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INTEGRATED ENVELOPE AND LIGHTING TECHNOLOGIES FOR COMMERCIAL BUILDINGS

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ABSTRACT

Fenestration systems are major contributors to peak cooling loads in commercial buildings and thus to HVAC system costs, peak electric demand, and annual energy use. These loads can be reduced significantly through proper fenestration design and the use of daylighting strategies. However, there are very few documented applications of energy-saving daylighted buildings today, which suggests that significant obstacles to efficient fenestration and lighting design and utilization still exist. This paper reports results of the first phase of a utility-sponsored research, development, and demonstration project to more effectively address the interrelated issues of designing and implementing energy-efficient envelope and lighting systems. We hypothesize that daylighting and overall energy efficiency will not be achieved at a large scale until true building integration has been accomplished to some meaningful degree. Moving beyond the vague concept of "intelligent" buildings long popular in the design sector, we attempt to integrate component technologies into functional systems in order to optimize the relevant building energy performance and occupant comfort parameters. We describe the first set of integrated envelope and lighting concepts we are developing using available component technologies. Emerging and future technologies will be incorporated in later phases. Because new hardware systems alone will not ensure optimal building performance, we also discuss obstacles to innovation within the design community and proposed strategies to overcome these obstacles.

INTRODUCTION

Proper fenestration design can significantly reduce HVAC system costs, peak electric demand, and annual energy use in commercial buildings. However, low shading coefficient fenestration systems that reduce cooling impacts also limit light transmittance and may produce adverse occupant responses. They will also limit the potential for daylighting strategies to reduce electric lighting, which is often the single largest electric load in commercial buildings. Computer simulations predict that large daylighting savings should be routinely achievable. But despite the decade-long revived interest in daylight utilization, there are very few well-documented applications of energy-saving daylighting strategies in buildings today, which suggests that the achievement of the energy-saving potential of daylighting will require a new approach to fenestration design.

We have recently completed the first phase of a multi-year utility-sponsored project to address the interrelated issues of energy efficiency in envelope and lighting design. While the general concept of building integration has existed in spirit for some time, it has yet to be defined, clarified, or otherwise approached in a meaningful manner. Based on analysis of the successes and failures of new technologies in buildings, we believe that envelope and lighting technologies must be available to specifiers as integrated systems, who can then focus on design for *whole building* optimization. This is in contrast to the current typical scenario that requires a design team to successfully select, specify, and construct a total system from a large array of separate components, providing many opportunities for omissions and failures. Design fees, the pace of the design process, aversion to risk, and the technical complexities inherent in this integration task all prevent designers today from routinely and successfully specifying and implementing solutions that meet occupant needs while substantially improving energy efficiency over conventional construction.

This long-range project will ultimately produce buildable schematic designs for integrated systems, including all necessary control hardware and software, after a full range of predictive and field test performance analyses plus possible full-scale demonstration. We report here on our Phase I work, which set out to establish critical background and performance target data and to develop necessary new methods of analysis.

Simulation studies in this phase of the project suggest the technical potential for 70% reductions in perimeter zone electricity use with an integrated strategy in envelope and lighting design. We describe the first set of integrated system concepts we are developing using currently available technology, including combinations of selective glazings, motorized blinds, electronic ballasts, high-efficiency lamps and fixtures, daylight-redirecting elements, and new control systems to link the components. In later phases of the project, other emerging and novel technologies will be incorporated. The ultimate technical goal is to reduce perimeter zone electric needs to zero by additionally integrating photovoltaic systems into the envelope system.

New hardware systems alone will not ensure successful utilization in buildings. We discuss results of studies addressing obstacles to innovation within the building community and propose strategies to overcome these obstacles. Two major elements of our approach are collaboration with utility design assistance and incentive programs, and pursuit of demonstration projects. In the longer term, development of a new set of design and commissioning tools incorporating expert system software is planned.

PROJECT OVERVIEW

This research, development, and demonstration project divides into three major task areas:

1. establishment of goals, framework, constraints, and methods;
2. design, analysis, and evaluation of candidate integrated systems;
3. demonstration of integrated systems in scale models, field tests, and buildings.

Task Area 1: Goals and Constraints

Work in this area serves the purpose of establishing the groundwork for subsequent tasks. We began by developing an initial utility impact assessment for available and emerging technologies. An analysis of the energy performance potential of these technologies resulted in preliminary "targets," or building performance goals for this stage of the project. 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.

Having established "potential" performance and benchmarking it against "current" performance, we then examined the palette of influences and components in building design. We reviewed available technologies, and characterized the opportunities, constraints, and other issues involved in design decisions. In order to establish a working base of technologies for analysis throughout the project, we reviewed existing, emerging, and future technological options in several categories of envelope and lighting hardware (LBL 1991a). Similarly, we reviewed design tools and utility design assistance programs, since these can be a critical factor in the effective application of a given technology. We examined obstacles, opportunities, priorities, and potentials with respect to market, industry, and design concerns. We reviewed the state of the U.S. construction industry, examined its historical patterns regarding technical innovation and envelope design, interviewed a sampling of key individuals in design and construction, and investigated the non-energy benefits potentially associated with integrated envelope systems.

Task Area 2: Design and Analysis

Integrated system design, analysis, and demonstration are the core of this project. No single integrated system or set of systems will cover the diversity of needs in commercial buildings. The key component envelope, lighting, and control elements of a generic conceptual system are shown in Figure 1. Operational software would also be a major element of this system. Figure 2 diagrams the control and operation of the system elements.

We developed initial designs for the integrated systems, drawing from our technology base and aiming for our performance targets. We created commercial building prototypes as base models for analysis in this stage, representative of typical California design, construction, and operation and fitting a matrix of building skin typologies we defined for the purpose of characterizing integrated design solutions. These prototypes serve as the basis for computer models and for keying results of analysis to architectural practice. The focus in this first phase is to address the concept of integration using currently available technologies in conventional design, while simultaneously looking ahead at the potential of emerging technologies and innovative design strategies as features in future phases.

The systems we designed in Phase I and will develop in later phases have no analytical precedent because of their dynamic capabilities and unique optical properties. We created new algorithms for computer simulation and analysis of integrated control systems for shading and lighting systems, as well as for other new fenestration systems never previously analyzed or modeled. In this exploratory process, we developed a new method for performance analysis of complex integrated envelope and lighting systems, modeling the thermal and luminous performance of our prototype systems through a combination of physical model photometry and DOE-2.1D software modification (LBL 1991b). Our use of DOE-2 in this manner differed from standard building modeling procedures. We also departed from well-established methods that establish correlations between building performance and design parameters using regression analysis (Sullivan et al. 1988) due to the difficulties in modeling our proposed complex systems. Instead, we investigated the dynamic relationship between a subset of critical envelope and lighting parameters in our prototype systems and the resultant energy performance of the building. For example, we isolated the effects of solar heat gain (since solar gain plays a major role in electricity use in California commercial buildings) and were able to thus draw conclusions about the resultant cooling due to solar radiation; similarly, by examining the variations in workplane illuminance, we were able to compare the resultant cooling load and electricity use due to lighting. The net result of these three energy end-use analyses led to our development of design criteria and targets for the integrated envelope and lighting systems.

We developed and then analyzed a series of proof-of-concept integrated systems within the new building prototypes using physical scale-model tests and newly developed computer simulations. We began with 26 combinations of various glazing, shading, light shelf, and daylighting control configurations (Tables 1 and 2). We narrowed the field to three combinations plus a baseline case. All were modeled at 1.5 W/ft^2 lighting power density. The four prototype systems were:

- baseline—no shading, tinted glazing;
- shades with spectrally selective glazing;
- motorized blinds with spectrally selective glazing;
- light shelf with spectrally selective glazing.

Task Area 3: Demonstration

This task area is an opportunity to field test and monitor our integrated systems and to demonstrate their potential and feasibility to others. In the first phase of the project, we initiated two simultaneous paths in this task area: (1) partial or small-scale demonstrations of advanced prototype systems prior to commercialization and (2) full-scale demonstrations in real construction projects of interim integrated systems (using available technologies that are to be *elements* of the future advanced integrated systems). The reason for these two near to mid-term approaches is our recognition that new technologies must be well tested before they will be adopted into construction. In later phases we will pursue full-scale demonstrations of advanced systems.

We have begun to establish selection criteria for demonstration candidates, have selected two potential short-term projects to date, and have spent several months working directly with their design teams. These two projects have helped us develop an initial method of interaction with design teams who are exploring new technologies. Lessons learned from these efforts should prove highly useful both for us, when we promote emerging technologies in later phases, and for utility design assistance programs. Once we have successfully promoted inclusion of integrated technologies into a constructed project, we will monitor and evaluate results to compare the final building performance to our initial predictions. A special emphasis in these later tasks will be visual comfort assessment. It is our intent to address this important evaluation area because there are not well-developed procedures currently in use.

RESULTS

Goals and Constraints

In our background tasks, we first identified the lighting and envelope parameters that would produce the most substantial effect on the cooling and lighting loads and then began the process of optimizing the combination of these parameters to yield the best energy performance. Glazing luminous efficacy (K_e, or visible transmittance + shading coefficient), 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. Optimal building performance "targets" were derived for the years 1995 and 2005, based on theoretically achievable values for the performance criteria of the three key parameters and tempered with expert judgement. These targets then yielded projected energy performance and potential energy savings for these improved commercial buildings. The method of this analysis is described in detail in a companion paper (Sullivan et al.

1992). We next compared the targets to performance data from other simulation studies, to measured data from California building studies, and to typical performance as would be required by the California energy code (Title 24) for new construction (Figure 3). This benchmarking exercise enabled us to highlight missed opportunities for high-performance envelope and lighting technologies in California. Through computer modeling of advanced building technologies, we projected the potential savings (Sullivan et al. 1992)

- a 38% lighting and cooling reduction by 1995,
- a 73% lighting and cooling reduction by 2005,
- peak demand reduction of 22% by 1995,
- peak demand reduction of 40% by 2005.

The companion effort of examining priorities and potentials for the development of integrated systems, as viewed from the design and construction industries, yielded the following findings:

1. These industries are highly fragmented into specialized and diverse trades and are highly localized. These characteristics, combined with the uniqueness of each building project, makes mass production difficult.

2. The consequences of failure in the building sector are serious, leading to caution regarding new technologies. Partially due to this conservatism, innovation in the building industry often requires implementation assistance beyond natural market forces, e.g., subsidies or legislation.

3. New technologies require careful introduction to the market, since news of failure travels fast and lives long in the building industry.

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

Design and Analysis

In our initial system design efforts, we began to integrate the technologies examined in previous tasks and to perform more detailed analysis of these proposed integrated systems. The intent of these tasks was to specify preliminary sets of integrated technologies to fit characteristic building skin types we defined for the purpose of simplifying this early design effort. The two building skin types we have targeted are (1) a typical planar facade, where technological improvements can only be applied at the glass plane (e.g., coatings) or inside the space (e.g., efficient electric lighting), and (2) a more unusual articulated facade, where the envelope of the building contains technologies extending either inside or outside the skin (e.g., light shelves).

In this task we developed prototypical integrated systems and appropriate tools and analytical methods to evaluate them. Another objective of these activities was to refine our performance projections, with a focus on suitability for demonstration. This proof-of-concept exercise indicated (LBL 1991b) the following:

1. An estimated 50% lighting energy reduction, 57% cooling energy reduction, and 36% peak electric demand reduction with our initial complex systems. Figure 4 shows data with respect to lighting energy reduction.

2. Variations in lighting power density have more impact on energy performance than variations in glazing luminous efficacy within the ranges studied.

3. Examination of energy use at the component level (lighting electricity, cooling due to lights, cooling due to solar) was informative in comparing alternatives and isolating performance tradeoffs.

Demonstration

In our early demonstration activities, we initiated two short-term demonstration partnerships. By definition, short-term projects will not offer the possibility of demonstrating the advanced system integration we propose to develop over the next few years; however, they are helpful in promoting *pieces* of these integrated systems that are currently commercially available. They are also a vehicle for us to learn the best method of interaction with a full design team and client so that demonstration of future prototypical systems proceeds smoothly through the design and construction phase.

Both of our short-term demonstration projects utilize the combination of spectrally selective glazing, solar control devices, efficient electric lighting, and daylighting controls. Both have as their primary goals (1) reduction in energy use, (2) reduction in electric peak demand, and (3) maximum visual comfort for a pleasing and productive work environment. Both projects are utility office buildings, one in Los Angeles and one in Sacramento (LBL 1991c).

We performed extensive computer and scale model analysis for the Los Angeles building. In addition to several well-known energy-efficient features, this building may also include an innovative daylight-redirecting device. This device is a modification of the light shelf principle, where the usually flat horizontal surface is curved to more efficiently redirect most incoming solar rays onto the ceiling deep in the space over a wide range of incident solar angles. This type of light-distributing element has been called a passive solar optical device (Architectural Graphic Standards 1988). Performance is enhanced with the application of a "solar daylighting reflective film" to the upper surface of the device. The film has a high specular reflectance but also slightly diffuses and broadens the outgoing reflected beam to spread light evenly over a large ceiling area and thus improves interior lighting quality. A sample of our analytical results for predicted energy performance of the Los Angeles building is shown in Figure 5. The improved daylight distribution performance for the specialized light shelf is compared to two more conventional fenestration options in Figure 6.

DISCUSSION

Our Phase I analysis has allowed us to better understand the key parameters that affect the energy performance of integrated lighting and envelope systems. We have examined their effect on both the lighting and cooling energy performance of an office building on an hourly, monthly, and annual basis and have come to several conclusions related to their design and performance prediction:

1. The criteria by which the dynamic shading device is deployed in the model can have a significant impact on the predicted success or failure of the integrated system.

2. Maximizing daylight benefit must be balanced against solar heat gain liabilities within control strategies. For both the light shelf and the motorized venetian blinds, the key design objective was to maximize workplane illuminance. The daylighting results from these systems far exceeded the illuminance design criteria. Even the simple integrated system with drapes, which was not designed specifically for this purpose, provided adequate daylight in the shallow perimeter zone. Daylighting benefits were offset partially by increased cooling due to solar radiation, as would be expected. A more sophisticated control strategy that seeks an optimum between these two effects should allow us to realize greater savings. This will be a major focus of the Phase II effort.

3. Further study must be conducted on the appropriate placement of the light reference points and the size of the area that each point controls. The new fenestration systems can direct daylight deeper than we initially expected; hence, a much larger area of the perimeter can potentially be daylit. The magnitude of lighting energy use suggests that efficiency measures that address this end-use component will have a large impact on the total whole-building energy use. Future work will concentrate on a more detailed daylight analysis, examining the spatial and temporal distribution of daylight by window orientation. This will guide us to the optimum selection of reference point depths with respect to energy performance.

4. The cooling load due to solar radiation contributes significantly to the summer peak demand in the late afternoon hours, as expected. By addressing this component of the cooling demand through the reduction in the overall fenestration shading coefficient, significant operating cost savings can be realized. Spectrally selective glazings permit lower shading coefficients without loss of significant additional daylight. In the future, switchable glazings with dynamic shading coefficients will optimize the cooling and daylighting trade-offs.

The perceived barriers to new technologies in the building sector must be adequately addressed before such technologies, no matter how well developed or tested, will be widely adopted. A primary obstacle we will address in Phase II is perceived risk in the application of new technologies. Research and development of new technologies in Phase II will include new and improved methods of performance modeling and simulation, leading to demonstration, to reduce designer risk.

Demonstrations are important but difficult and expensive to carry out. Issues of schedule, budget, and risk often conflict with requirements for the demonstration. One powerful lesson emerging in our work to date is the reminder that persistent hurdles remain in basic attitudes among designers regarding even the most proven of building technologies and strategies that we have long regarded as attractive. A major accomplishment of short-term demonstrations may simply be a greater overall acceptance in the community for daylighting; this nonradical change in attitude would have far-reaching impact. We now better understand that a demonstration project begins with some base level of general education of the participants, who may all enter the project with different degrees of preparedness, and then continues with subsequent specific education at each stage of design or for each innovative design strategy proposed. A focus on education of design professionals may become an important aspect of this demonstration phase in order to increase the potential for efficient design to eventually occur without intervention from outsiders. We have started to develop a specific procedure for demonstration participation and will refine this throughout the project.

Good candidates for demonstration are those projects with time included for exploration and research. For example, both of our short-term demonstration projects have a pre-schematic "research" phase, a highly unusual addition to the traditional design stages initiated by the utility clients. In spite of this, we still find there is not enough time or budget allocated for significant strategy exploration and analysis. An ideally attractive demonstration, particularly if advanced building systems are to be considered, will have an even longer research phase and/or such a phase will begin with more clearly defined objectives or starting points. As this is unlikely to occur on a broad basis, we need to find alternative means of expediting the work that requires so much pre-design time.

Finally, we look at our demonstration projects with an eye toward lessons for design assistance in general, with the objective of providing utilities with useful information for demand-side management programs. These projects have reminded us that energy-efficiency expertise and knowledge of new technologies is in high demand. Our involvement has been welcome, which indicates a likely widespread justification for effective design assistance programs. In terms of our project demonstrations, we have concluded that design assistance should be tackled from three fronts: it should provide experts for direct consulting at the beginning of the project, provide a data base of case study "models of success," and provide continuing education to enable repeat performances without assistance. This latter issue should ultimately be addressed with the development of a new generation of more powerful, sophisticated, and user-friendly design tools. We are developing prototypes of portions of such tools for use in later phases of this project.

CONCLUSIONS

Although more efficient envelope and lighting component technologies have been developed in recent years, they are used in a piecemeal manner, and their performance falls short of predictions. New emerging technologies with even better performance potential can be expected to encounter the same problem. Thus, while the technical potential exists for significant energy savings in California commercial buildings, the full impact of these new technologies has not yet been realized. Successively stringent building codes in California have reduced average building energy consumption slowly, but claims of 50%-75% improvements in energy efficiency have not yet been routinely achieved. Furthermore, the prescriptive code compliance pathway used by most designers may limit design freedom with respect to new technologies.

We believe the problem is best addressed through (1) better application of existing discrete technologies and (2) combination of technologies (hardware and software) into integrated systems for whole building optimization. The success of new technologies depends not only on their technical performance but on an understanding of the forces that shape design decisions as well. A focus on technologies alone will not be adequate to achieve projected savings in real-world applications due to several significant aspects of building design and construction. We have characterized the issues and our approach in the following manner:

Problem	*Approach*
Building designers are not aware of existing and emerging high-performance envelope and lighting technologies.	Identify the most promising underused existing technologies and the most promising emerging technologies, and examine missed opportunities and current obstacles with respect to their wider application.
Building designers are not comfortable deviating from standard practice or are not knowledgeable enough to use new technologies without help.	Provide designers with appropriate tools to assist in design, specification, and performance evaluation of advanced envelope and lighting technologies.
Building designers are not confident in the performance of new technologies.	Provide greater assurance to designers of the expected performance of individual technologies and of new, integrated technology systems. Develop demonstration projects as an integral vehicle to verify performance claims, generate interest, and reduce perceived risks by other designers.
When new envelope and lighting technologies are used, they are typically applied in a piecemeal fashion that yields less than optimal results.	Develop new concepts for *integrated* technology systems and create prototypes for testing and analysis, with appropriate industry participation. Provide analysis of new technologies in the context of *whole building* performance, rather than in terms of discrete components, and move toward packaging technologies as integrated systems.
New technologies are often presented to the building community in a manner that does not recognize the various constraints and priorities influencing design decisions, impeding quick adoption of these technologies.	Encourage industry to develop and market these technologies in collaboration with design and construction representatives so that new systems meet the full range of needs in the building sector.

Demonstration projects are an important strategy for accelerating the introduction and wide acceptance of new technologies. Other mechanisms to assist are utility incentives, utility-sponsored design assistance, and ultimately advanced tools to assist designers in specifying advanced technologies and in providing some assurance of performance.

Our proposed integrated systems should improve occupant comfort and productivity in buildings. Buildings with advanced integrated systems would be considered "intelligent buildings;" this is a more accurate and complete interpretation of that description than often used in the architectural and engineering press today. Thus, our focus in the remainder of the project will be to examine the links between building systems with respect to (1) integration opportunities and potential problems, (2) building performance, and (3) potential impacts on comfort and productivity. With respect to implementation, our short-term goal is better integration of existing technologies. Our long-term goal is the development of new technologies designed from the beginning to function as assemblies of integrated components.

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TABLE 1
Design Variations of the DOE-2 Building Simulation Model

No Shades and Shades Parametrics

1 City	Los Angeles
2 Window Systems	No shades, no daylighting controls. Shades with daylighting controls.
4 Glazing types	Tinted, reflective, spectrally selective and low-E (see Table 2)
2 Lighting power densities	1.5 W/ft^2 (16.17 W/m^2) 1.0 W/ft^2 (10.78 W/m^2)
1 Building orientation	North-south

Motorized Venetian Blinds Parametrics

1 City	Los Angeles
1 Window System	Motorized venetian blinds on all orientations with daylighting controls
1 Glazing type	Tinted glazing with modified shading coefficient (SC default = 0.75)
2 Lighting power densities	1.5 W/ft^2 (16.17 W/m^2) 1.0 W/ft^2 (10.78 W/m^2)
1 Building orientation	North-south

Light Shelf Parametrics

1 City	Los Angeles
1 Window System	Light shelf at south perimeter and corner windows with daylighting controls and shades at lower glazing; shades with daylighting controls at all other orientations.
4 Glazing types	Tinted, reflective, spectrally selective, and low-E for the lower glazing unit; "clear" double-pane glazing at upper glazing unit.
2 Lighting power densities	1.5 W/ft^2 (16.17 W/m^2) 1.0 W/ft^2 (10.78 W/m^2)
1 Building orientation	North-south

TABLE 2
Characteristics of Glazing Types
Used in Design Variations of the DOE-2 Building Simulation Model

Description	U-value (Btu/ft2·h·F°)*	Shading Coeffi-cient (SC)	Visible Transmit-tance (Tvis)	Ke (Tvis/SC)	Effective Aperture (Tvis·WWR)**	Solar Aperture (SC·WWR)**
Tinted	1.348	0.71	0.53	0.746	0.254	0.341
Reflective	0.373	0.20	0.10	0.500	0.048	0.096
Spectrally Selective	0.373	0.30	0.37	1.233	0.178	0.144
Low-E	0.373	0.41	0.61	1.488	0.293	0.197
Modified for blinds	0.373	NA	NA	NA	NA	NA
Upper light shelf	0.373	0.85	NA	NA	NA	NA

* U-value without the outside air film coefficient.
** WWR = window-to-wall ratio = 0.48
NA Not applicable. Workplane illuminance determined by function expression based on scale model measurements to override DOE-2 daylighting calculation, which would normally be based on these values.

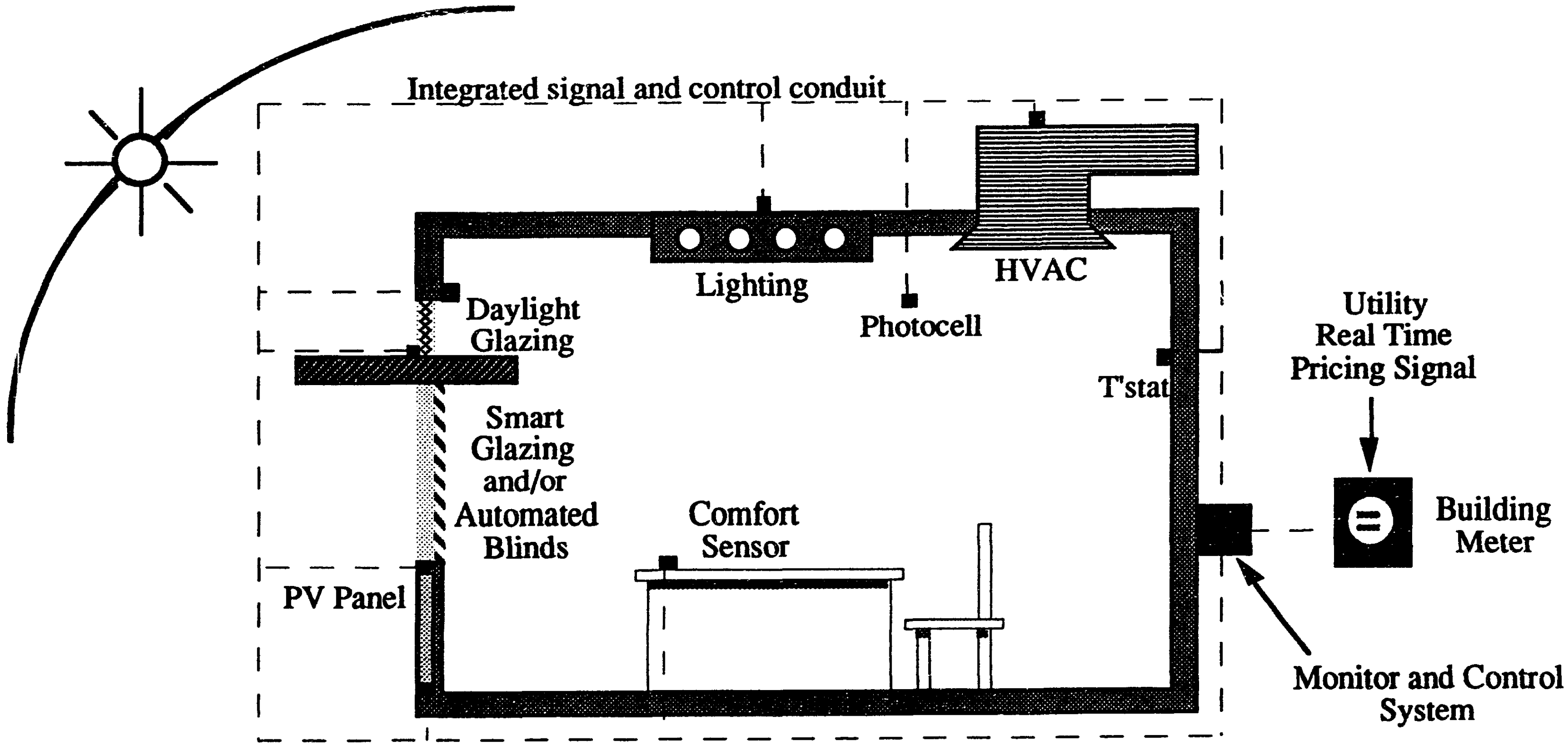

Figure 1. Schematic room section with optimum systems integration. Included here are photovoltaic curtain wall elements (PV), "switchable" glazing, a daylighting optical system (the light shelf), shading devices, and efficient lighting.

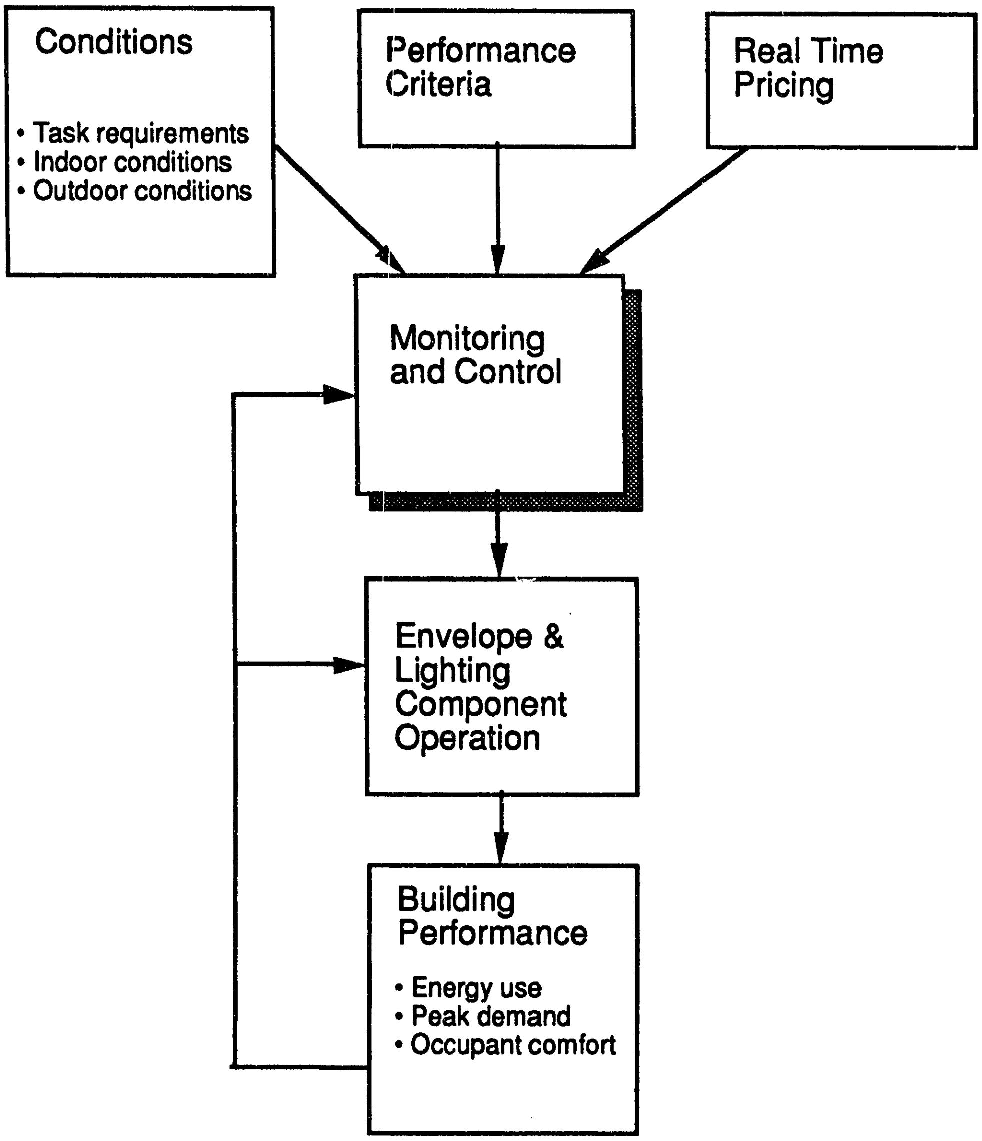

Figure 2. Schematic operational diagram for an integrated envelope/lighting system.

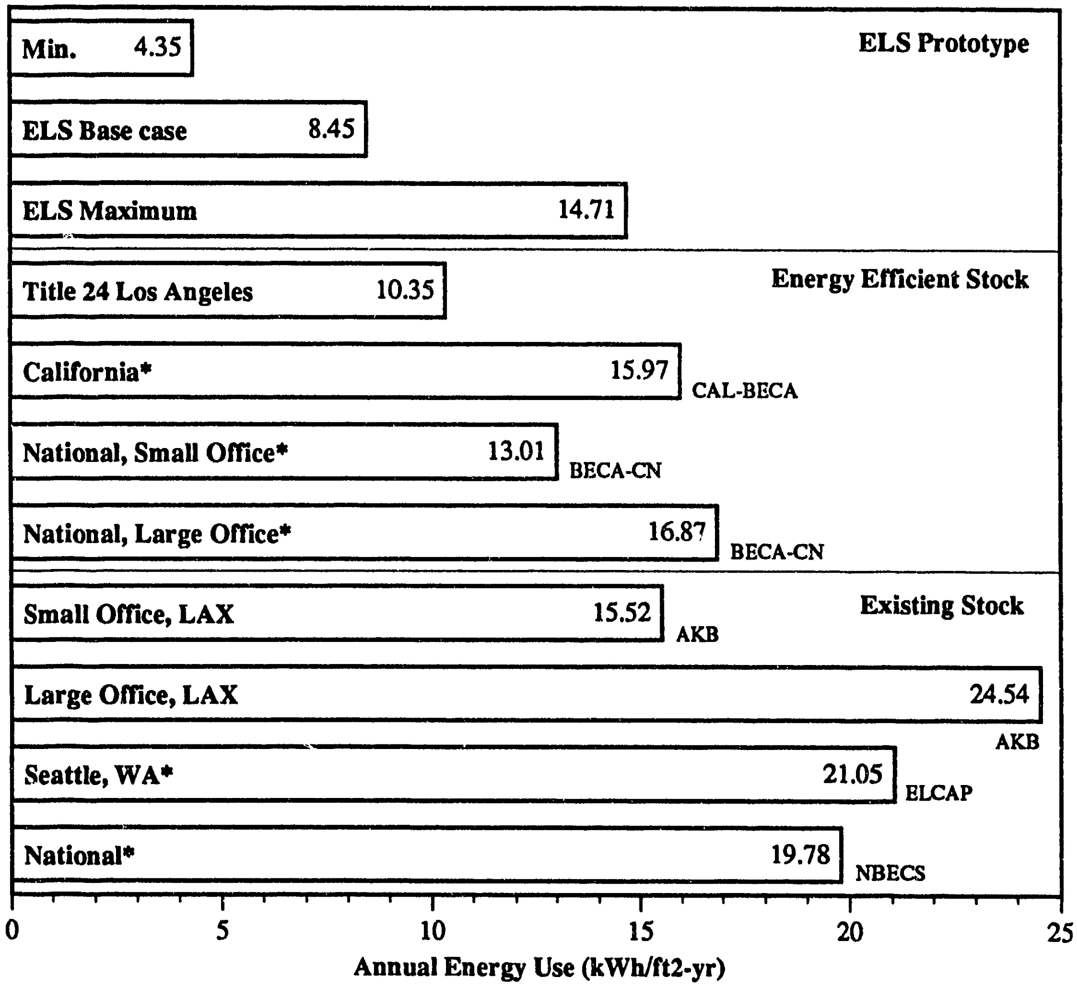

Figure 3. Annual total electricity use for a prototypical commercial office building module in Los Angeles as modeled in an impact assessment study for new combinations of integrated envelope and lighting systems (ELS). Minimum and maximum ELS values mark the range of performance for the parametric design variations in this computer simulation. This range is compared to data from other energy use surveys of existing and energy efficient building stock and to typical requirements of California's energy code (Title 24) to highlight area of conservation potential. Studies that used measured data without simulation models to determine annual energy performance are denoted with an asterick. (AKB: Akbari et al. 1989; NBECS: Energy Information Administration 1988; ELCAP: Taylor and Pratt 1989; BECA-CN, CAL-BECA: Piette and Riley 1986.)

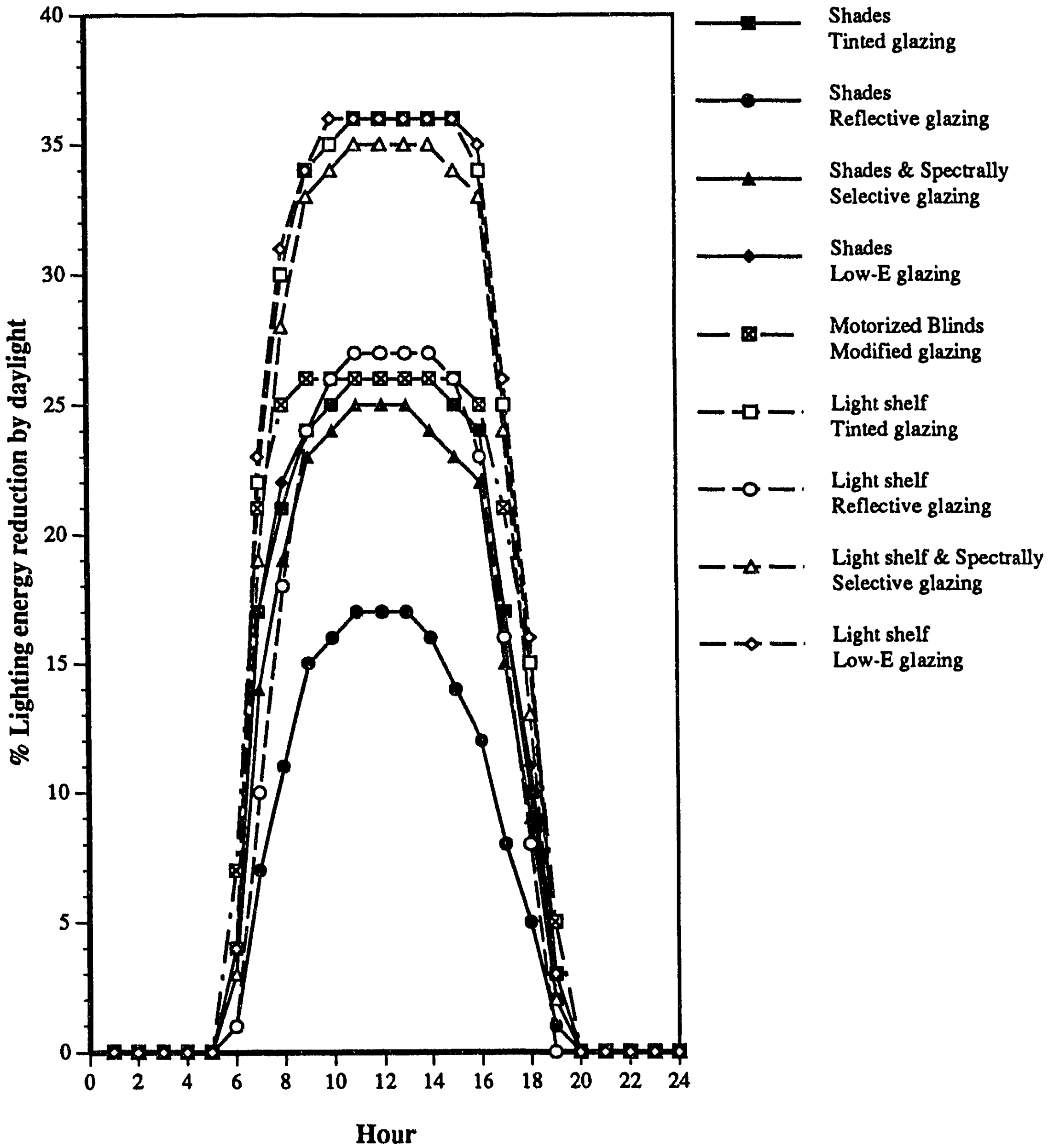

Figure 4. Computer prediction of lighting energy savings in Los Angeles for various combinations of glazing type and shading strategy, with the assumption of lighting and motorized shading control automatically operated as integrated systems. Percent lighting energy reduction due to daylighting is shown for the nine different technology combinations. Lighting power density in all cases is 1.0 W/ft^2.

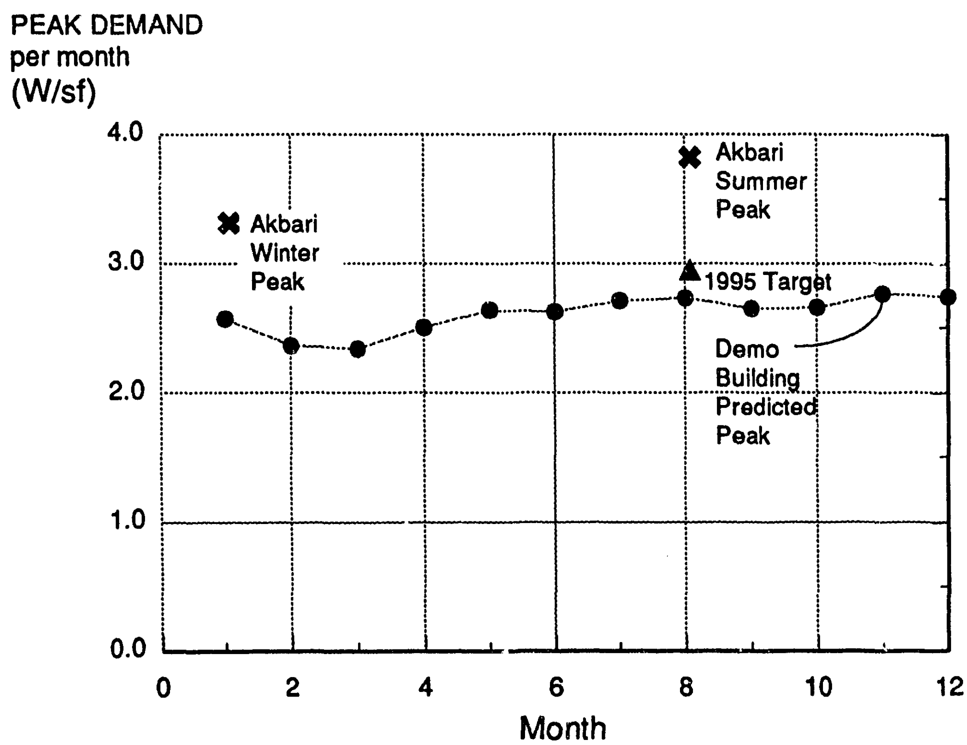

Figure 5. Computer simulated performance of the first candidate demonstration building, compared to our 1995 target value for Los Angeles (Sullivan et al. 1992) and compared to data from a simulation study of existing Los Angeles office building performance (Akbari et al. 1989).

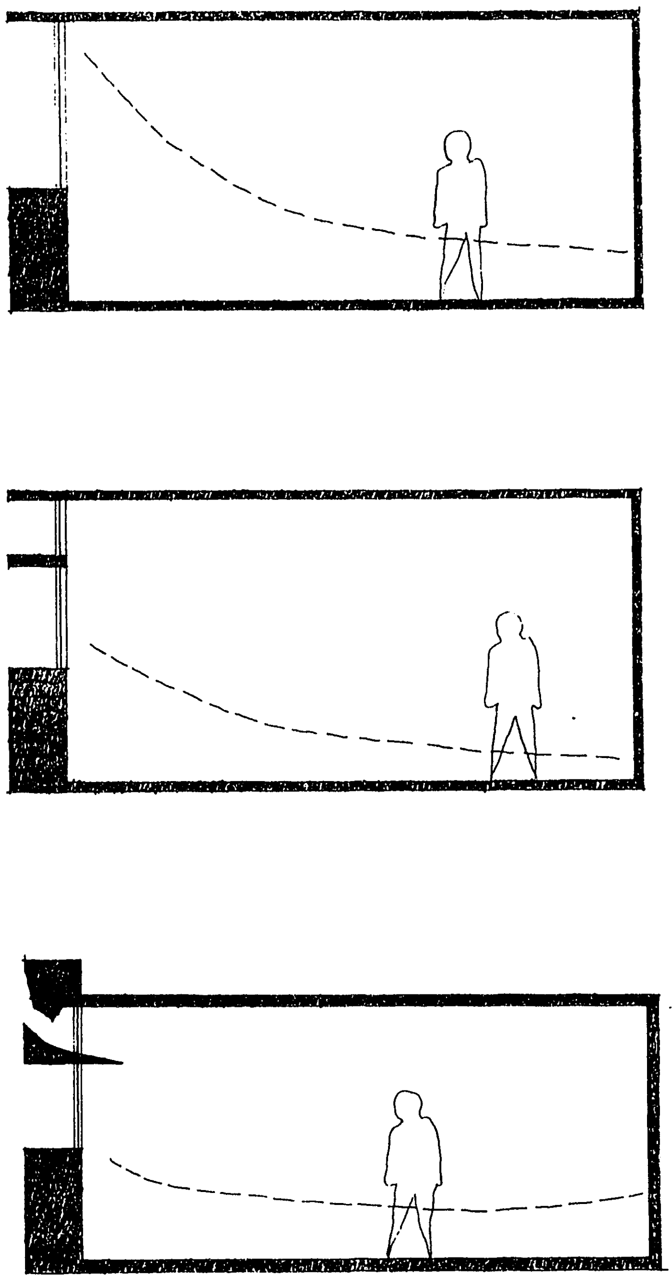

Figure 6. Dayight distribution analysis for first candidate demonstration building, comparing (top to bottom) a simple window, a standard light shelf, and the proposed "passive optical light shelf" for an east orientation facade. Room section is shown for each option with horizontal daylight illumination measured at workplane height plotted through the section. Note the third option has the highest values in the back of the room and the most uniform distribution and thus implies an environment with less potential for window glare. Measurements reflect clear day solar conditions at 9 a.m. on September 21 at latitude 34°N.

END

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