for residential air-distribution systems to California utilities and other residential audit and retrofit groups.
- Provide a technically and economically defensible analysis of residential distribution system options for new buildings as well as a set of recommendations for the Title 24 residential energy code.

The second-phase efforts are focused primarily on the second and third objectives, the results and implications of which are discussed in the following subsections.

BACKGROUND

Approximately half of the households in the U.S. have central warm-air furnaces and air-distribution ducts. Given their widespread use and the fact that they are a vital link between houses and their space-conditioning plants, residential duct systems—in particular, their comfort and energy effectiveness—are regularly revisited as a topic of study. Those studies have uniformly concluded that the performance of thermal energy distribution merits further examination.

The issue of residential air-distribution system performance, particularly the duct-leakage problem, is especially important in California, where just over half of the residences contain a total of approximately 100,000 miles of ductwork and where virtually all new construction uses air-distribution systems.

Duct leakage is especially important in California because ductwork is almost invariably in unconditioned attics and crawl spaces (due to the scarcity of basement construction in the state). Earlier studies suggested that the air leakage from a typical duct system in a Sacramento house represents between 1 and 2 kW (depending on the location of the ducts) of peak-hour demand and 20 to 40% of the peak cooling day consumption; it also represents approximately 1 kW of peak heating demand and 2,000 to 3,500 kWh of annual electricity consumption for a heat-pump-heated house.

In addition to their energy and peak-demand implications, leaky duct systems have also been shown to double air-infiltration rates when the distribution system is on, representing between 20 and 40% of the average annual ventilation of residences.

In the first phase of this project, we studied the air-distribution systems of 31 houses in California, developed a detailed simulation tool for such systems, and conducted a survey of HVAC contractors. The first-phase results generally confirmed earlier findings and pinpointed several additional ways to improve duct efficiency.

RESULTS

Second-phase tasks included:

- Investigating (both theoretically and experimentally) an aerosol-based duct-sealing technology.
- Refining and using an integrated duct-system/infiltration/thermal-performance simulation tool.
- With Pacific Gas and Electric, extending modeling and measurement efforts to zone-conditioned houses.
- With Sacramento Municipal Utility District (SMUD), developing a duct-system retrofit protocol.
- With Southern California Edison, developing and testing a technique to measure duct leakage during the building construction process.

The most significant result of the aerosol-sealant effort was the confirmation that a spherical aerosol can seal leaks at least as large as .12 in. (3 mm) in diameter and as far as 26.25 ft (8 m) away from aerosol injection. Based on numerous tests with the experimental apparatus developed, we found the aerosol-injection process to be a critical factor in sealing effectiveness.

Refinement of the duct/house simulation tool developed in Phase I resulted in an automated tool that runs approximately 10 times faster. One application of the revised tool was to simulate the thermal siphon effect that occurs even if a duct system is completely sealed. Preliminary results suggest that this effect can be significantly larger than the effect of typical duct leakage when the fan is not operating. The new tool is being used in sensitivity analyses of several duct-system modifications in various climates as well as to analyze the components of the SMUD retrofit protocol for duct systems. A refinement of the simulation model to treat a two-zone house/conditioning-system prototype was also completed, and a comparison with experimental data is under way.

The field test of the direct duct pressurization technique developed for new construction indicated that approximately 50% of duct leakage could be sealed within half an hour on average, suggesting that this technique could profitably be incorporated into new-construction demand-side management programs. One blower-door manufacturer is now marketing such systems based on our research results, with other manufacturers following suit.

MAJOR ACCOMPLISHMENTS

The major accomplishments of the first year's efforts are:

- Construction of a small-scale experimental setup for determining aerosol transport and deposition efficiencies and experimental demonstration of the sealing effectiveness of a spherical aerosol under various conditions.
- Completion of a new model to simulate multizone air-distribution systems and major streamlining of the single-thermostat duct/house simulation tool, which can now perform an hourly annual simulation in two to three hours versus a run-time at the end of Phase I of approximately 24 hours.
- Incorporation of the field results obtained in Phase I into the simulation tool and simulation of the thermal-siphon effect of a sealed duct system.
- Completion of three publications, including one for the American Council for an Energy Efficient Economy Summer Study and one for the Thermal Performance of the Exterior Envelopes of Buildings conference.
- Development and successful field demonstration of a direct-pressurization technique for measuring duct leakage during construction.

MEASURED SAVINGS IN AIR CONDITIONING FROM SHADE TREES AND WHITE SURFACES

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The objective of this monitoring project is to investigate the potential air-conditioning energy savings of shade trees and white surfaces. From late August through early October 1991, we measured air-conditioning electricity savings resulting from painting roofs white and planting shade trees for six houses and two portable school buildings in Sacramento.

Preliminary data indicates that painting the roof of one of the houses white eliminated the air-conditioning energy use, a savings of about 12 kWh/day in energy and 2.3 kW in peak power. Painting the roof and one wall of a portable building reduced its air-conditioning energy use by more than 50%. Shading the west and south windows and the air-conditioner condenser units of two of the houses with trees lowered cooling electricity use by 10 to 40%. The data has not been corrected for changes in solar radiation during the monitoring period on the horizontal and vertical building surfaces; in the case of the shade trees, much of the savings would most likely disappear if such corrections were made.

The Sacramento Municipal Utility District estimates that an extensive tree-planting and white-surfacing program in Sacramento (reaching 250,000 unshaded houses) would yield residential cooling savings of about 600 peak MW. These energy savings can be delivered with little cost: In many cases, white surfaces incur no incremental costs if incorporated in routine maintenance, whereas young trees cost about $10 each. Including purchase, planting, and watering costs, the present-valued cost per saved peak kW of these measures would be less than $150 per kW in Sacramento.

We identified seven sites in which to monitor the impact of shade trees and white surfaces. We selected one of the houses and both school buildings for studying the effect of albedo; the remaining houses were used to test the impact of shade trees.

For each site, we measured and examined cooling electricity use as a function of outdoor temperature (means and maxima), indoor temperatures, and indoor/outdoor temperature differences. Figure 1 shows hourly cooling electricity use plotted against

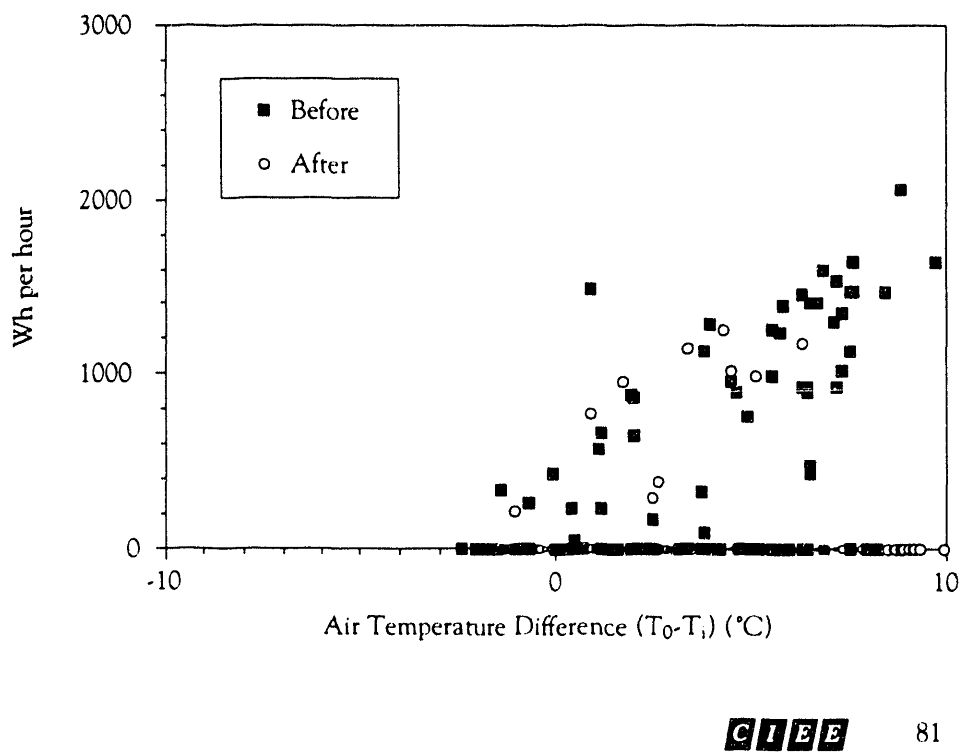

Figure 1. Hourly cooling electricity use plotted against the difference between hourly outdoor and indoor air temperatures.

the difference between hourly outdoor and indoor air temperatures for both pre- and post-retrofit (albedos of 0.18 and 0.77) periods for the "albedo house." In effect, increasing the albedo of the roof canceled all the cooling energy use in that building. The reason cooling energy was used even after the roof was whitened is that the thermostat setting was lowered from 78 to 75°F (25.5 to ~23.5°C) for a few days. Data indicates that cooling was needed when the outdoor temperature was in the range of 0 to 16°F (0 to 9°C) higher than the indoor temperature.

This site's most intriguing aspect is its pronounced microclimate. Coupled with the near-total blockage of window solar gain by trees, this produced a house with a cooling load dominated by solar insolation on the roof. In other words, the cooling load disappeared because the roof was the only significant source of cooling load. It's not surprising, then, that painting the roof eliminated the cooling load entirely.

Figure 2 shows data for one of the portable school buildings. Increasing the albedo of the roof from 0.08 (brown) to 0.68 (white) reduced the air-conditioning energy use by about 50%. While cooling in the low-albedo case started at an outdoor air temperature of 72°F (22°C), cooling in the white-coated case started at an outdoor air temperature of 88°F (31°C). Cooling needs in the low-albedo case range from outdoor-indoor temperature differences of -5 to 20°F (-3 to +11°C), while the cooling needs in the high-albedo case were confined to a range of 7 to 22°F (4 to 12°C).

As for the impact of shade trees, the results were less dramatic. The fact that the trees used in this study were extremely small, combined with the uncertainty regarding the impact of variations in solar intensity, leads to the conclusion that the results for all the vegetation cases are of questionable significance. In one house, adding two trees on the west and one tree on the south reduced cooling energy use by ~40%, whereas the addition of two southwest trees to another home reduced cooling energy use by ~30%. The other two cases showed even less dramatic effects; adding two trees on the east side of a well-shaded house reduced cooling energy use by ~10%, while adding six trees on the south side of a completely unshaded home reduced cooling energy use by only ~10%. Much of the cooling energy reduction for the vegetation sites may be the result of reduced solar insolation over the course of the study.

This project demonstrated the potential for cooling energy savings using high-albedo surfaces and shade trees. The tests were limited to the direct effect (direct reduction of incoming solar radiation), and in the vegetation sites the effects of trees were limited to shading only. The savings in cooling energy use would have been greater had the trees been bigger and denser; such trees could have cooled the ambient air by evapotranspiration and reduced infiltration by slowing the wind in the vicinity of buildings. We plan to continue monitoring the buildings to remove uncertainties associated with the measured savings.

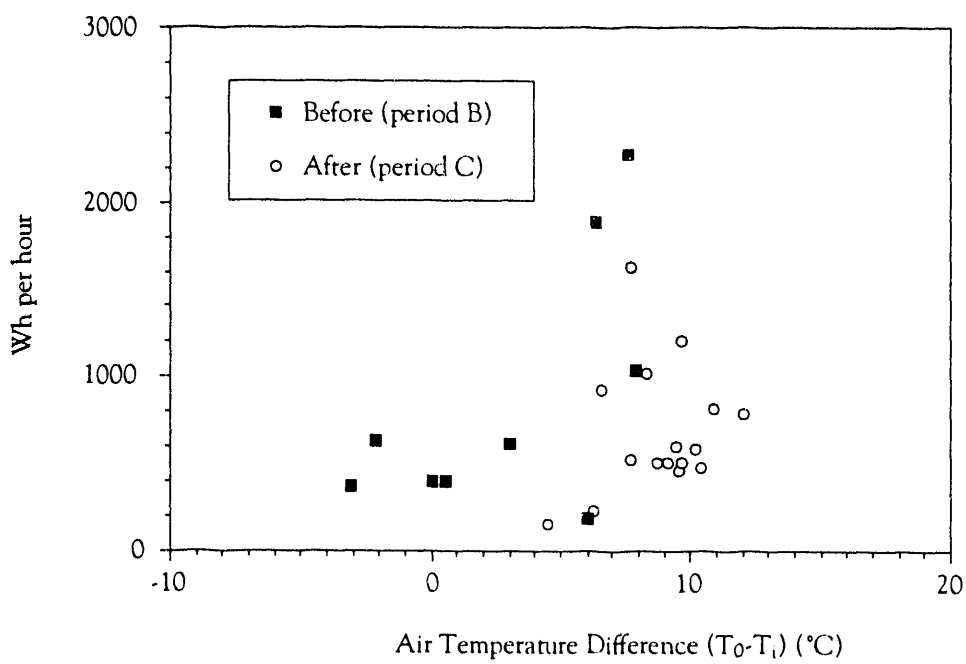

Figure 2. Data for one of the portable school buildings.

ALTERNATIVES TO COMPRESSOR COOLING IN CALIFORNIA TRANSITION CLIMATES

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Compressor-based cooling is growing rapidly in California as housing activity expands inland from the major coastal urban centers while the public's demand for comfort remains high. For utility companies, the residential cooling load profile is very disadvantageous, with sharp peaks that are generally coincident with system peaks in the late afternoon. The use of noncompressor passive cooling techniques in place of energy-intensive air conditioning will dampen the peaking nature of residential cooling loads as well as drastically reducing cooling electricity use.

The adoption of these alternative cooling strategies, however, is hampered by skepticism about their performance, the absence of analysis tools and design guidelines, and the lack of demonstrated effectiveness. The aim of this project is to overcome these technical and institutional barriers. This three-year effort will demonstrate to builders, home buyers, and the housing industry that comfortable and practical houses can be built in California transition climates (also known as *Inland Cool climates*) without resorting to air conditioning.

The project team will address the various issues preventing the residential housing market from adopting these energy-saving strategies. These issues include the absence of design guidelines, institutional and sociological barriers, and the need for a proof of concept.

The team will follow a roughly sequential course of action consisting of research, application, and demonstration.

- Research will involve measuring and developing analytical tools to predict the performance of cooling strategies, such as night venting, thermal storage, and evaporative cooling; defining comfort and health criteria through laboratory studies; and identifying public perceptions and institutional barriers to alternative cooling strategies.

- Application will involve using the measured data and computer tools to identify the optimum mix of cooling strategies by location and house type and working with architects and builders to create housing designs incorporating these cooling strategies without radical changes in typical construction practices.

- Demonstration will entail collaborating with utility companies and builders to construct a number of demonstration houses and evaluate their energy use, indoor comfort, and market acceptability.

The project started officially in July 1992. The project activities for the first year are devoted primarily to research on the technical and sociological issues related to alternative cooling strategies. The first major tasks are to define the climate conditions and cooling loads of typical houses in the transition climates and to make a preliminary assessment of the effectiveness of alternative cooling strategies using the current state of knowledge and modeling capabilities. These tasks will be completed within the first three months of Phase I.

For the remainder of the year, the project activities will be devoted to the research topics shown in Table 1.

Table 1. Project research areas.

Lead Researcher and Institution	Research Area
Ed Arens Architecture/UC Berkeley	Study indoor comfort and health conditions in relation to alternative noncompressive cooling strategies.
Helmut Feustel LBL	Improve air-flow modeling and develop control algorithm for integrated ventilation control strategies.
Baruch Givoni Architecture/UCLA	Measure the effects of ventilation strategies and thermal mass on building conditions.
Bruce Hackett Sociology/UC Davis	Study the variability of cooling equipment use and the institutional barriers against the use of alternative cooling strategies.
Joe Huang LBL	Improve computer modeling of evaporative coolers.
Fred Winkelmann LBL	Improve computer modeling of building heat transfer under conditions of air movement.
Hofu Wu Architecture/Cal Poly Pomona	Validate evaporative cooling model and study the architectural implications of alternative cooling strategies.

List of Acronyms

AIPS	Advanced Integrated Ponding System
CARB	California Air Resources Board
CCS	Commercial Cooling Systems
CEC	California Energy Commission
CFC	Chlorofluorocarbon
CIEE	California Institute for Energy Efficiency
COP	Coefficient of Performance
CSR	Cool Storage Roof
CSU	California State University
DSM	Demand-side management
EDA	End-use disaggregation algorithm
EER	Energy efficiency ratio (equal to COP • 3.412)
EMCS	Energy management and control system
EUI	Energy utilization intensity
EV	Electric vehicle
GW	Gigawatts
HCFC	Hydrochlorofluorocarbon
HVAC	Heating, ventilating, and air conditioning
kWh	Kilowatt hour(s)
LBL	Lawrence Berkeley Laboratory
LTD	Localized thermal distribution
MBtu	Thousands of British thermal units
MPS	Marketable Permit System
MW	Megawatts
NFPA	National Fire Protection Association
NGV	Natural-gas vehicle
OSP	Office of State Printing
PEM	Personal Environmental Module
PG&E	Pacific Gas and Electric Company
PIREG	Purchase Intentions and Range Evaluation Game
PSTAR	Primary and Secondary Terms Renormalization
QF	Qualifying facility
ROG	Reactive organic gas
SBS	Sick building syndrome
SC	Shading coefficient
SCAQMD	South Coast Air Quality Management District

SCE	Southern California Edison Company
SDG&E	San Diego Gas and Electric Company
SDSU	San Diego State University
SEER	Seasonal Energy Efficiency Ratio
SMUD	Sacramento Municipal Utility District
SoCAB	South Coast Air Basin
TAM	Task Air Module
TED	Thermal energy distribution
TES	Thermal energy storage
TOU	Time of use
UAM	Urban Airshed Model
UCB	University of California, Berkeley
UCD	University of California, Davis
UCI	University of California, Irvine
UCLA	University of California, Los Angeles
UCSB	University of California, Santa Barbara
USC	University of Southern California
VOC	Volatile organic compound

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