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The Energy Impact of Daylighting

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Electric lighting and its associated cooling requirement consume 30% to 50% of the energy used in a typical commercial building.[1,2] The Energy Information Agency[3] estimates that lighting U.S. commercial (office, retail, hospital, etc.) buildings consumes between 205 and 321 billion kWh/yr., costing Americans between $15 and $23 billion annually. Electric lighting replacement by daylighting using advanced glazings (windows) offers the possibility of reducing the cooling load.

In addition to energy savings, some evidence indicates that exposure to daylight reduces stress.[4] A post-occupancy evaluation[5] of daylit buildings found that over 90% of those with offices near windows had the right amount of sunlight as opposed to 61% of people with more interior offices. While construction costs of commercial buildings are typically around $150/ft^2 and total utility costs are about $1/ft^2·yr, the salaries and overhead for office workers are estimated at $150/ft^2·yr. Thus, it is important that any daylighting strategy either enhances, or at the very least, does not reduce worker productivity.

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The Zero Energy Building

The building investigated here is a small 17,400 ft^2 or (1,620 m^2) two-story, commercial building (*Figure 1*). The building is dubbed the "Zero Energy Building," because it was designed to be eventually self-sufficient in energy, i.e. to take zero energy from the electric and natural gas grids. Details of the HVAC system are available elsewhere.[6] This article describes the results of Phase I of the design effort, using advanced lighting and HVAC strategies. The energy conserving features described here add only 3% to the construction costs of the building.[7]

The Zero Energy Building was designed using load avoidance rather than using alternative sources of energy. The walls, roofs and floors would be insulated to a thermal resistance (R-) values of 19°F · ft^2 · h/Btu (3.35°C · m^2/W), 32°F · ft^2 · h/Btu (5.64°C · m^2/W); and 14°F · ft^2 · h/Btu (2.47°C · m^2/W), respectively. The windows would have a center of glass R-value of 8.1°F · ft^2· h/Btu (1.43°C · m^2/W) and an overall resistance of 5.5°F · ft^2 · h/Btu (0.97°C · m^2/W). This is because the frame is more conducting than the glass assembly of two low-emissivity (low-e) Mylar sheets sandwiched between two sheets of glass. This proposed daylit building would have a window to wall area ratio of 17.4%.

For maximum cooling capacity, an indirect-direct evaporative cooling system was specified for the Zero Energy Building. For only a few hours per year, this enhanced evaporative cooling system would not meet the required cooling load. During hot and humid periods, the water in the direct evaporative cooler can be mechanically chilled using a thermal energy storage system that sensibly cools the air leaving the indirect evaporative cooler. However, the thermal storage system is not modeled here so that the interactions between the HVAC system and daylighting would be simplified. Phase II of the effort would further examine a thermal storage system.

Though single story spaces can easily be daylit using skylights and roof monitors, these are only readily usable on single story buildings. Since this design was to be applicable to multistory commercial buildings, skylights and roof monitors were ruled out. Light pipes and fiber optic daylighting systems also were not considered, as it was desired to investigate a simpler, less expensive alternative. An interior-exterior specular light shelf was chosen for several reasons: utilizing direct beam light reduces the area of low-R glazing, the exterior light shelf reduces the seasonal variation of light entering the clerestory window and provides control of sunlight entering the view window (more in the winter when the heat is needed and less in the summer when it is not), which eliminates much of the overheating typical in spaces with significant daylighting.

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The south-facing room geometry modeled for this building is shown in *Figure 2*. This room measures 20 ft by 20 ft (6 m by 6 m) and has an 8 ft (2.4 m) dropped ceiling. A 3-ft (0.91 m) tall view window that is 4 ft (1.2 m) above the floor extends the entire 20 ft (6 m) width of the perimeter wall with mullions and structural supports that occupy 20% of the nominal glazing area. The 12-ft (3.6 m) long light shelf is a dropped ceiling that has a specularly reflective Mylar film on its top surface. This Mylar film is applied also to the ceiling and walls above the light shelf and is illuminated by a 2-ft (0.61 m) tall by 20-ft (6.1 m) wide clerestory window. The rear of the specular light shelf opens up to the ceiling of the rear half of the room on the north side of the room.

The specular light passage above the dropped ceiling maintains the interior direction of the light until the last bounce off of a diffuse surface to spread the light downward. A daylighting simulation without the view window indicates that the specular light shelf lights nominally the rear two-thirds of the room, while the view window lights the front one-third. Horizontal mini-blinds are used on the view windows during the winter to control glare and to direct the sunlight up onto the diffusely reflecting ceiling for a more even distribution of light through the room. Perforated mini-blinds are recommended so occupants can see outside even when the blinds are closed.

The primary means of daylighting the north rooms is to provide a view to a large part of the sky. The first floor rooms facing north have a 3 ft (0.91 m) high view window, a 2 ft (0.61 m) high clerestory window and a 3 ft (0.91 m) high skylight that span the entire width of the room. The second floor offices have two 3 ft (0.91 m) high skylights. A cross-section of one of the north rooms can be seen in *Figure 1*.

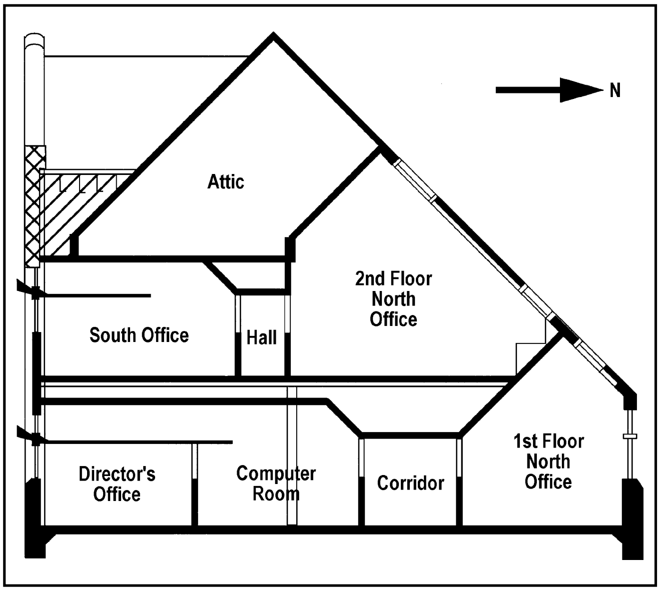

Figure 1: Cross-section of the Zero Energy Building.

The lighting system is designed with a luminous efficacy of 80 lm/W (T-8 fluorescent lamps with dimmable electronic ballasts) and fixture coefficients of utilization that range from 0.62 to 0.28 depending upon fixture type and room geometry. The total connected lighting power necessary to provide an average 75 fc (750 lux) in the offices and 20 fc (200 lux) in the hallways is 29.2 kW or 1.68 W/ft^2. This lighting power density is below the more stringent (whole building) method of complying with the *ASHRAE/IESNA Standard 90.1-1989, Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings* energy code. Given the credits for daylighting controls, the adjusted connected power is about half of the allowed lighting power budget. Dimming ballasts are used to optimize the amount of energy savings possible from "daylight harvesting," i.e. providing only as much electric light as is necessary to meet desired interior light levels. Though it costs more to provide dimming controls for fluorescent lights, fluorescent lighting provides four times as much light per input watt as does incandescent lighting.

Predicting Daylight Inside Buildings

To predict the amount of daylight inside of buildings, two questions must be answered: 1) how much direct beam and diffuse light are available outside of the building throughout the day and over the course of the year, and 2) what is the spatial distribution and intensity of light inside the building enclosure?

The weather data used herein for the whole building energy analysis are the Typical Meteorological Year (TMY) data compiled by the National Climatic Center.[8] Unfortunately, there is a dearth of measured illuminance data available, so a model for illuminance is used. To achieve consistency between illuminance and weather data, we linked the thermal simulation to the daylighting simulation by using hourly TMY solar data in the daylighting simulation. The irradiance data are converted to illuminance data using the luminous efficacy (lumens/Watt) model of Perez.[9]

The illuminance data are used in a ray tracing analysis to distribute the incident light. Ray tracing follows the path of a "particle" of light from its origin in the "sky" (defined as a plane just outside of the window) across the interior space as it bounces from reflective surface to reflective surface until it is absorbed. Ray tracing models are robust: radiative properties (reflection, transmission and absorption) of any material can be modeled, only if probabilities of reflection, transmission and absorption and their angular variations can be described mathematically.

In particular, specular reflectors are modeled accurately using ray-tracing methods. A further discussion of this method and a procedure for determining the accuracy of this method is given in Maltby & Burns.[10] McHugh describes how this method is applied to calculate illuminances in a space.[6] This method is computationally intensive—the geometry modeled here with approximately 100 surfaces requires the tracing of 1.2 million photons for each position of the sun modeled. Separate runs are performed for direct beam sunlight and diffuse skylight. Since the diffuse light is independent of the position of the sun (isotropic diffuse model), the number of diffuse runs was dependent only on the number of positions modeled for the mini-blinds. Each simulation requires about 10 minutes of computation time on a fast processor. Over 1,000 runs were performed to optimize the performance of the daylighting design shown in *Figure 2*.

Any daylight simulation predicts the illumination factor, defined as the ratio of light transmitted through the "work plane" (an imaginary surface located at a height above the floor where work is performed), to that incident outside. In an office, the work surface is typically at the height of the desktop. Here, the work plane is divided into a regular 10 by 10 grid of subsurfaces to yield the spatial distribution of illuminance. For this study, the subsurface size is 4 ft^2 (0.37 m^2). Where the illuminance level is low, it can be augmented with electric lighting according to a control scheme. Millions of photons are emitted from the "solar" surface, which represents the position of the sun at the particular date and time for the run.

A photon may pass through the window, then through the work surface (tallied for the subsurface through which it passes), and be reflected (probabilistically) from the floor and the ceiling before it again passes through a different subsurface (again tallied). It is eventually absorbed and tracing proceeds with a new emission. Note that a photon may be tallied more than once as it passes through the work surface. Given the ambient diffuse and direct beam illumination for every hour of a "typical" meteorological year (TMY), this is multiplied by the appropriate illumination factor which specifies how much of the ambient light passes through a given subsurface of the work plane. Thus, for every hour of every day, the footcandles of daylight on each subsurface are available on all work plane subsurfaces.

Predicting Whole Building Energy Usage

The novel aspects of this approach are the detailed daylighting calculations. For this, a representative room is divided up into nine lighting zones and the average light level for each zone is compared to the lighting set point, in this case 75 fc (750 lux). Where a zone is underlit, electric lighting is used to achieve 75 fc (750 lux). A variety of lighting control strategies could be used such as: on-off, stepped lighting, continuous dimming; and functions could be generated to describe the relationship between light output and electrical input into the lighting system. However, for simplicity's sake, a directly proportional relationship is used. This yields the hourly fraction of electric lighting that is displaced by daylighting for the entire nine zones (room), which is written to a file for each of the 8,760 hours of the year for each class of room.

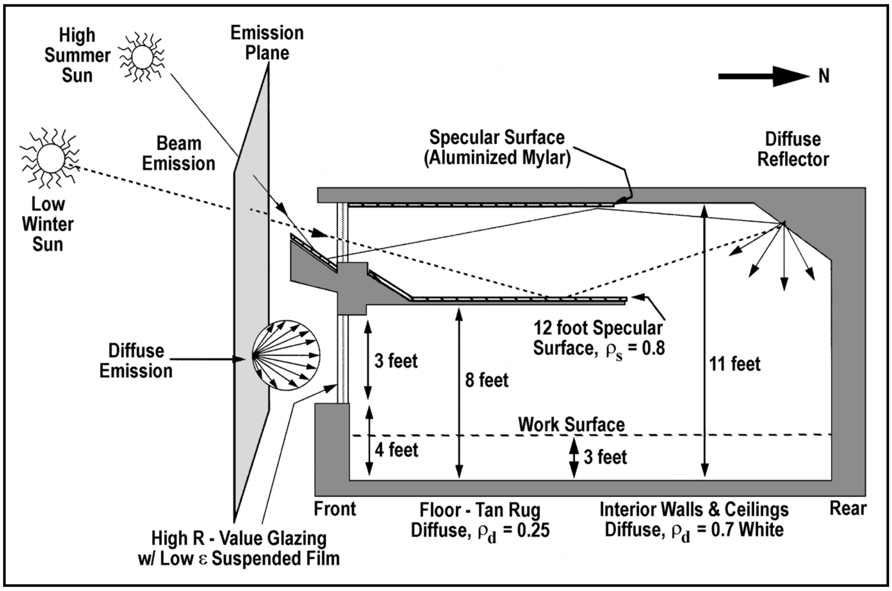

Figure 2: Daylighting geometry—south rooms.

The Building Loads and System Thermodynamics (BLAST) program is then used to calculate the energy used by the entire building: lights, plug loads, and HVAC system and plant. Using the BLAST program, a direct-indirect evaporative system and a conventional electric chiller system are simulated. The BLAST program accepts inputs that describe building orientation and construction, HVAC system type, and schedules of set points, fan operation, light and plug loads. Besides providing a thermal model of how the building responds to these inputs and weather data, BLAST accumulates these loads to result in annual energy and peak demand for each run.

The BLAST program was altered so that the daylight fraction file is read, and electric lighting loads are reduced accordingly. Because both the daylight fractions and the weather data used to calculate solar thermal loads derive from the same source, daylighting and electrical usage are predicted coincident with HVAC system performance. This enables the determination of the monthly peak demand and the energy usage, thereby allowing accurate estimates of energy (usage and demand) cost savings to be made.

Results

Combining the results of a daylighting simulation into an annual building energy simulation captures the interaction of daylighting with other building energy mechanisms. A building energy simulation also predicts the effect on electrical demand. Electrical demand (in units of kW) typically costs the building owner as much as the cost of electrical energy (in units of kWh).

The six-building/HVAC system configurations considered are:

A. The base case. No clerestory windows or skylights, but with an overhang above the south-facing view windows, electric lights are not dimmable and the air-conditioning system uses a vapor-compression chiller with an evaporative condenser.

B. The same as Case A except that cooling is provided by a direct-indirect evaporative cooling system with a chiller backup.

C. Daylit building with north skylights, south clerestory windows with light shelves, dimming (daylight harvesting) controls on electric lighting, and a chiller to provide cooling.

D. The same as Case C except that cooling is provided by a direct-indirect evaporative cooling system with a chiller backup.

E. The same as Case C except with no daylight controls on lighting (i.e. electric lighting power usage is the same as Case A).

F. The same as Case C except with no clerestory windows and skylights but using the same reduction of lighting power as in Cases C and D. Case F is hypothetical since the elimination of clerestory windows and skylights would affect the amount of daylight available to displace electric lighting.

As seen in *Figure 3*, daylight displaces 70% of the annual electric lighting usage. As expected, most of the lighting savings occur in the middle of the day and in the summer. Indeed, many hours exist where no electric lighting is required. Daylighting reduces chiller usage, but only by 5%; the plug loads are slightly less than the peak lighting loads and chiller energy consumption is not that large due to the economizer operation. Thus, the electric lighting savings dwarf the chiller energy savings. As expected, evaporative cooling all but eliminates chiller energy usage. However, since the evaporative cooling system cannot provide cooling on the peak cooling day, the chiller size and peak energy usage are approximately the same as without an evaporative cooling system.

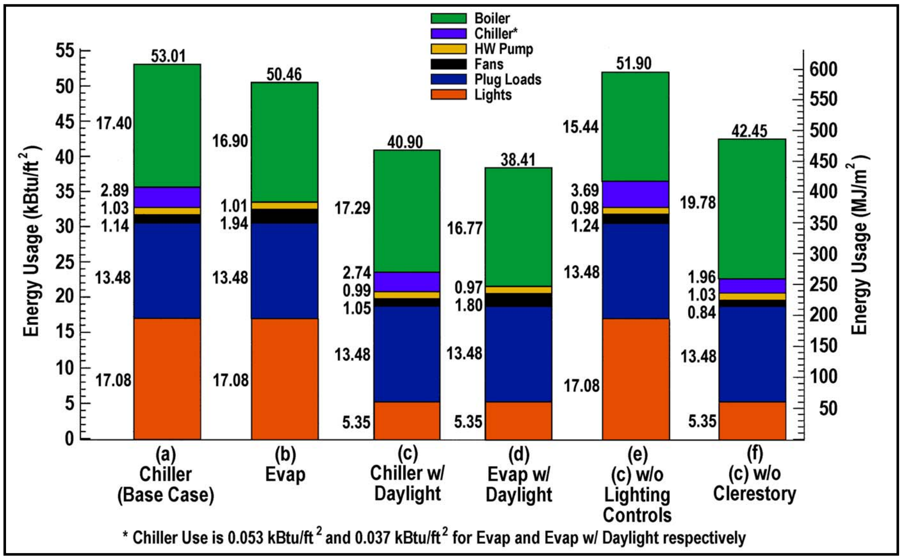

Figure 3: Annual energy end uses from BLAST results.

The heating energy results are initially surprising. One might expect that boiler fuel consumption would increase under the daylit case; the glazings are more thermally conductive than the opaque wall assemblies and electric lighting internal gains have been reduced. However, an additional 588 ft² (55 m²) of south-facing glazing in the daylit case admits more solar heat gain which is coincident with the reduction in internal heat gains from electric lighting.

In Case F with no clerestory windows and skylights, the base case building has the same electric lighting load profile as a daylit building, and the boiler usage, increases by 14% over the base case, thus substantiating the solar gain hypothesis. Conversely, if the daylighting geometry is used without lighting controls, the results given in *Figure 3* (Case E) show that boiler usage decreases by 11% over the base case; again illustrating that the daylighting geometry also provides significant passive solar energy.

Boiler fuel use is also reduced for the evaporatively cooled system. The higher airflow rates of an evaporative system allow higher supply air temperatures to provide the same amount of cooling than for the supply air temperatures of a mechanical cooling (chiller) system with lower flow rates. During the swing season, the core zones in an evaporative system are cooled with a greater flow rate of warmer air than would be with a chiller system. Because the supply air temperature is higher for the evaporatively cooled system, this supply air does not have to be reheated as much in the perimeter zones. (A terminal reheat system is used as an easy and convenient way to provide heat to perimeter zones.) Thus the evaporatively cooled building uses less boiler fuel because there is less reheating of cooled air.

The evaporative cooling system uses more fan energy (1.94 kBtu/ft² [22 038 kJ/m²]) than its mechanical cooling counterpart (1.14 kBtu/ft² [12 950 kJ/m²]) since a greater volume of air is necessary to remove the same cooling load due to the higher supply air temperatures. Daylighting reduces the amount of cooling loads due to electric lights, thus in Case C less fan energy is used than in Case A, and in Case D less fan energy is used than in Case B. Notice that in Case E, greater fan energy is used than in any of the other chiller cooling cases—Cases A and C, because without daylight controls on the electric lighting, this building must reject the heat from the sunlight entering the clerestories and skylights and the heat of the electric lights.

Figure 4 shows the monthly peak demand for all cases. The daylighting in the Zero Energy Building reduces electric demand by eliminating the need for electric lighting for most of the day. The effect is not as pronounced due to the small cooling loads, but daylighting decouples the coincidence of cooling and illumination needs. Due to this decoupling, the annual peak (which drives power plant construction) is not only reduced significantly but shifted from the summer to the winter.

Without daylighting, the evaporatively cooled building has a large demand spike in August, because for a few hours in the summer, wet bulb temperatures are so high that the evaporative cooler is unable to provide the required cooling. As a result, the backup DX chiller is engaged, and the monthly demand is set by these few hours of chiller operation. When evaporative cooling is used in conjunction with daylighting, on the hot sunny days when the chiller is needed, the demand by the chiller is offset by the reduced electrical and cooling loads of the electric lighting. Thus, daylighting enhances the value of evaporative cooling to electric utilities interested in reducing their summer peak.

Relatively low energy costs, for Fort Collins, Colo., were used to predict annual energy costs. Annual energy usage costs are, for the various cases, in \$/ft²-yr: a) 0.714, b) 0.660, c) 0.538, d) 0.500, and e) 0.726. The operating costs are lowest for the building that is evaporatively cooled and daylit, Case D. Daylighting the building has a much greater impact on operating costs than the addition of evaporative cooling. This corroborates the results of elimination para-metrics as discussed in Ternoey et al.[11]—reducing internal loads in commercial buildings will have the largest impact on reducing energy costs. Case E, the building designed for daylighting with clerestory windows and skylights but without the lighting controls, costs the most to operate. This points to the necessity of following a daylighting project through to the end. Scrimping on lighting controls, as often happens as a building project is nearing completion, can produce a building that is more costly to operate than one which is not carefully designed.

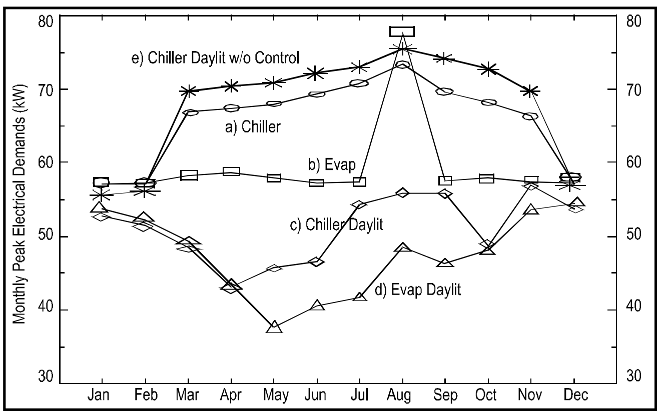

Figure 4: Electrical demand impacts of daylighting.

Conclusions

A novel daylighting design has been presented that utilizes beam radiation, thereby avoiding the classic problem of overheating, while simultaneously displacing over 70% of the annual electric lighting load. The novel aspects of the design are: 1) geometry, including a specular light shelf, an exterior reflector and an overhang over a view window, 2) advanced glazings (low-e and high R-value, yet passing more than 50% of the visible light) and 3) evaporative cooling. The simple payback of the energy conservation measures listed here is about 13 years. Though a building constructed now should last until the 22nd century, energy efficiency design features with more than a 10-year payback are often eliminated in the design process. However, the cost-effectiveness of such designs can be increased as follows:

• Over time, the cost of dimming ballasts should drop as the technology matures.

• Judicious use of dimming controls should also be considered. The luminaires closest to the windows are not needed most of the time during the work day; a simple on-off control may capture the most savings whereas a dimming control may be more appropriate for a luminaire at an intermediate distance from the windows.

Since the productivity benefits from daylighting and evaporative cooling are hard to quantify, the building community in general has not assigned a monetary value to these benefits. A multi-disciplinary approach that elevates the importance of occupant satisfaction with temperature, humidity, air quality, lighting quality, daylighting quality and view of the outdoors may allow these aspects to be quantified.

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