A Case Study in Integrated Design: Modeling for High-Performance Façades

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ABSTRACT

This paper presents a case study of an 11-story, 267,000 ft^2 (24,804 m^2) office building for San Francisco, California. Integrating building performance consultants early in the design process enabled strategic use of thermal, daylighting, energy use, and comfort modeling to produce a sustainable building with a high-performance exterior envelope. Analytical techniques included site shading evaluation, physical test cells of advanced daylighting products, and energy modeling parametrics during schematic design and design development phases. A method to evaluate the thermal comfort performance of curtainwall alternatives was developed to quantify human comfort conditions within the perimeter zone. This method utilizes noncommercial thermal performance software, including WINDOW and THERM, DOE2.1e and UCBCOMFORT, as well as a newly developed method of calculating mean radiant temperature (MRT).

INTRODUCTION

The office building that forms this case study is located in downtown San Francisco, adjacent to a 1977 building also occupied by the client. Construction is scheduled to start in 2004. The new 11-story building will be a 267,000 ft^2 (24,800 m^2) building and will house 800 employees. The downtown site is constricted and land values and construction costs in San Francisco are both high. This results in a need to maximize allowable floor area and fill much of the volume of the site. The street grid south of Market in San Francisco is approximately 45 degrees off cardinal, resulting in a building volume with façades oriented to the northeast, southeast, southwest, and northwest. The northwest façade faces the earlier, 16-story building and is canted back from bottom to top to let light into a shared plaza between the two buildings. The entrance is on the southwest through a double-height lobby. The challenge of designing this building to act in concert with the earlier building led the architects to design the southeast and northeast corners of the exterior wall to refer to the curtainwall design of the 1977 building (Figure 1).

Figure 1 *View of the proposed building (top) from the north indicating the northwest curtainwall and rooftop photovoltaic array (rendering courtesy of the architect).*

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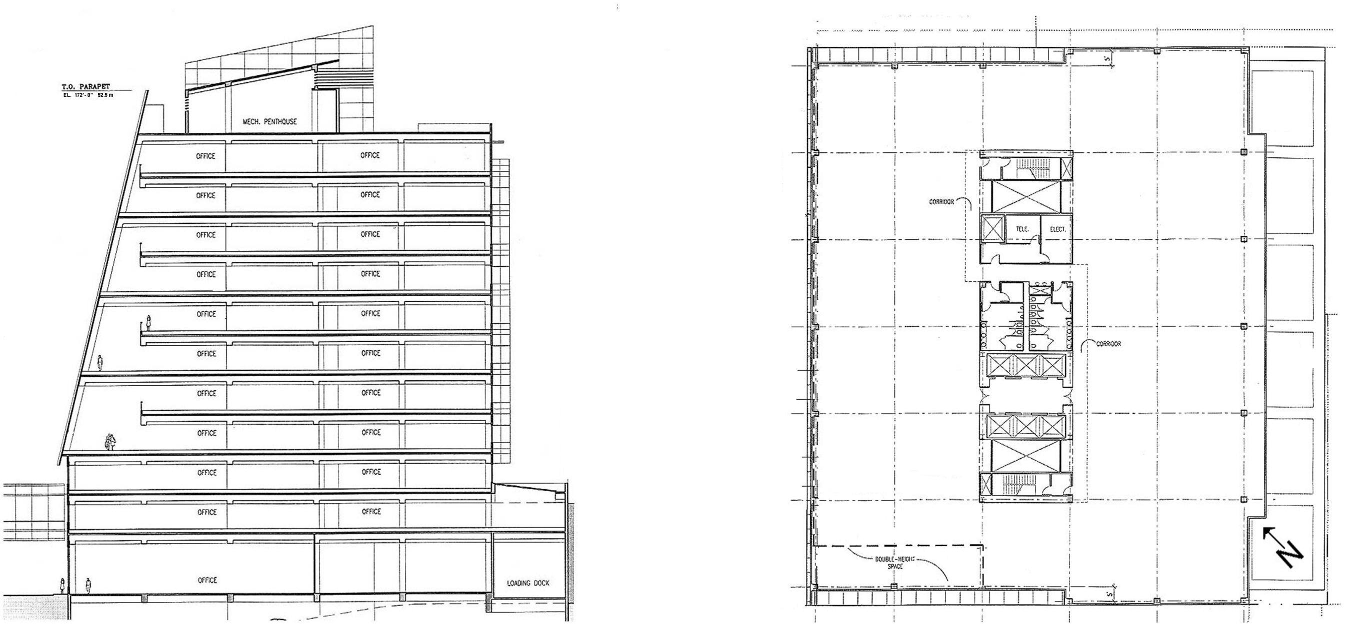

(a) (b)

Figure 2 *(a) Full building section cut through NW and SE curtainwalls. (b) Plan for typical office floor.*

Site constraints formed a large, rectangular building plate with bays that average 140 ft (42.67 m) by 184 ft (56 m) around a central core. This leaves 63 ft (19.20 m) deep office bays on the northwest and southeast, with narrower bays of 34 ft (10.36 m) depth on the southwest and northeast. Recognizing site height restrictions, the floor-to-floor dimension is 13 ft-9 in. (4.2 m) with a 9 ft-10 in. (3.0 m) floor-to-ceiling height to accommodate deep beams for the long spans (Figures 2a and 2b).

The client requested a sustainable building and intends to apply for U.S. Green Building Council LEED^{TM} certification at the Gold level. This goal established, from the beginning, a focus on energy efficiency, renewable energy, and interior environmental quality in the design. A high-performance curtainwall, including daylighting and sun control, was considered to address a number of LEED^{TM} requirements (USGBC 2003). The roof of the building has been designated for photovoltaic arrays.

This mid-rise office building offered an opportunity to explore an integrated design process in delivering a sustainable building design (Monroe 2002). The architects focused quickly on the curtainwall as the major design challenge and gathered together a design team that included structural, mechanical, and building performance consultants (the authors). Frequent meetings between team members, working design sessions, and increased communication was the primary management strategy for the integrated process. A critical method for making the integrated design process work on this project was to incorporate a wide range of modeling and simulation techniques early in the schematic design phase with followup detailed studies in the design development phase. These are the methods discussed in the sections below.

THE CURTAINWALL AND THE DESIGN PROCESS

The complexities of designing a high-performance façade range from coordination of disciplines (architectural, structural, mechanical, curtainwall, daylighting, electrical lighting, and space planning) to cost and value considerations in value engineering and specifications. While the design and evaluation of a curtainwall system in relation to single performance criteria (daylight, energy use, cost, lateral loads, etc.) are not necessarily difficult, resolving all performance criteria within the design process and timeframe poses significant challenges.

The curtainwall itself performs a highly integrative role in overall building performance. As the primary building envelope in multi-story office buildings, the curtainwall is responsible for controlling the flow of heat, visible light, solar radiation, sound, water, and view between inside and out. It must resist gravity and lateral loads from wind and seismic activity. It must be designed to be washed regularly. In addition, the curtainwall creates the aesthetic image of the building; it determines what the building looks like and how it will fit visually into the site and city context.

The design team is usually organized to address only a few of these issues in the early phases of design. In schematic design (SD), the design team typically determines the massing, orientation, plan, and section organization of the building, initial structural and mechanical systems, and a first pass at material selection. Most aspects of curtainwall performance, including glass specification, are addressed in the design development (DD) phase, when consultants are brought into the project to size and specify components and systems.

Integrated Design Process

In order to achieve a highly integrated envelope design and associated sustainable building performance, traditional design delivery must be rethought and reorganized. As Mendler and Odell (2000) note, "We should not expect to produce fundamentally new buildings using the same traditional design process." Those disciplines that bring expertise in the performance issues need to be brought into the design team early in the schematic design phase in order to identify and exploit the opportunities that may arise as initial design decisions are being made.

Putting this into practice is more difficult than it would seem. Standard practice is structured to exclude many relevant consultants until later in the design process, to the extent that the standard architectural contracts and documents describe consulting work in the early design phases as "special services" (AIA 1994). The architects need simultaneously to establish a design direction and to accept input from a wide range of disciplines, which is quite difficult. This integration of expertise in the design process can be somewhat cumbersome and unwieldy, with a large number of consultants sitting around the table before a design has enough direction to talk about.

As the sustainable design community recognizes the need for an integrated design process, much of the literature suggests the strategy of a "design charette" as an initial means of pulling all these voices together, but it does not offer much additional advice or guidance. Sustainability and building performance consulting is a relatively young, emerging discipline, currently being defined through the efforts of those working in the field. Although there are recently published general guides for incorporating sustainable issues into practice (Mendler and Odell 2000; AEC/CEC 1999), there is at present no generally understood or agreed on set of services or methodologies recognized as standard practice.

In many ways, this project offered an ideal set of conditions for developing an integrated design process. Because the building was designed virtually to fill out the available envelope, design issues were quickly focused on the curtainwall and exterior envelope. This is different from early schematic design phases on low-rise or suburban office buildings where the architects have more leeway in the massing and orientation decisions. It was easier to bring advanced modeling techniques to bear on the early design because the design team recognized that many of the performance questions and LEED^{TM} evaluations would focus on the curtainwall. Because of this, the design team was able to employ energy and daylight modeling to optimize the envelope at the schematic design stage.

INITIAL THERMAL MODELING

The thermal and energy modeling software DOE2.1e performs hour-by-hour calculations based on a building description and weather data. A powerful technique for modeling, the software is often used to model annual energy use once many of the building design decisions have been made. However, in this project, very early simulation was possible. The overall building envelope was unlikely to change shape or area due to project constraints and the downtown site provided extensive site information unaffected by design changes. The input files could be generated and then changed incrementally as various performance issues were addressed.

The schematic design phase DOE2.1e runs used a California Energy Code Title 24 compliant envelope as the base case to help determine the objectives of the curtainwall design. From the beginning of the project, the design team was concerned that the large, canted northwest curtainwall exposed the building to excessive summer afternoon solar loads. A series of sun and shade projections for summer and winter conditions in a three-dimensional modeling program supported this concern. The other orientations received some shading from the surrounding city blocks and did not appear to be as much of a problem as the northwest façade.

Parametric runs were used to generate heating and cooling loads that result from the performance of the building envelope (Ternoey et al. 1985). In these, the input model was rich in architectural detail; the size of each floor plate, the size and location of the core, the orientation of each façade, and the floor-to-floor height were known. Additionally, the surrounding site geometries and differentiation of glazed curtainwall and punched openings at the northeast and southeast corner bays were established very early in schematic design. The office floors were defined by nine thermal zones, each determined by a unique orientation and curtainwall conditions (Figure 3). The vertical elevation of each of the ten office floors was also specified and therefore took into account specific conditions of site shading. The hour-by-hour simulations used the San Francisco Typical Meteorological Year (TMY) climate data file and were run without lighting or mechanical systems to isolate the loads.

Unexpected Results

The heating loads (Figure 4) quantify the annual conditions on a typical floor. The northeast and northwest corners of the building (simulation zones 4 and 2 in Figure 3) are areas with the highest heat loss and the greatest need for heating during winter months. These results were as expected and supported the initial direction of the design team to have some concern for the perimeter zones and early morning building warmup during the cooler winter months.

As indicated in Figure 5, the southeast façade (zone 8) has the highest cooling loads. Once identified by the parametric runs, this made sense because the full façade is without significant site shading and receives direct sun during warmer months. The cooling loads for the west corner (zone 1) are also higher than the other zones, receiving late afternoon solar radiation during the warm months. It was determined that the southwest façade (zone 5) contributes less heat gain than expected due to site shading but nevertheless requires shade. The northwest façade (zone 2), which had concerned the design team, proved to be less of a cooling load problem than initially imagined.

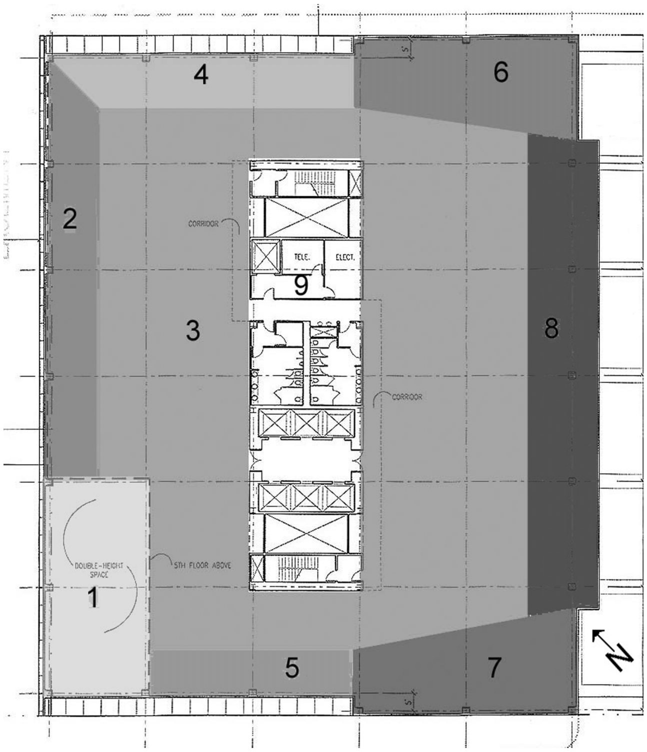

Figure 3 *Typical floor plan showing thermal zones.*

The results of this very early modeling changed the priorities for shading and the resulting approach to daylighting and glass specification on the various building façades. It set the stage for discussions of allocation of funds to the various façade strategies. With these results in hand, the design team could turn to an examination of daylighting strategies with specific knowledge of each orientation, rather than the more generic daylighting design strategies generally used at this stage of design.

SCHEMATIC DAYLIGHTING ANALYSIS AND DESIGN

The results from the initial DOE 2.1e parametric runs indicated that daylighting and shading strategies needed to be specific to orientation. The challenges and issues varied for each wall, requiring a range of modeling techniques to assist the architects in design decisions. Within the specific approach for each façade, however, general daylighting strategies are still important and applicable (ESC-EEC-EAEC 1993). Daylighting design goals for office spaces include:

- Maximize daylight illumination levels in work spaces
- Minimize the gradient for daylight distribution from perimeter to interior zones
- Avoid glare due to sky brightness within visual field

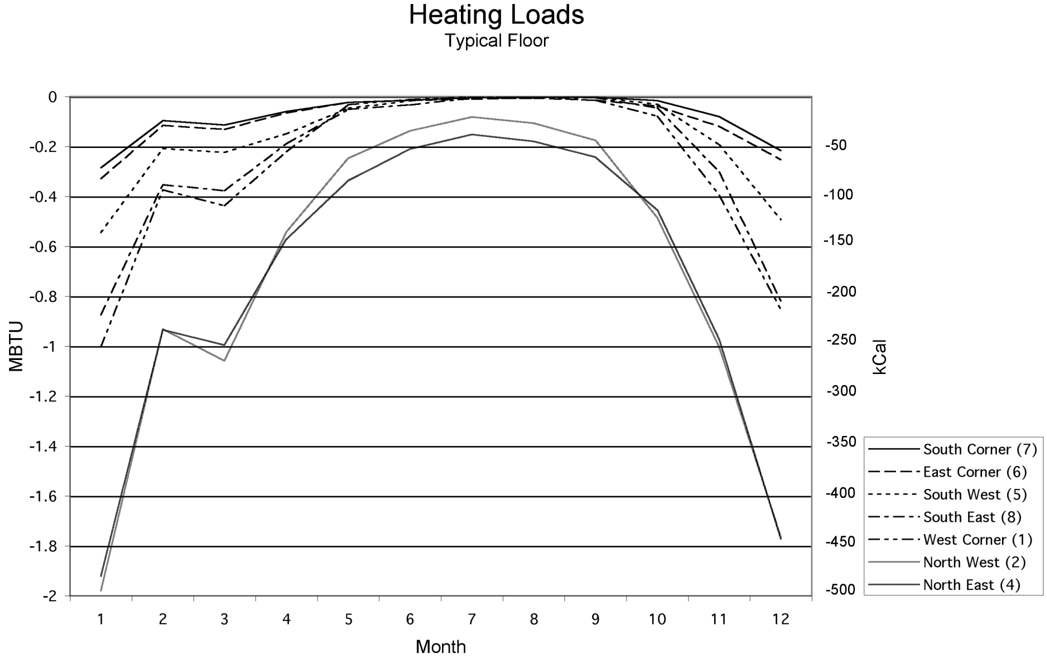

Figure 4 *Typical floor heating loads.*

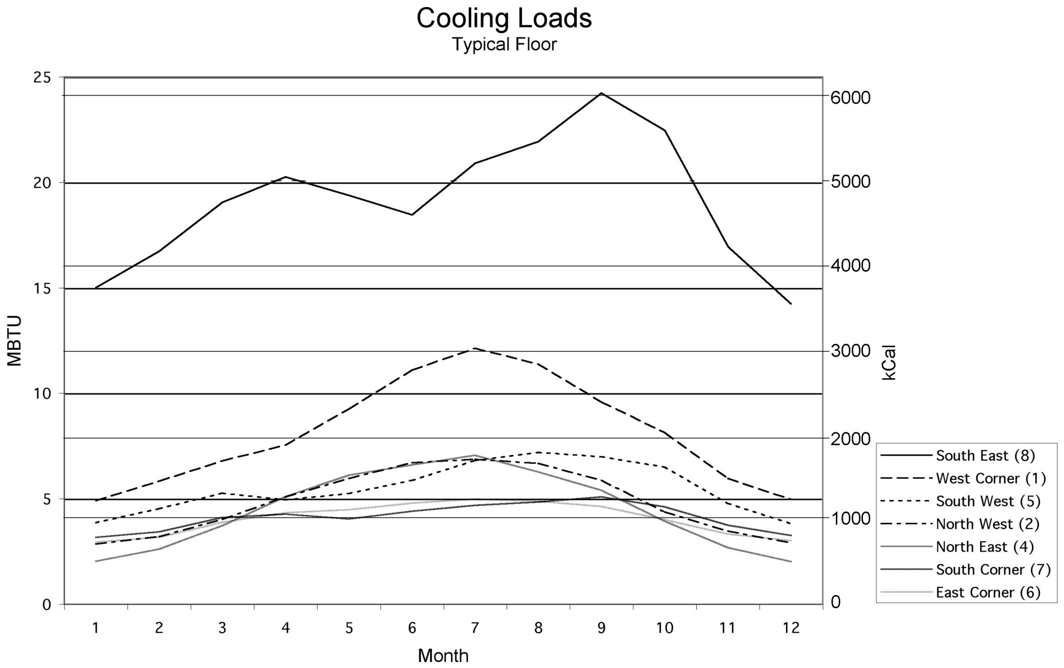

Figure 5 *Typical floor cooling loads.*

- Control direct sunlight on work surfaces (desks and computer monitors)
- Illuminate the ceiling and not just desktops for visual comfort and lighting control coordination
- Coordinate space planning with daylight availability

Architecturally, the most important move to achieve these goals is to maximize the head height of the curtainwall glazing for deep daylight penetration. Due to site and program constraints discussed above, the floor-to-floor dimension is 13 ft-9 in. (4.2 m). Structural and mechanical decisions were happening in parallel and were discussed at design team meetings. Coordination with the mechanical design developed the approach of underfloor air delivery and air return through a reduced ceiling plenum. However, the resulting head height is only 9ft-10 in. (3.0 m), which delivers just a 15 ft (4.57 m) zone of usable daylight (Hopkinson et al. 1966). Structurally, the initial design had a perimeter beam with a lower edge that dropped below the ceiling line along the entire window wall. This was likely to create significant fall-off as daylight moved into the office bay. By working with the structural team at this stage, they were able to redesign and size beams so that their entire shape is contained above the ceiling. This initially was resolved for the northwest façade by upturning the beam into the spandrel area, although in the final documents the beam sits within the ceiling plenum. Most important for daylighting, this design request was continually understood by the structural designers, resulting in flush ceiling from the curtainwall glazing back.

Southeast Façade

Once the orientation of the façades was determined to be a critical distinction for curtainwall performance and design, a separate solar load simulation was developed for each orientation. The modeling for the southeast façade (Figure 6) indicates a fall equinox peak in solar gain, with June second to September. December and March solar radiation loads are diminished by winter fog and overcast sky conditions. Shading is important for this façade for sun angles from June to September.

To explore strategies to optimize the southeast curtainwall design for shading, the design team proposed four possible options (Figures 7a-7d). The base case (a) included an interior light shelf to improve the daylight gradient and visual comfort. The first modification (b) increased shading by adding three short mullion extrusions on the exterior. The next (c) added one short extrusion and one deep exterior shade. The final option (d) included sloped glazing (at 13 degrees) in addition to the base case interior light shelf.

The four alternatives were modeled with DOE2.1e to reveal solar loads (Figure 8). In September, identified as the worst period of the year earlier, option (b) delivered only 89% of the solar load, option (c), 82% of the solar load, and option (d) 71% of the solar load relative to the base case, making the case that exterior shading would contribute to cooling load reduction on the southeast elevation.

In concert with effective shading, the southeast curtainwall must deliver daylight to a deep bay office space, 63 ft (19.20 m) from window wall to core. Working with the best

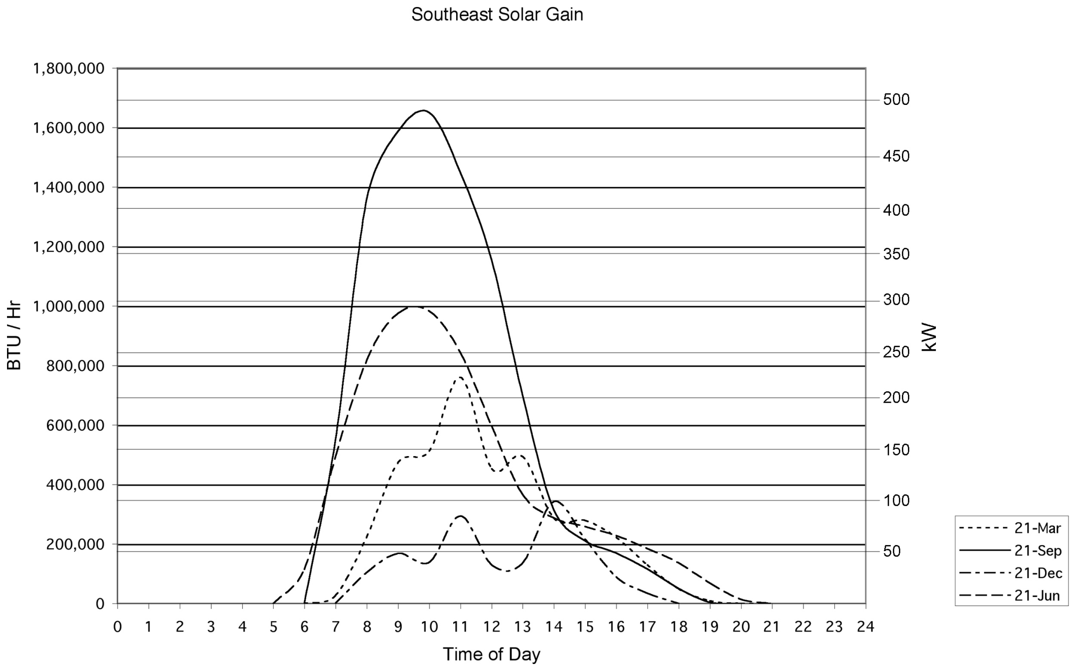

Figure 6 *Southeast façade solar loads.*

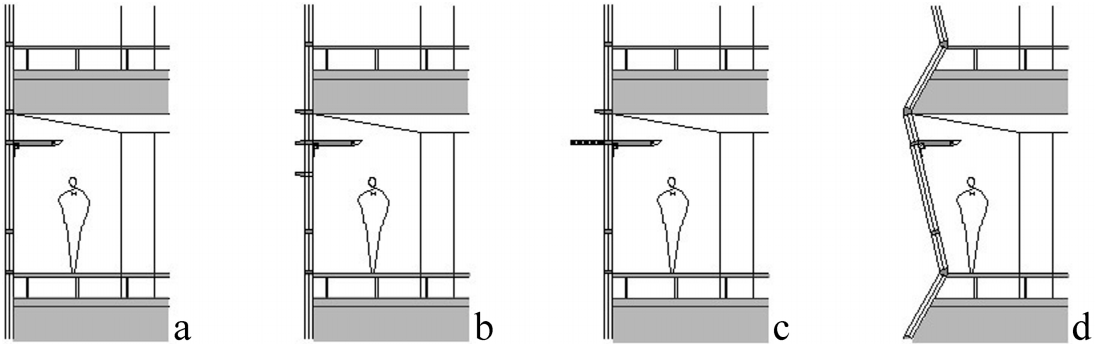

Figure 7 *Four alternative curtainwall designs proposed for the southeast façade: (a) base building with interior light shelf, (b) three small exterior horizontal shades added to base building, (c) 2 ft exterior shade added to base building, and (d) sloped glass with base building light shelf.*

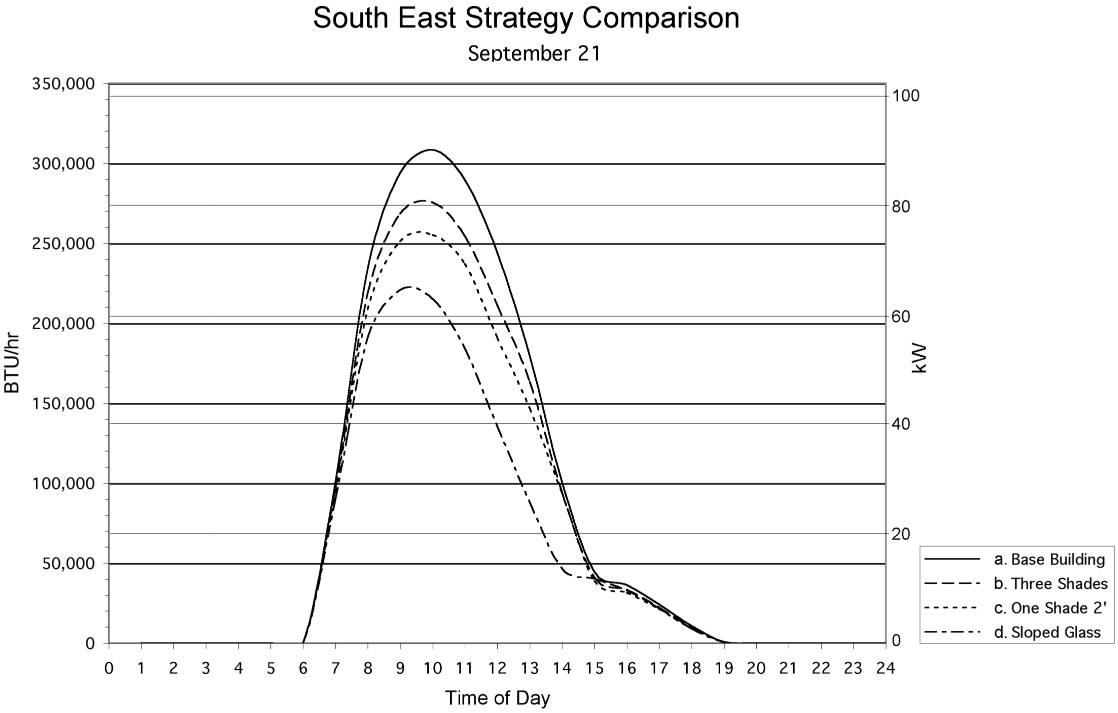

Figure 8 *Comparative solar loads during four seasons of the four architectural façade design options.*

nonslanted curtainwall option, the team turned to a combination of exterior overhang, interior light shelf, and light-redirecting glazing to boost the daylight penetration (Littlefair 1996). The authors identified a newly developed, polyester-based, total internal reflection film as a possible glazing selection to throw daylight deeper into the office bay. A physical model was constructed for use as a test cell and the performance of the light-redirecting film used in the upper lights was measured in a calibrated mirror-box overcast sky simulator (Figure 9). The film increases the daylight illumination level from a 1% daylight factor to a 2% daylight factor at 30 feet back from the window plane (Figure 10). A daylight factor of 2% is the required level of daylight illumination for 75% of the working area for LEED^{TM} credit for daylighting.

These tests demonstrated that this glazing technology can deliver daylight much farther into the office plan than usually achievable with a simple high clerestory design. Work with various glass manufacturers and suppliers determined that we could specify this material for its first U.S. architectural application, ensuring that the economics and production schedule would be satisfactory. However, the redirecting film does not provide shade from beam radiation. The exterior overhang and the interior light shelf were then sized to work together to block direct sun penetration through the upper light. The view glass will be shaded with manually controlled diffuse roller shades as desired by the occupants. The final configuration of the southeast curtainwall is shown in Figure 11.

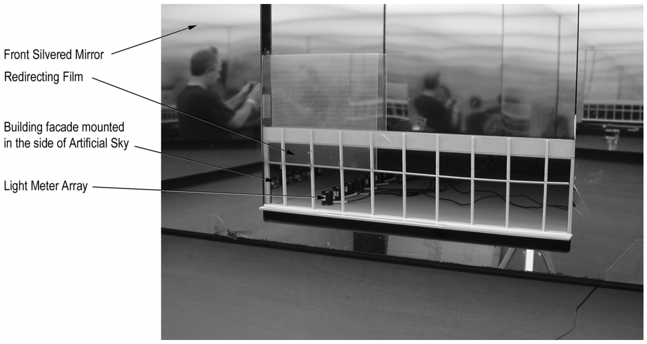

Figure 9 *Test cell of southeast façade mounted in artificial sky for tests.*

Northwest Façade

As discussed above, the solar gain through the northwest façade does not require a significant shading response for thermal concerns, either with a spectrally selective glass or with clear glass (Figure 12). However, the offices facing this orientation are vulnerable to serious visual discomfort from low sun angles in the late afternoon. With the sun nearly horizontal, exterior overhangs, light shelves, and other conventional shading geometry will not perform as needed.

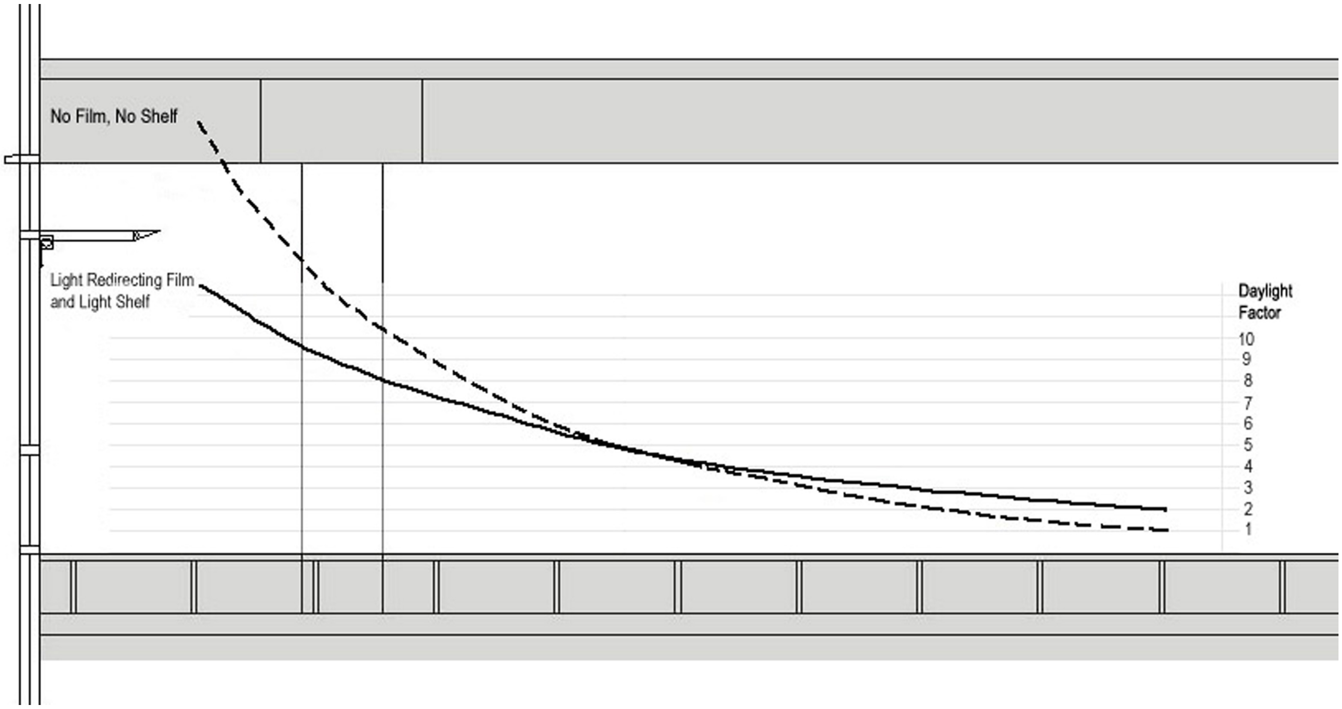

Figure 10 Section of test cell with measured daylight factors.

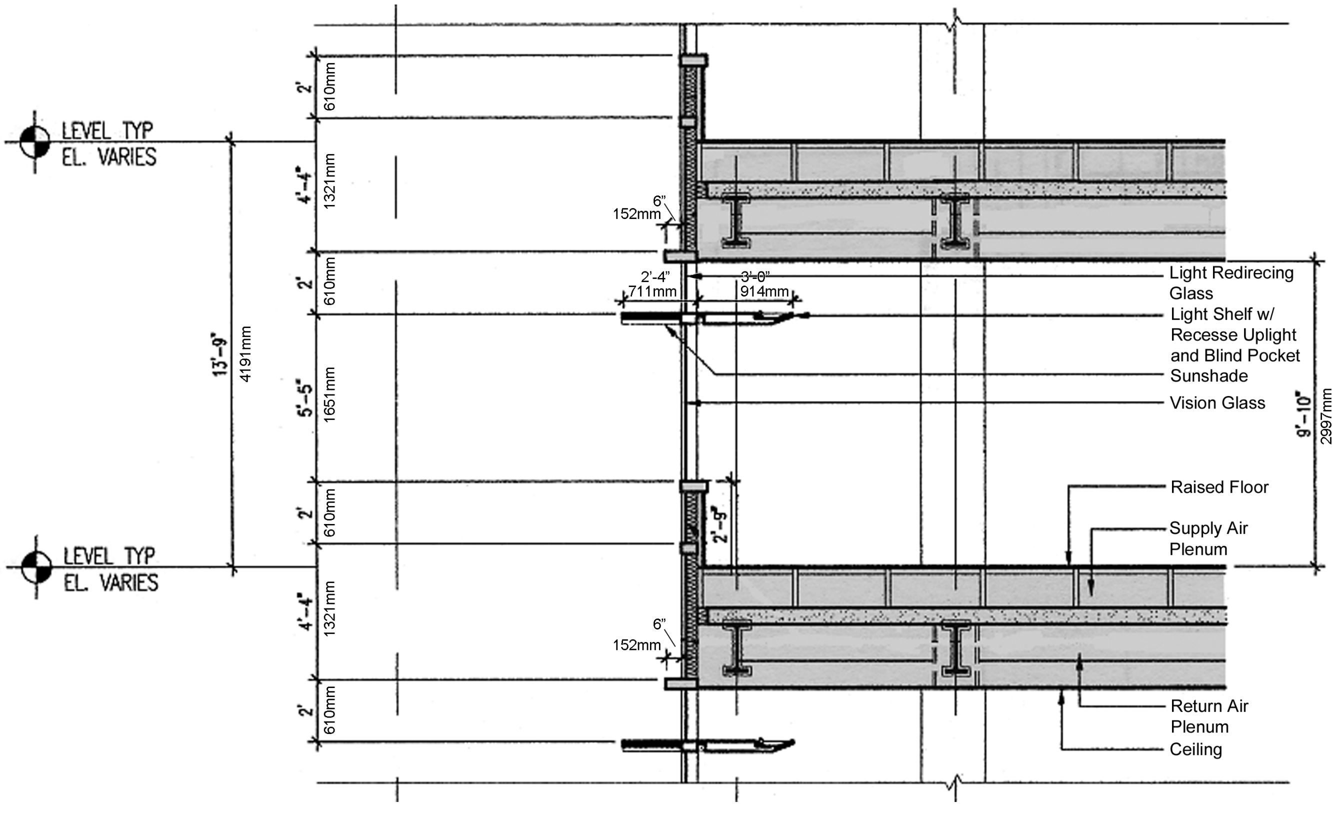

Figure 11 Final configuration of SE façade showing shading and daylighting components.

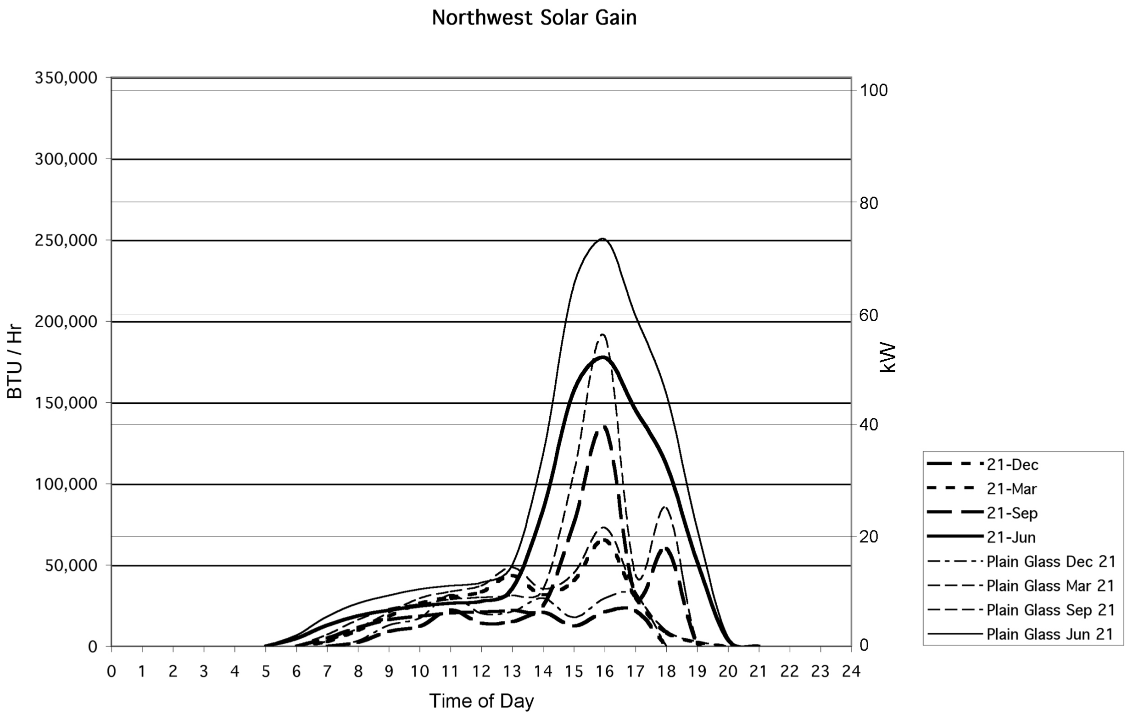

Figure 12 *Comparative solar loads on NW for two different glazing types by season.*

A relatively new glazing product that is well suited to this application—insulated glass with specular louvers in the cavity—was proposed by the daylighting consultants. This product is designed to redirect direct beam radiation toward the ceiling rather than allowing it to penetrate deep into the office floor. Unlike the redirecting film, the manufacturer was unwilling to release a sample for testing so the performance could not be quantified. However, the low, late afternoon, western sun poses a shading geometry challenge that can only be solved with this type of approach. The internal louvered system does not allow view out, which makes it appropriate for the clerestory but not the view glass on the northwest side. A tracked roller shade will then be used on the view glass to control sun penetration. Although quite expensive, the internal louvered unit is applicable for just the northwest elevation clerestory where it is the highest performing glazing for the task. Since the total area of the application is relatively low, the total cost is very small within the overall building budget (Figure 13).

Southwest and Northeast Façades

The curtainwall on the southwest façade is somewhat hidden from afternoon sun by site shading conditions; however, it still receives a peak of solar radiation in September and has radiation to deal with in June. Like the other orientations, winter months do not pose a pose a problem for shading (Figure 14). Unlike the other orientations discussed, the sun penetration geometry demands significant exterior shading and possibly some additional response. The southwest side (as well as the northeast) contains a “punched opening” condition at the southeast corner for visual reference to the 1977 building. This creates a depth of wall in which the addition of deep exterior overhangs is architecturally consistent. While performing an important thermal function, the exterior overhangs do not prevent all sun penetration through the curtainwall areas of this same orientation, and the design team was concerned about work stations near the glazing. Double-height spaces, initially conceived to connect two floors at a time to improve the community feel of the workspace, were located along this edge. These more public break spaces can be improved with some direct sun penetration during the winter months, creating visual relief from the diffuse light of the workstations and celebrating a connection with the outside world. By turning from purely technical means of dealing with shade to a more synthetic approach, the integrated design process improved the interior life of the office building and solved a problem of visual comfort (Figure 15a.) The northeast and southwest curtainwalls do not have to deliver daylight as deeply as the other two elevations, so the solutions developed for shading (which are repeated for aesthetic purposes on the northeast façade) are sufficient for daylighting performance as well (Figure 15b).

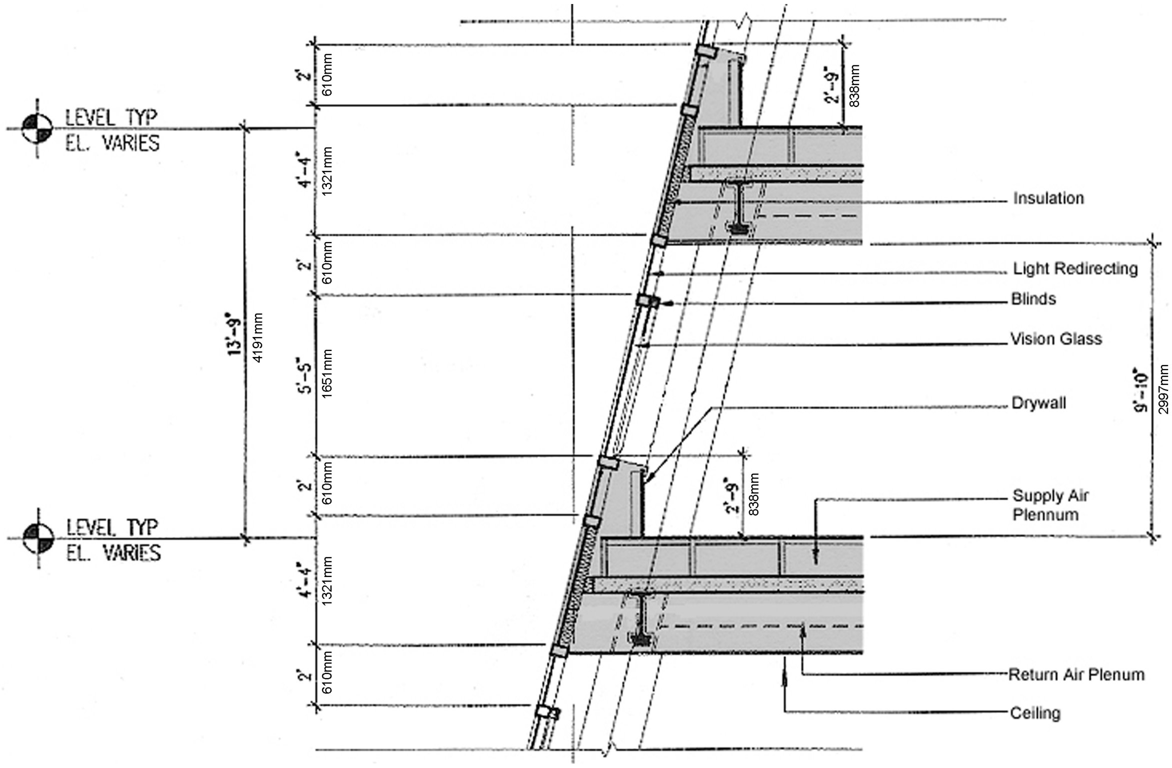

Figure 13 *Final configuration of NW façade showing daylighting components.*

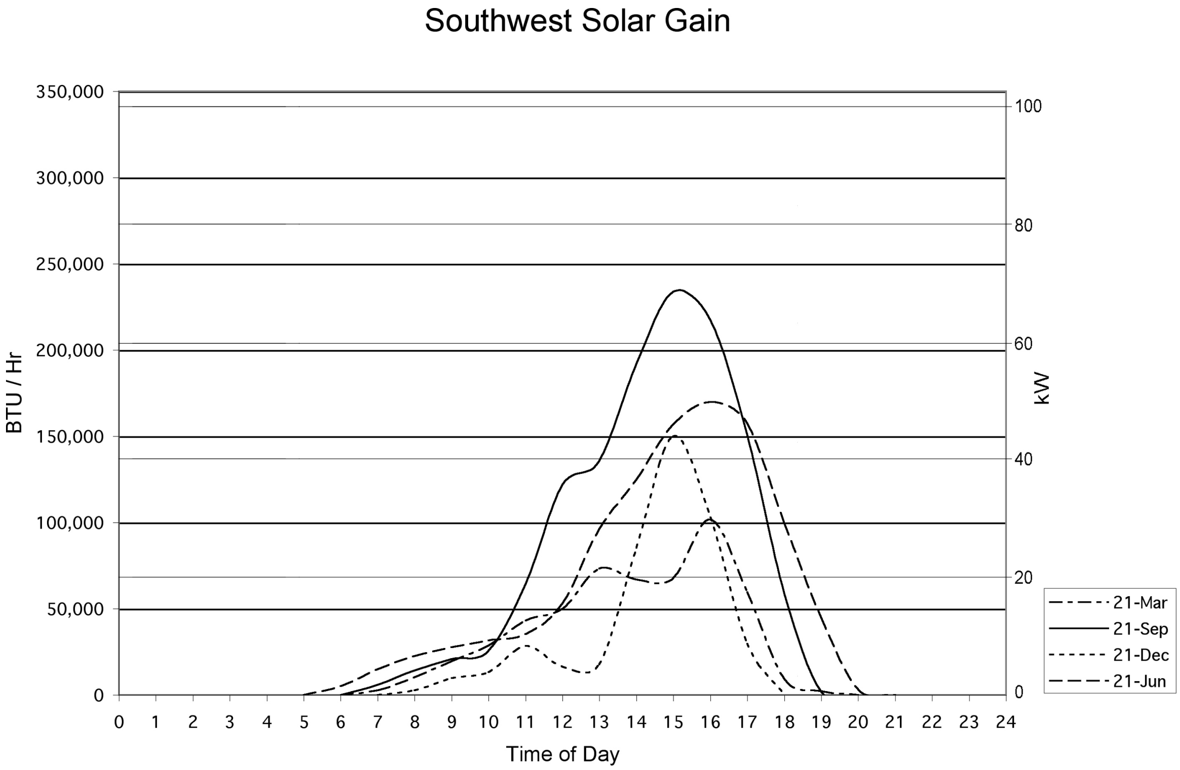

Figure 14 *Comparative solar loads during four seasons for the SW façade.*

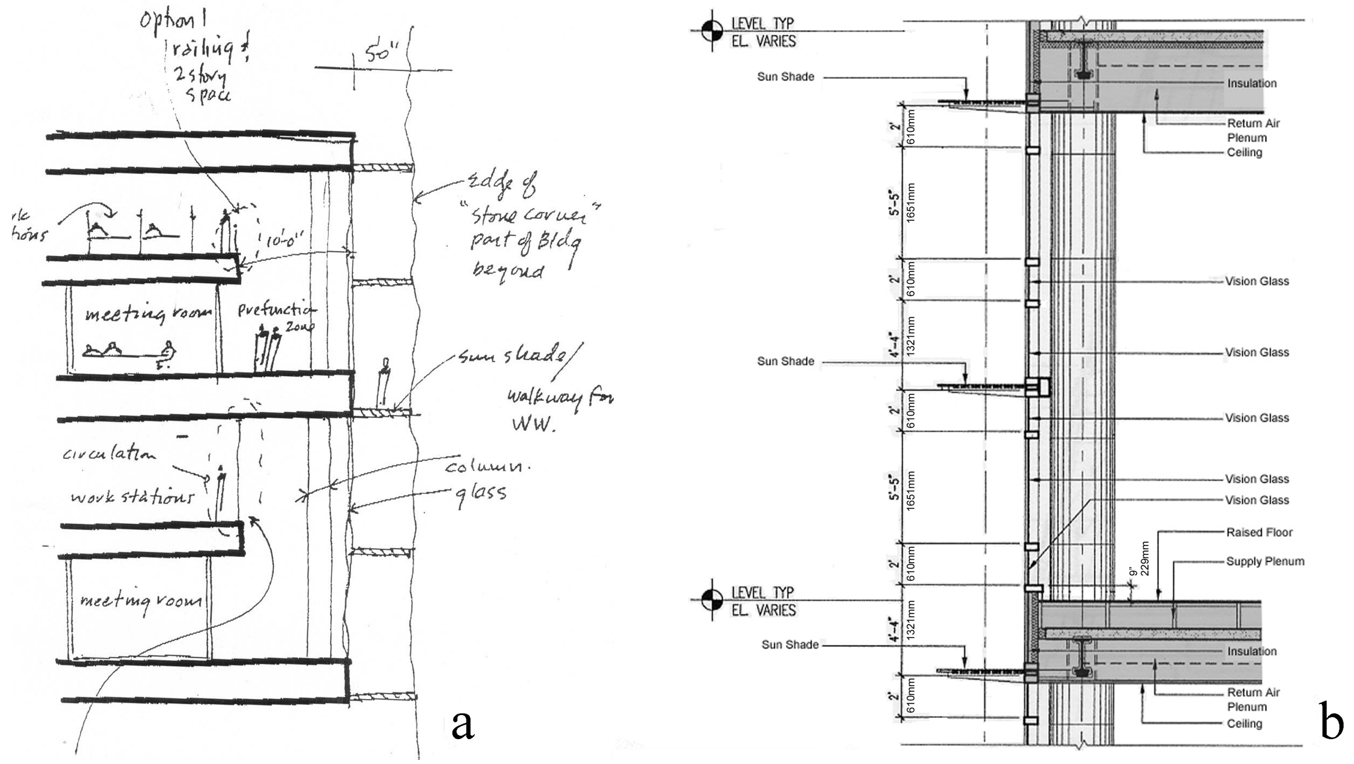

Figure 15 *(a) Sketch section of double-height space on SW and (b) final section of SW façade showing deep horizontal sun shades.*

SCHEMATIC DESIGN MECHANICAL SYSTEM ANALYSIS

As the work continued on the curtainwall strategies for each façade, there remained some thermal and energy issues to be addressed in schematic design. The mechanical engineers were concerned with occupant comfort in the perimeter zone as a result of the underfloor air delivery system. Other offices with no perimeter heating had recently been completed by the architectural firm and there was some question as to whether this building could proceed in that direction without increasing occupant discomfort during the morning building warmup period. Additionally, the mechanical engineers were considering a number of possible system approaches and were interested in using the already existing energy model to understand more about the trade-offs before they selected one.

Comfort and Perimeter Heating

As this project began, the new 2001 version of the Title 24 energy code required increased performance by the building envelope, producing a baseline building performance with increased thermal comfort. The thermal performance of the building perimeter zone on a cold winter morning, however, creates challenges for occupant comfort. A set of DOE2.1e simulations were run to see how the building would react in a prolonged warmup period during the winter with a range of envelope U-factors (Figure 16). The weather information selected was not a design day, but the coldest winter condition available in the San Francisco TMY data. The thermal performance of a single floor with and without the heating system on was modeled for a Monday morning after a four-day, unoccupied weekend, giving the building time to cool down. This thermal modeling indicates there is an important decrease in the interior temperature during morning building warmup in an envelope performing to even the new code requirements. The results led the design team to believe that perimeter reheat could be dropped from the mechanical design if the curtainwall design could improve the U-factor of the glazing and the spandrel panels were more heavily insulated.

Mechanical System Performance

Although it is more conventional than the modeling discussed to this point, the DOE2.1e model was available to do some analysis related to the choice of a mechanical system strategy for the building. This analysis would not typically have been included in a regular design process and the mechanical engineers were interested in understanding more about system choices for the upcoming value engineering sessions. The annual energy use for each mechanical option—including total kWh and the annual energy costs, including demand charge and energy charge—was modeled for six systems:

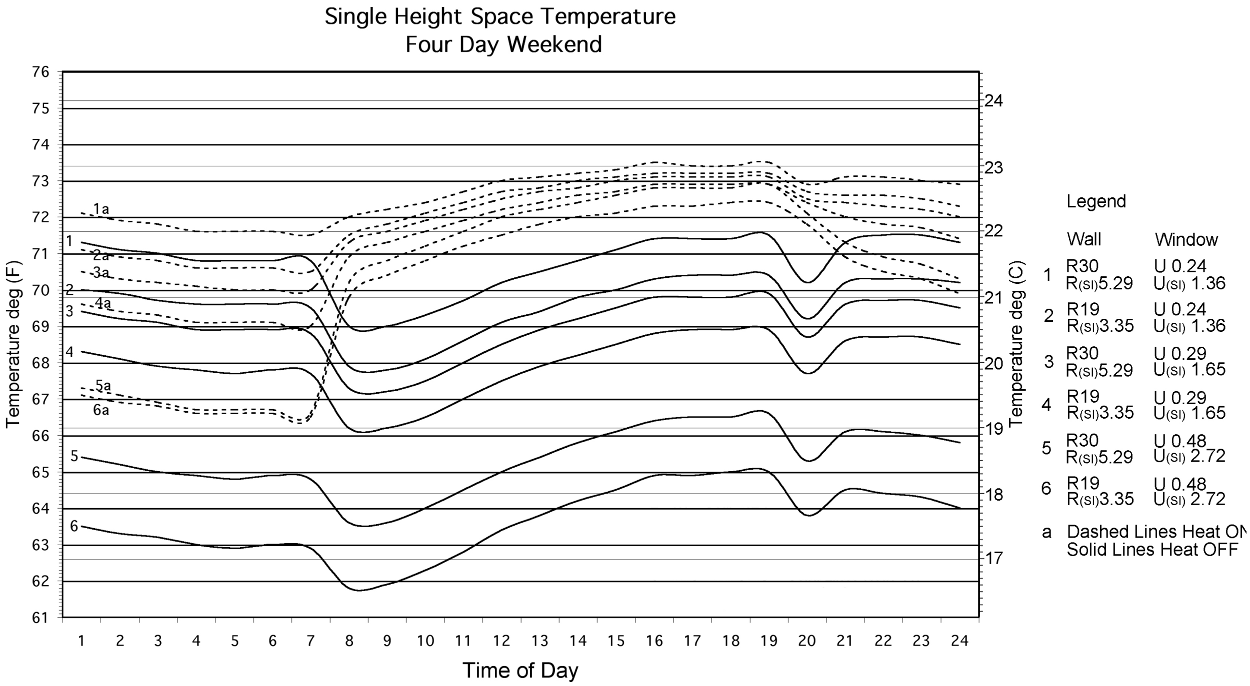

Figure 16 *Interior temperatures for TMY coldest winter condition in January after a four-day weekend for six curtainwall U-factors comparing heat on and heat off conditions.*

1. Chilled water system with thermal storage
2. Chilled water system without thermal storage
3. Built-up DX system with cooling towers
4. Built-up DX system with evaporative condensers
5. Packaged DX system with cooling towers
6. Packaged DX system with integral evaporative condenser

The first system (chilled water system with thermal storage) delivered the least annual cost and required the least kWh. System 3 cost 14% more to run annually, while the others ranged from 6% to 10% initial greater cost. The first system also presented the largest first cost, which usually would be enough to remove it from consideration, but this was the system chosen for the building.

SCHEMATIC DESIGN VALUE ENGINEERING

Many building designs have reached the end of schematic design only to find that the "sustainable" elements that enable reduced energy use, such as successful daylighting, shading, and similar options, are stripped out during a value engineering (VE) session. The format of value engineering decisions, in which each individual part and component of the building has a discrete cost in a spreadsheet, supports the view that any one part of the building design can be deleted for cost savings without consequence greater than missing that one part. However, almost everything that delivers sustainable building performance, especially energy savings and daylighting, is the result of a integrated behavior between many parts and components. If one piece is deleted, the entire system is at risk. Sustainable building designs have a much better chance of surviving the value engineering process if three aspects of the process are present.

First, one of the most important aspects of the integrated design process is the ability for all members to be present and engaged in the value engineering sessions. This can be as ungainly as early design meetings with many participants, but only in this way can the fully integrated design be understood, evaluated, and kept whole to perform as intended by the designers. The value engineering session for this building was unusual in recognizing this important aspect of the integrated design process and inviting discussion by all member of the design team. As a result, many aspects of the curtainwall design that would normally be deleted as "individually too expensive" were understood as part of a larger system and retained.

Second, the iterative modeling that generated quantitative performance information about thermal loads, daylighting levels, shading performance, and energy use contributed real information about the nature of the design choices that had been made. The consequences of deleting parts of these performance systems could be known, identified, and discussed with a rational rather than an intuitive or moral basis (the basis on which much sustainable design is advocated for in lieu of good modeling).

Third, the use and presence of the LEED^{TM} spreadsheet which tallies up the points necessary for certification presents a dueling spreadsheet to the financial. It posits that there is another bottom line for design decisions and that the client has requested the design team to resolve both systems of accountability.

DESIGN DEVELOPMENT

The design process for this office building was unusual because many decisions typically made during the design development phase were addressed during schematic design. The design team had fine-tuned the curtainwall design for each orientation and specified high-quality glazing performance, coordinated with mechanical and structural designs, and investigated occupant comfort related to the curtainwall and space planning in relation to the daylighting patterns and controls, and selected a mechanical system with thermal storage. However, there were still some questions in relation to the building envelope that precipitated additional studies: a small study of the lobby shading requirements and a more substantial examination of occupant thermal comfort in relation to curtainwall specifications and selection.

Building Lobby Shading

As the design for the building lobby developed, the design team realized that the location of the lobby on the southwest corner with a double-height space open to the street could result in direct sun problems. The lobby space does not require the same control of daylight and sun penetration as office workstations, since people are generally passing through; however, the security personnel must be able to perform without visual discomfort and thermal discomfort from sun penetration.

Site conditions relative to the path of the sun were complex enough to require an on-site survey to record potential obstructions and site shading conditions. The surrounding buildings were sited with a small transit from the actual lobby location and overlaid on a sun path chart developed for that location (Figure 17). The chart is a flat projection of a hemisphere drawn from the viewpoint of the building security desk and shows a simplified outline of the window mullion grid. Overlaid on this are the buildings visible across the street (shaded areas) and the sun paths in the sky, indicating times and day and year (the exaggerated figure eights).

The chart highlights two times of concern for sun penetration: two hours around noon in the winter and from 1:00 to 5:00 in the afternoon during late spring and early autumn. Additionally, upper sky brightness may cause uncomfortable glare. A glazing with a dense frit pattern for the horizontal skylight was specified to mediate the brightness.

Curtainwall Performances

During the design development phase, but after the curtainwall specifications were complete, a new curtainwall option became available to the project with an improved U-factor and shading coefficient (SC) but a slightly less good visible transmittance (T_{vis}) over that specified. The specified curtainwall was already delivering a high-performance building. The exterior shading devices had reduced the cooling load of the envelope by 25%. The building overall, relative to the average office building in the same climate and with same schedule, was using 25% less energy (CEC 1999). However, the curtainwall counts for slightly more than 10% of the total building cost. If superior performance could be achieved, it would be worth knowing this as the building completes design development.

A DOE2.1e model was used to compare the annual energy use between the specified curtainwall (Option 1) and the new curtainwall (Option 2).

- Option 1 glass: U-factor 0.386 (2.19 U-factor SI), SC 0.414, Tvis 0.598
- Option 2 glass: U-factor 0.260 (1.47 U-factor SI), SC 0.342, Tvis 0.545

The results indicated no significant difference in the annual energy use between the two, with an annual energy cost difference of less than 1%. At this point, the topic might have been abandoned, but there remained a question about the possibility of deleting the perimeter heating system. This issue had not been settled, and the new curtainwall option might offer increased occupant thermal comfort in the perimeter zone during winter mornings. We know that even if air temperature is maintained in the comfortable range, occupants may experience discomfort due to radiant heat exchange between them and the window surface. This is a problem with corner locations in the 1977 building already occupied by the client, and the client was concerned that this not be part of the new building experience.

COMFORT ANALYSIS

In developing an analysis of the two curtainwall systems, the following question was asked: what is the difference (if

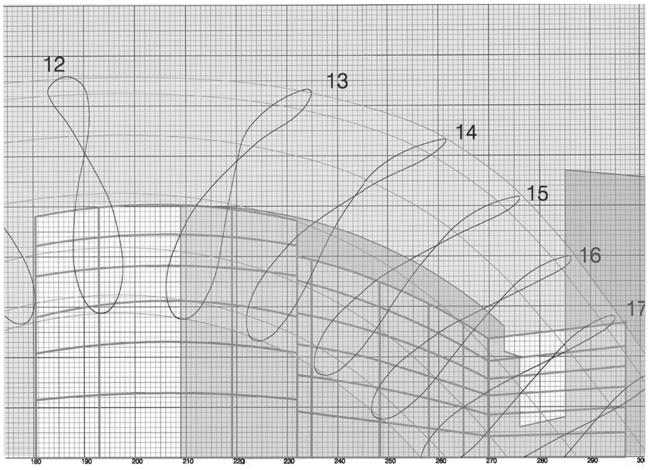

Figure 17 *Horizon shading diagram for SW main lobby.*

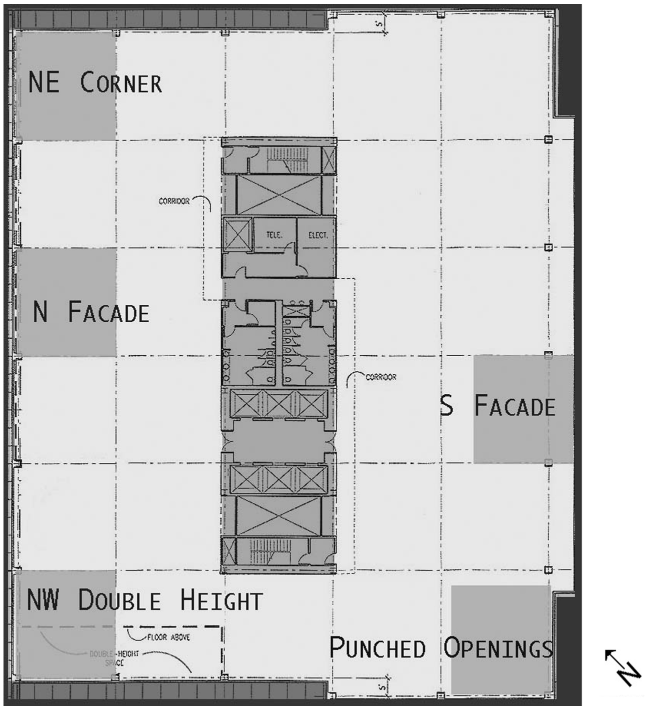

***Figure 18** Office bays selected for detailed thermal comfort investigation are indicated with shading.*

any) between the specified curtainwall and the newly introduced curtainwall for occupant comfort in the perimeter zone? Will this affect the need for perimeter heating?

As often happens in practice, it is easy to ask a question that seems quite straightforward but that requires a complex method for answering. Five perimeter locations were selected with varied glazing exposures (Figure 18). These were then analyzed to compare Option 1 and Option 2 curtainwalls described above. In addition to differences in the specifications, the frames of both options were thermally broken, but with different designs and technologies.

Comfort Metrics

Detailed comfort analyses have resulted in standards and practices to assist in the design of the buildings. The most accepted standard for thermal comfort in the United States and internationally is published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This document, ASHRAE Standard 55, has been developed and revised based on laboratory data and field studies over the last five decades. ASHRAE Standard 55 defines the conditions in which a specified percentage of the occupants of a space will find their immediate environment thermally acceptable. The main metric of comfort in Standard 55 is the Predicted Mean Vote (PMV), an index that predicts the mean value of the votes of a large group of persons on a seven-point thermal sensation scale. In addition, the Predicted Percentage of Dissatisfied (PPD) is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV.

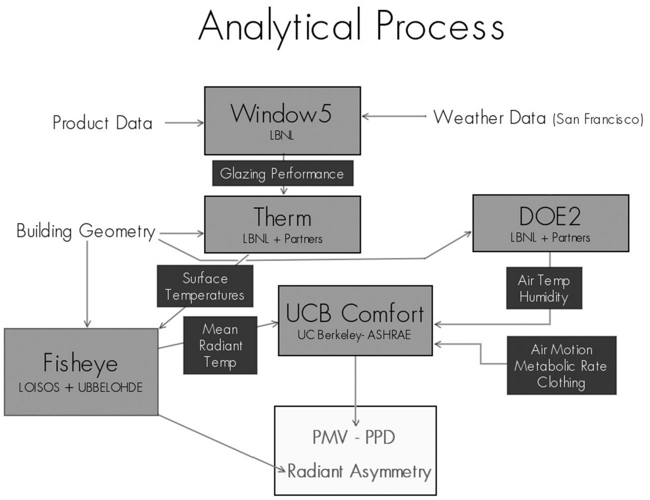

***Figure 19** Flow chart of the analytical process used for thermal comfort modeling of selected office bays.*

These metrics can be generated with a set of standard building environment inputs that affect thermal comfort, including dry-bulb air temperature, relative humidity percentage, air velocity and the mean radiant temperature (MRT), and a set of algorithms (ASHRAE 1992). When the building does not yet exist for these conditions to be measured, simulations should be able to provide them. DOE2.1e simulations can generate the air temperature and the relative humidity. The air velocity can be determined from the mechanical system design. However, the MRT default value is equal to the air temperature. This does not work to examine surfaces that are colder or hotter than air temperature, which is exactly the condition that needs to be investigated for the perimeter zone and the curtainwall alternative options. The final comfort calculation methodology, which is discussed in the following sections, is represented in Figure 19.

Calculating MRT

For this evaluation of curtainwall options, the objective was to establish the MRT for a specific location within the perimeter bay that simulates the workspace of a building occupant. ASHRAE has established the following procedure for calculating the MRT (ASHRAE 1977):

$$T_r^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \ldots + T_n^4 F_{p-n}$$

where

T_r = mean radiant temperature, K

T_n = surface temperature of surface *n*, K

$F_{p\text{-}n}$ = angle factor between a person and surface *n*

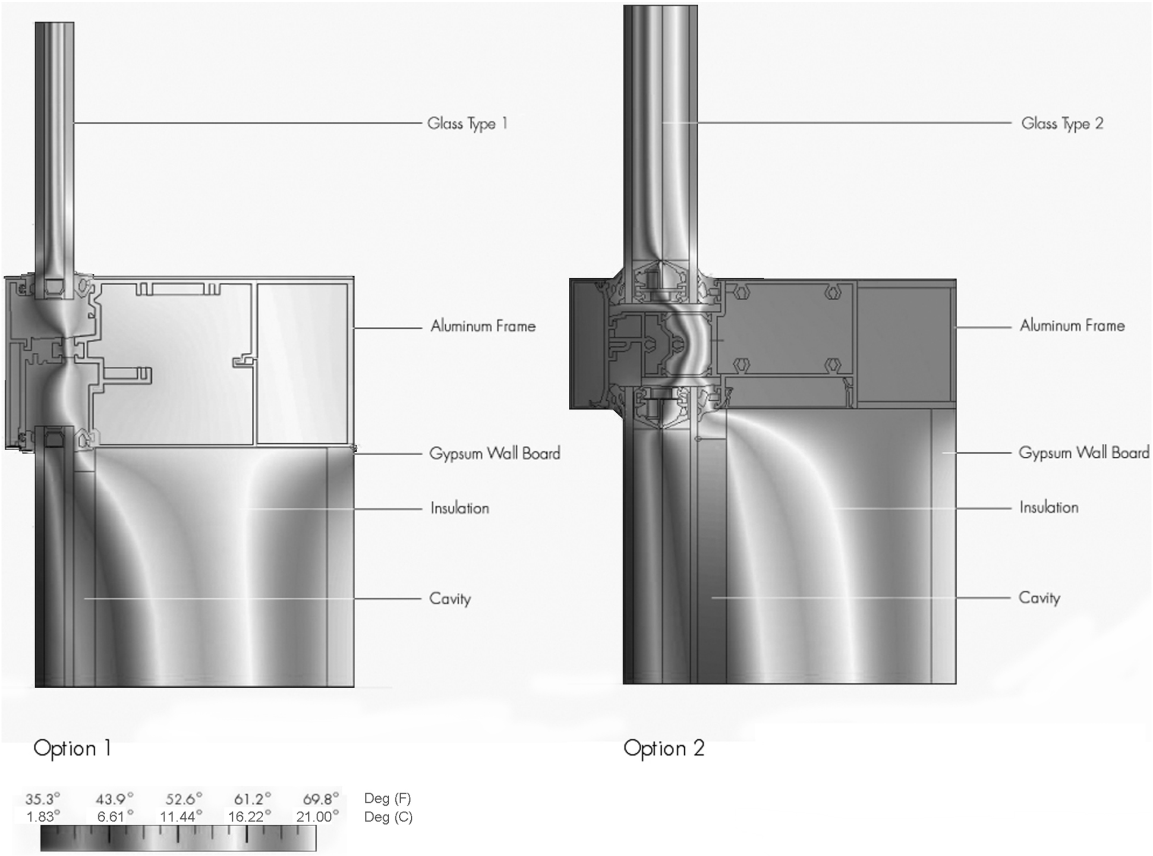

Figure 20 *THERM images of the two curtainwall systems under consideration, indicating temperature gradients through curtainwall sections under winter conditions.*

The above equation works only when the emissivity of the surface is high. In this case the emissivity is assumed to be 1.0. The surface temperature of the window can be calculated by starting with the configuration and specifications of the curtainwall system itself. WINDOW4 and WINDOW5 work with THERM to produce the window temperature (Figure 20).

The geometry and station point necessary to calculate the MRT pose challenges. The problem is how to calculate F_{p-n}, the angle factor of the surfaces. This is the same as saying, "How much of the surface can be seen from the station point." The graphical and analytical methods to calculate the MRT (ASHRAE 1977) are inaccurate when the station point is close to the surface and the view angle is acute. The locations where an occupant is most likely to be affected by cold glazing surfaces are those working in the perimeter zone near the curtainwall, so a number of the station points are close to the window surface.

A similar problem is faced in daylighting calculations, where the question is how much of the sky is visible from a station point. We looked at daylighting calculation methods to see if there were methods that could be applied to this situation. Ray tracing was explored as a method for calculating MRT, and an attempt was made to modify the daylighting software RADIANCE so as to calculate MRT. This was abandoned as too much effort.

Pleijel Diagrams and Fisheye Views

There is, however, a system of daylighting and radiation diagrams developed by Pleijel (Hopkinson et al. 1966) that is based on the stereographic projection of the sky vault. The Pleijel diagram for a horizontal plane has approximately 1,000 dots on it. Each dot on it represents 0.1% daylight factor. A stereographic photograph or drawing of the visible sky is placed on this diagram. The number of dots on the diagram that lie within the patch of visible sky as seen through the window is counted and related to the total dots in the entire diagram. This ratio gives the value of the sky factor of the daylight factor.

A similar technique can be used to find the view factor of each plane in the space. The number of dots falling within the visible patch of a specific surface is counted and related to the total number of dots in the diagram. This ratio gives us the view factor for that surface. For daylight calculations, the distribution of dots has to reflect the nonuniform brightness of the sky. The distribution of dots in the surface diagram is much

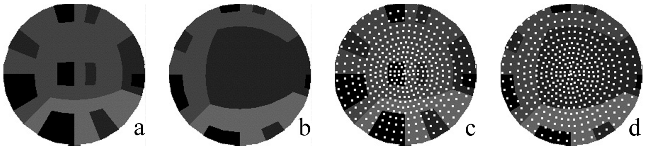

Figure 21 *FISHEYE images that illustrate method used for perimeter zone view factors: (a) view looking up from the workplane, (b) view looking down from the workplane, (c) overlay of dots onto view looking up, and (d) overlay of the dots onto view looking down.*

more straightforward. The dots are evenly distributed on a sphere and stereographically projected onto our diagram. But evenly scattering points onto a sphere is a nontrivial mathematical problem. (Saff and Kuijlaars 1997). The following algorithm was used to generate the points:

```
In spherical coordinates (theta, phi):
  for k=1 to N do
    h = −1 + 2*(k-1)/(N-1)
    theta[k] = arccos(h)
    if k=1 or k=N then phi[k] = 0
   else phi[k] = (phi[k-1] + 3.6/sqrt(N*(1-h^2))) mod (2*pi)
  endfor
```

In order to make this usable for perimeter zone comfort evaluations, a new software was developed to make the stereographic projection. Effectively this software acts as a fisheye camera. The “camera” can be pointed in any direction in the space and take a “snapshot” of all the surfaces it sees. Figure 21a shows the camera pointing up in a demonstration example. Two skylights are visible. The vertical windows are sliced by the horizontal plane on which the camera is placed. Figure 21b illustrates the camera pointing down. The lower halves of the vertical windows are visible. The color or value of the surface is a programming artifact that depends on the temperature and the emissivity of the surface. This software can also take a photograph of the dots that have been generated. Figure 21c and Figure 21d show the overlay of the dots on the surfaces. At this point we can count the dots on any surface. The ratio of the counted dots to the total number of dots will give us the view factor of that surface.

Once we have the view factors, the fisheye software calculates MRT with the ASHRAE (1977) equation:

$$T_r^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \ldots + T_n^4 F_{p-ns}$$

Comfort Results

Once the MRT calculation was solved, the five selected perimeter office bays could be evaluated for PMV and PPD results. Comfort software developed at the University of California, Berkeley (Huizenga and Fountain) was used to generate the predictions for multiple points within each 30 ft by 30 ft (9.14 m by 9.14 m) bay for both curtainwall options. The grid of predicted PPD was then presented in a three-dimensional graph of the space for each option. Figures 22 and 23 illustrate the results for the northeast corner space. The results indicated that corner situations, with greater exposure to cool glazed surfaces, showed the greatest dissatisfaction, with PPD nearly 25% at the greatest. The office bays with a single curtainwall exposure showed PPD peaking around 20%, which is still greater than the ideal 5%. In comparing the two curtainwalls, Option 2 with the improved U-factor and shading coefficient, consistently reduced the percentage of occupants who would perceive the space as uncomfortable. Since the improvement in performance is relatively small, it is still not clear whether the reduction is sufficient to eliminate perimeter heating. It is also not clear whether this increased thermal performance is significant enough to be a factor in the selection of the curtainwall system, once all other criteria (cost, availability, and explosion-resistance among them) are factored into the decision. As the project moves in the Contract Documents phase, this issue will still need to be addressed.

SUMMARY AND DISCUSSION

Designing a high-performance curtainwall for a building with sustainable goals requires an integrated design process that can include significant energy, comfort, and daylight modeling. This means breaking the mold of conventional consulting, from the timing and interaction with the design team to the choice and use of analytical techniques. All disciplines must be willing to work synthetically from the early stages of the project and to engage the implication and complication of the various design changes required for energy-efficient and sustainable performance. The introduction of the LEED^{TM} certification system, as well as a commitment to including the full design team in the value engineering sessions provided important shifts in practice that support the delivery of high-quality buildings.

The process that generated this office building relied on the early use of thermal, energy, and daylighting modeling techniques to optimize the curtainwall design. In evaluating the fine tuning and specifications of the curtainwall, additional modeling of occupant comfort issues created a greater understanding of building performance and alternative options for the both design team and the client. Unlike the normative practice of consulting on mechanical and lighting issues, the modeling techniques had to be varied, nimble, and adaptable to the questions asked at any stage in the process.

ACKNOWLEDGMENTS

This work was possible due to the desire on the part of the client (State Compensation Insurance Fund of California) for a sustainable building and to the commitment of the architect (Hellmuth Obata Kassabaum, San Francisco office) to sustainable design. The design team included Steve Worthington, Zorana Bosnic, Thom Burnham, and Dave Troup of HOK. Our

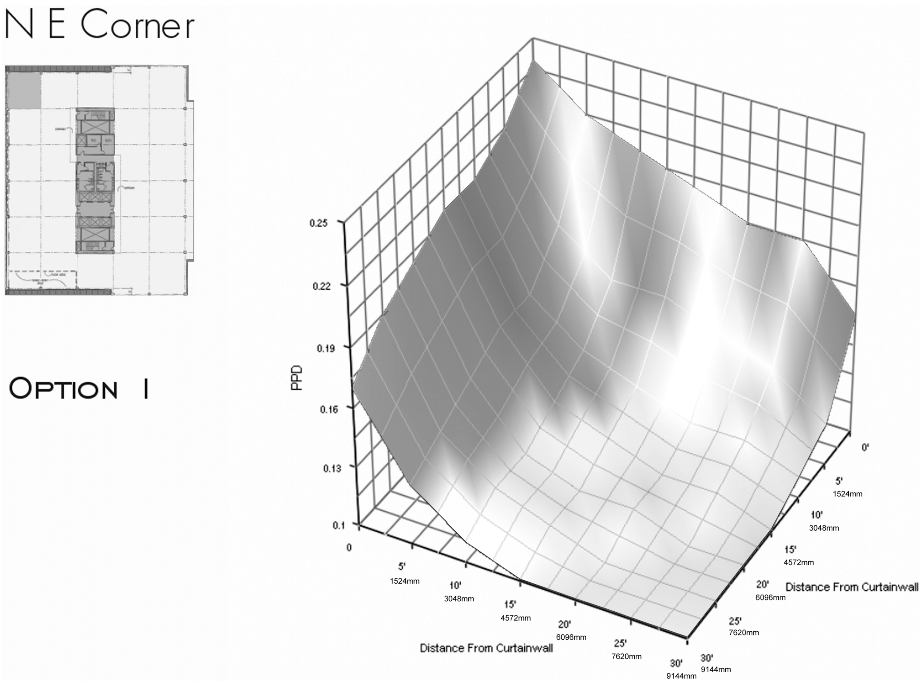

Figure 22 *PPD results for the NE corner office bay with curtainwall option 1. The two horizontal scales represent distances from the skin of the building, and the vertical scale represents PPD.*

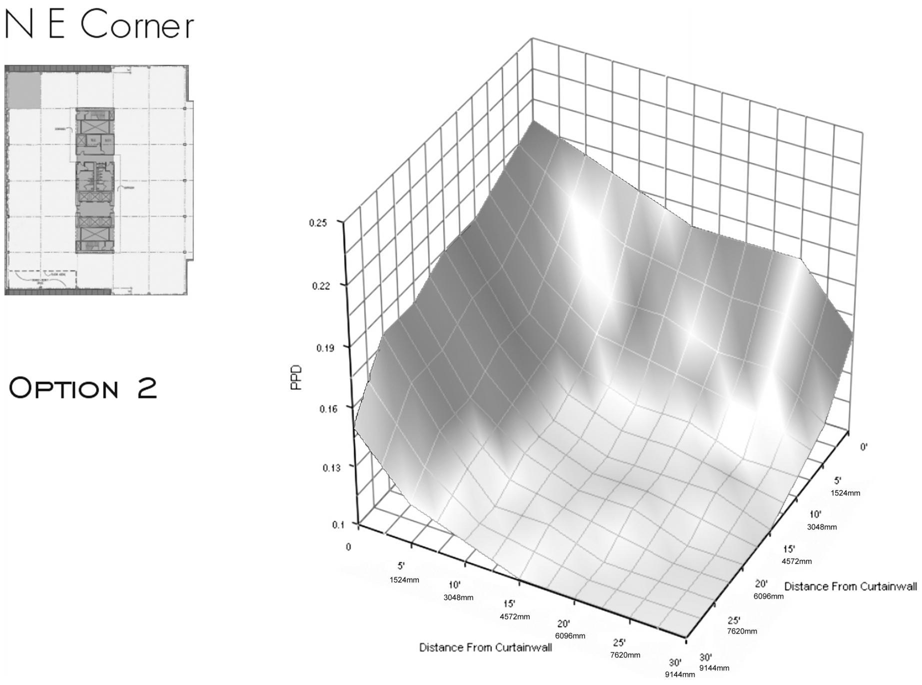

Figure 23 *PPD results for the NE corner office bay with curtainwall option 2. The two horizontal scales represent distances from the skin of the building, and the vertical scale represents PPD.*

own practice was responsible for all of the modeling discussed in the paper. Santosh V. Philip is responsible for the DOE2.1e energy modeling and comfort software, as well as the development of the FISHEYE software. Paul LaBerge assisted with the physical modeling and testing of the light redirecting glazings.

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