The Integration of Architectural Art and Load-Reducing Fenestration: Daylighting Case Studies

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ABSTRACT

A dramatic increase in the design of commercial buildings with daylighting manifests both a renewed discovery of the architectural art of glazing as well as an energy-saving feature. National building forecasters have predicted significant increases in building area for many occupancies. This includes office buildings, retail spaces, industrial buildings, and wholesale buildings. All of these building types are excellent candidates for implementing daylighting techniques because of the relatively high electric lighting power densities (W/ft^2) and long daytime use patterns.

Practitioners, researchers, utilities, and academics all recognize the benefits of analyzing buildings and documenting case studies. Six case studies will be presented for new commercial buildings that implement daylighting strategies. In all cases, the design philosophy of the architect will be presented along with the DOE 2.1C computer analysis that supported the design process. By discussing these five new buildings and reviewing the final building design process and technical analysis, valuable lessons and insights will be exposed. With this type of presentation, graphics are essential. Plans, sections, and evaluations of these five projects along with computer results are presented.

INTRODUCTION

Originally a requisite, then for pleasure and enjoyment, the design of apertures which allow daylight to penetrate a space became an essential motif. From the early pyramids to the medieval courtyards and cathedrals of fifteenth century Europe, natural light and all its magnificence was omnipresent. Contemporaries such as Wright, Le Corbusier, and Aalto have all studied daylight to brighten spaces and embellish the architectonics.

As architects delineate and articulate the building envelope and facades, we see fenestration and controls which respond to the sun tracking across the sky. Careful detailing ensures the appropriate responses for both daily and seasonal changes in sun movement. It is this dynamic environment that has long been recognized as the quality that gives occupants a sense of place. The result manifests buildings which in some way create spaces that are clement and well-lit to the occupants.

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As electric lighting systems and centralized space-conditioning systems were developed, those skills that designers for centuries so gracefully manipulated were ignored or forgotten. Soon after, there was a whole generation of practitioners concerned with conveniences and the associated predictability of systems.

With the proliferation of easily installed and relatively cheaply operated lighting and space-conditioning systems virtually any space could be lighted and conditioned through brute force. Post-war construction set unprecedented growth records for new buildings. This continued without exception except for slowdowns due to economic cycles. Utilities enjoyed the growth and responded by continually building new generating capacity to meet the peak loads.

In the early 1970s, oil embargoes dramatically made society aware of its vulnerabilities. The design community began to look closer at the impacts of its designs on its clients and globally in terms of society.

Utilities found themselves in a situation whereby building additional generating capacity meant huge daytime capacity with very little need to have this equipment produce during the evenings. This phenomenon is indicative of a load factor is the relationship between a peak load and the average load. To help rectify this dilemma most utilities designed rate structures so rational decision-makers would respond through price signals. Not only were costs different in winter and summer but within these seasons the cost for each kilowatt hour used varied. During the evening, costs were very low while during afternoon periods or peak periods costs were significantly higher. Additionally, demand charges were introduced whereby a special meter would be installed on the building to ascertain the kilowatts (kW) (instantaneous) for a given time. For each kW of demand the building owner would be charged. This also varied by the time of day. The most severe demand charges occurred during a utility's peak period, usually during summer in the afternoon. This rather complex price structure is called time-of-use rates and is typically referred to by the acronym "TOU." Buildings that do not respond to these price signals typically have significantly higher operating costs.

We now add another dimension to the application of daylighting features. Not only are there special quality issues and people/performance issues, but the management of the energy usage of buildings has become a paramount issue. The effective design of apertures reduces peak loads, thereby reducing the operating cost for the owner.

MAIN BODY

One of this country's largest electric utilities initiated an energy management program which encouraged the use of daylighting features in commercial buildings. Design assistance, computer analysis, and incentive dollars were offered to facilitate the effective use of daylighting apertures. As a result of the program, approximately 300 commercial and industrial buildings implemented some type of daylighting features with photoelectric controls. This paper will review several buildings in terms of design strategies and predicted performance. In each case the hourly simulation program DOE 2.1C was implemented. It is very important to begin looking at daylighting features early in the design process. The sooner the design team identifies that daylighting strategies are going to be articulated, the better the results. Architects typically take a building project through a predictable design process. A building program is usually established with considerable dialogue between the owner and the architect. It is important that this programming phase identify not only the types of spaces that are required, but also any particular energy management features. This would include daylighting and controls.

Once the program is understood, the architect initiates a "schematic design" phase. During this phase, the architect begins to delineate the various space requirements. It is very common for many sketches to be generated at this time. Often initial discussions between the various consultants will be initiated and general concepts discussed. Choosing a consultant who is sympathetic to daylighting concerns is important. The mechanical or electrical consultant who does not understand or is not willing to perform to make a technology work will, in all likelihood, make any daylighting strategies fail and will be eliminated in the design. Without the right design team working together, anything that can go wrong, will go wrong. The owner will normally approve some conceptual schematic design drawings. Figure 1 shows a flow chart of a standard design process and a daylighting design process. Once approved, the architect will begin design development.

Design development is a shakedown phase. The architect will work out space requirements, prepare study elevations, and usually start working on building sections of the project. Many decisions are made in design development, not only in terms of the building design but also structural, mechanical, and lighting decisions. Daylighting analysis usually occurs in this phase to ascertain the relative merits (cost effectiveness) of any given fenestration design. Typical questions asked and solved during this stage include:

- How much aperture should be used?
- What type of glazing?
- What type of photoelectric controls (stepped vs. on/off)
- How will this daylighting system work?
- What are the cost implications?

Daylighting and thermal analysis was initiated on virtually all of the buildings associated with the aforementioned utility program. We have found that by initiating the DOE 2 analysis we can generate the required numbers to satisfy the owner, architect, and mechanical and electric consultants.

RESULTS

Six buildings are presented here. In each case the design team will be described, followed by the engineering assumptions used for the analysis and a summary of the loads. I believe the graphic material is paramount in a case study paper. To help readers understand the design concept, building plans, sections, and elevations are included.

Project: **HOFFMAN SOUTHWEST OFFICE/WAREHOUSE**

Area: 15,000 ft^2

Location: Irvine, CA

Engineering assumptions for DOE analysis

Light Design Level	=	50 fc office 30 fc warehouse
Light Power Density	=	1.2 W/ft^2
Aperture	=	Bronze/clear windows, diffusing skylight
Electric Controls	=	On/off-warehouse, dimming office
Mechanical System		Roof-mounted heat pumps

The design team identified daylighting early in the design process for this project. Both toplighting and sidelighting were implemented. A cast-in-place concrete light shelf was poured on the first floor. Interior light shelves were placed along the perimeter glazing and under the skylights. These light shelves will slightly increase room brightness but, more importantly, will help decrease aperture brightness, which improves occupant comfort. The interior light shelves were fabricated in a mill shop, then installed at the site. A glass transom was installed across the interior portion. This allows diffuse borrowed light to enter the circulation area. The ceiling material is a typical T-BAC system except that it was installed high and angled to direct light deeper into the space. These details are shown in Figure 2.

Based on these assumptions, the energy performance for the building can be summarized in the following table:

Run	Site Energy $kBtu/ft^2$	Source Energy $kBtu/ft^2$	Lights kWh/yr	HVAC kWh/yr	Total kWh/yr	Summer Peak kW
Basecase	44.4	127.9	91659.8	68942.7	174310.7	71.4
Daylighting	40.0	113.3	66050.3	62650.9	135438.4	53.4

Summary:		
	Reduction in lighting:	25,609 kWh/yr
	Reduction in mechanical:	6291 kWh/yr
	Reduction in total electric:	38,872 kWh/yr
	Reduction in peak kW:	18 kW
	Reduction in operating costs:	$3110/yr

This building was modeled with DOE 2.1C and the accuracy is limited to the algorithms therein.

Project: **HERBERT TEMPLEMAN EDUCATION CENTER**

Area: 8765 ft^2

Location: Ventura, CA

The engineering assumptions used in the analysis include:

Light Design Level	= 50 fc (office area)
Light Power Density	= 2.10 w/sf^2 (office area)
Skylight	= Single-pane acrylic dome (T = .32 and Sc .45)
Elec. Controls	= Two steps on/off, controlling two-thirds of the lights
Window Glazing	= 1/4 inch solex tinted glass
Mechanical System	= Heat pumps

A crusifix shaped top lighting aperture was designed into this building. The skylight material is a diffusing acrylic while the side windows are a high-performance glass. The interior partitions on the second floor were kept low in order for the light to bounce around more freely and for simulation purposes were not modeled. This is shown in the building section in Figure 3.

Based on these assumptions, the energy performance of the building is summarized in the following table:

Run	Site Energy $kBtu/ft^2$	Source Energy $kBtu/ft^2$	Lights kWh/yr	HVAC kWh/yr	Total kWh/yr	Summer Peak kW
Basecase	39.6	132.4	48,330	28,860	88,800	68.5
Daylighting	25.6	84.7	21,717	23,188	56,500	35.2

Summary:		
	Reduction in lighting:	26,613 kWh/yr
	Reduction in mechanical:	5672 kWh/yr
	Reduction in total electric:	32,300 kWh/yr
	Reduction in peak kW:	33.3 kW
	Reduction in operating costs:	$2907/yr

This building was modeled with DOE 2.1C and the accuracy is limited to the algorithms therein.

Project: **CROSSROADS SCHOOL**

Area: 15,000 ft^2

Location: Santa Monica, CA

Engineering assumptions for DOE analysis

Light Design Level	=	50 fc (classroom areas) 30 fc (circulation areas)
Light Power Density	=	2.5 w/ft^2 (office area)
Skylight	=	Double-pane clear dome with louvers
Electric Controls	=	One-step on/off
Window glazing	=	1/4 inch glass
Mechanical System	=	Heat pumps

Crossroads School has square skylights with an exterior louver system over the workshop spaces and office. The large tower over the court area has a ridged cupola aperture. The building sits in an urban setting in Santa Monica, CA. The high side windows are operable from the exterior. Daylighting is also used in circulation areas as wall washes which tend to lure one in the direction of the area source. These strategies are delineated in Figure 4.

Based on these assumptions, the energy performance for the building can be summarized in the following table:

Run	Site Energy $kBtu/ft^2$	Source Energy $kBtu/ft^2$	Lights kWh/yr	HVAC kWh/yr	Total kWh/yr	Summer Peak kW
Basecase	54.0	158.2	76,030	51,805	135,300	64.2
Daylighting	46.7	131.6	53,208	49,452	110,100	45.0

Summary:		
	Reduction in lighting:	22,822 kWh/yr
	Reduction in mechanical:	2353 kWh/yr
	Reduction in total electric:	25,200 kWh/yr
	Reduction in peak kW:	19.2 kW
	Reduction in operating costs:	$2268/yr

This building was modeled with DOE 2.1C and the accuracy is limited to the algorithms therein.

This building is currently under construction.

Project: **SANTA BARBARA SOCIAL SERVICES BUILDING**

Area: 50,000 ft^2

Location: Santa Barbara, CA

Engineering assumptions for DOE analysis

Light Design Level	=	50 fc
Light Power Density	=	2.0 W/ft^2
Clerestories	=	South-facing sawtooth over atrium
Electric Controls	=	Dimming
Mechanical System	=	Variable air volume

The Santa Barbara Social Services Building was designed with south-facing sawtooth clerestories. Physical models were built and tested for the summer and winter solstice to test where the direct beam would fall. The aperture was positioned so no beam daylight would fall into the office space. Exterior fenestration controls, shown in Figure 5, further scatter and diffuse the direct beam component for the perimeter daylighting zone.

Based on these assumptions, the energy performance for the building can be summarized in the following table:

Run	Site Energy $kBtu/ft^2$	Source Energy $kBtu/ft^2$	Lights kWh/yr	HVAC kWh/yr	Total kWh/yr	Summer Peak kW
Basecase	43.3	137.0	378,620	99,001	560,248	323
Daylighting	40.7	123.4	331,145	80,231	494,599	160

Summary:		
	Reduction in lighting:	46,879 kWh/yr
	Reduction in mechanical:	18,770 kWh/yr
	Reduction in total electric:	65,649 kWh/yr
	Reduction in peak kW:	163 kW
	Reduction in operating costs:	$5908/yr

This building was modeled with DOE 2.1C and the accuracy is limited to the algorithms therein.

This building is currently under construction.

Project: **TRUCK MARKETING INSTITUTE**

Area: 9300 ft^2

Location: Ventura, CA

The engineering assumptions used in the analysis were as follows:

Light Design Level	=	50 fc (office area)
Light Power Density	=	2.10 W/ft^2 (office area)
Skylight	=	Single pane acrylic dome (T = .53 & SC = .67)
Elec. Controls	=	one step on/off, controlling two-third of the lights
Mechanical System	=	Heat pumps

The Truck Marketing Institute makes use of clerestories and diffusing skylights over the second floor. Interior light shelves were designed into the window wall to help reduce window brightness. An atrium in the center of the building allows daylight to penetrate the interior zones of the first floor.

Based on these assumptions, the total energy performance of the building is summarized in the following table:

Run	Site Energy $kBtu/ft^2$	Source Energy $kBtu/ft^2$	Lights kWh/yr	HVAC kWh/yr	Total kWh/yr	Summer Peak kW
Basecase	29.5	98.3	34,928	17,269	57,400	30.1
Daylighting	22.9	75.9	22,874	14,541	44,200	16.9

Summary:		
	Reduction in lighting:	2054 kWh/yr
	Reduction in mechanical:	2728 kWh/yr
	Reduction in total electric:	13,200 kWh/yr
	Reduction in peak kW:	13.2 kW
	Reduction in operating costs:	$1188/yr

This building was modeled with DOE 2.1C and the accuracy is limited to the algorithms therein.

Project: **MONTEBELLO TOWN CENTER**
(Mall Area and Food Center Only)

Area: 120,000 ft^2

Location: Montebello, CA

The engineering assumptions for DOE analysis

Light Design Level = 30 fc
Light Power Density = 1.2 W/ft^2

NOTE: This includes fluorescent, high pressure sodium, and incandescent lamps.

Skylight = Single acrylic dome T = 75 & diffusing panes T = 20%
Elec. Controls = one step on/off
Mechanical System = Variable Air Volume

Daylighting in a large regional mall makes perfect sense. Unlike offices some direct beam is desirable. It creates a dynamic space and adds interest. A barrel skylight tracks the circulation space below. A deep light well helps cuts off the sun at certain times of the year although still allows a slice of light to hit the floor. Additional diffusing panels were added to the aperture system to ensure enough light for all the plants to grow and look healthy. Details are shown in Figure 7.

Based on these assumptions, the total energy performance of the building is summarized in the following table:

Run	Site Energy $kBtu/ft^2$	Source Energy $kBtu/ft^2$	Lights kWh/yr	HVAC kWh/yr	Total kWh/yr	Summer Peak kW
Basecase	64.2	218.4	425,620	878,796	1,361,300	502.8
Daylighting	47.0	159.8	160,026	778,209	995,600	263.7

Summary:

Reduction in lighting:	265,594 kWh/yr
Reduction in mechanical:	100,587 kWh/yr
Reduction in total electric:	365,700 kWh/yr
Reduction in peak kW:	231 kW/yr
Reduction in operating costs:	$29,256/yr

This building was modeled with DOE and the accuracy is limited to the algorithms therein.

DISCUSSION

In each of the previous building descriptions, parametric analysis was performed implementing the DOE 2.1C simulation program. We have found this public domain program to be very useful, as it is able to model the mechanical systems, lighting, and building envelope on an hour-by-hour basis. This is useful to ascertain the proper fenestration detailing. One feature that has consistently proved useful is the ability of DOE 2 to calculate not only the radiation gains through fenestration but also the reduction of heat to space from electric lights. The notion of lumens per watt is not well understood by some practitioners and this analysis allows one to look at these trade-offs.

Each of these buildings was modeled early in the design process. Design development is the phase where most of the details are worked out so the base case was defined generically by the building type in terms of all schedules. Internal loads such as lighting, people, and equipment were also set based on code requirements. The building footprint and envelope were well defined and modeled as such. The primary variations between the base case and the daylighting design was the activation of photo controls and the detailing of the fenestration. Where complex fenestration systems were implemented, physical models were built and tested. The results of these tests were folded into the electric lighting schedules to reflect the change in the power densities. This methodology is described in detail in Ander and Wilcox (1985).

Presented for each building is a Building Energy Performance Summary (BEPS). The base case building in all cases meets California Energy Code, which is called Title 24. This energy code has many similarities to the ASHRAE 90 standards. The case study performance summary includes lighting, HVAC, and total loads in kWh. The summation of lighting and HVAC loads will not equal the total load because equipment or receptacle loads are included in the total loads anly.

The climate for these buildings is relatively mild. Heating degree days range from 1800 to about 2800, depending on location. The coastal areas frequently have hazy skies in the morning, which burn off later in the day. In most cases economizer cycles are effective for a large component of the cooling load.

The BEPS summaries are very useful when working with the owner. The impacts on the lighting loads are usually easily understood. Mechanical loads and peak loads are not and this helps articulate the performance impacts. The total electric load will lead us to the estimated operating costs. The design team and owner find this important in order to cost-justify a particular fenestration/photo control treatment.

CONCLUSIONS

The most common misconception about the application of daylighting features is that apertures in a building will always increase cooling loads and tonnage requirements. By closely analyzing the design implications and the thermal implications during the design process, the design team and the owner can test and optimize any given fenestration design. One must understand that as power densities for lighting become lower and lower, the cost effectiveness for daylighting as a load management strategy becomes more marginal.

Building standards that have a performance approach, that is a kBtu/ft^2/yr target, allow for higher power densities, providing the fenestration is properly designed and a photoelectric control is installed. California's Title 24 and the ASHRAE 90 standard are sensitive to these daylighting issues.

The architectural art of glazing systems indeed has merits in this post-oil-embargo era. We as practitioners are seeing new design tools and new materials to help support those skills which the masters of decades past intuitively understood. Daylighting has a bright future for the high-fashion designers. Many gained valuable knowledge through the support of organizations such as the Department of Energy; the American Institute of Architects; the California Energy Commission; the American Society of Heating, Refrigerating and Air-Conditioning Engineers; and the Illuminating Engineering Society. Case study information documenting what designers were able to accomplish will further help the design community understand daylighting issues.

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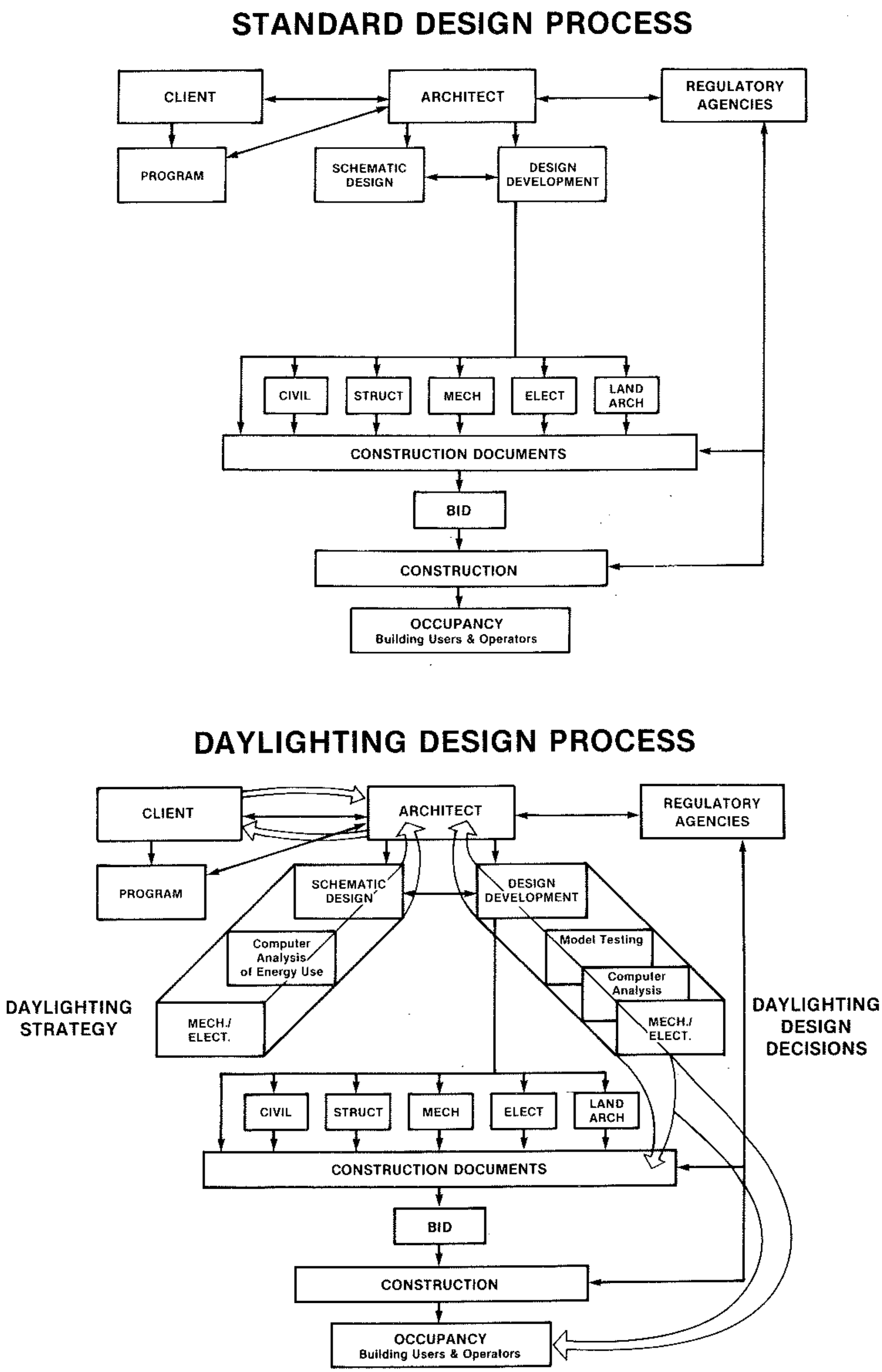

Figure 1. *Standard vs. daylighting design process*

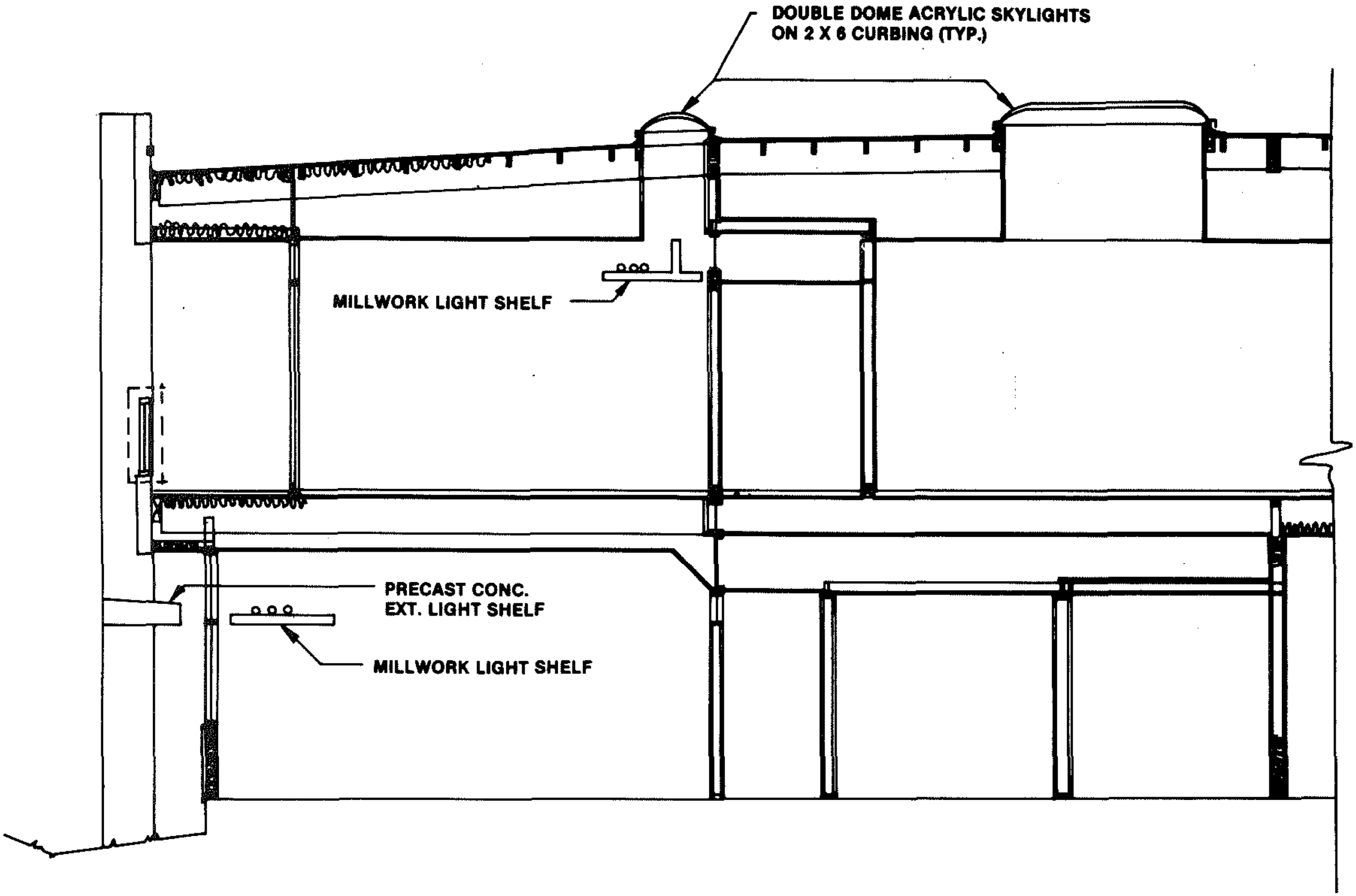

Figure 2. Hoffman southwest section

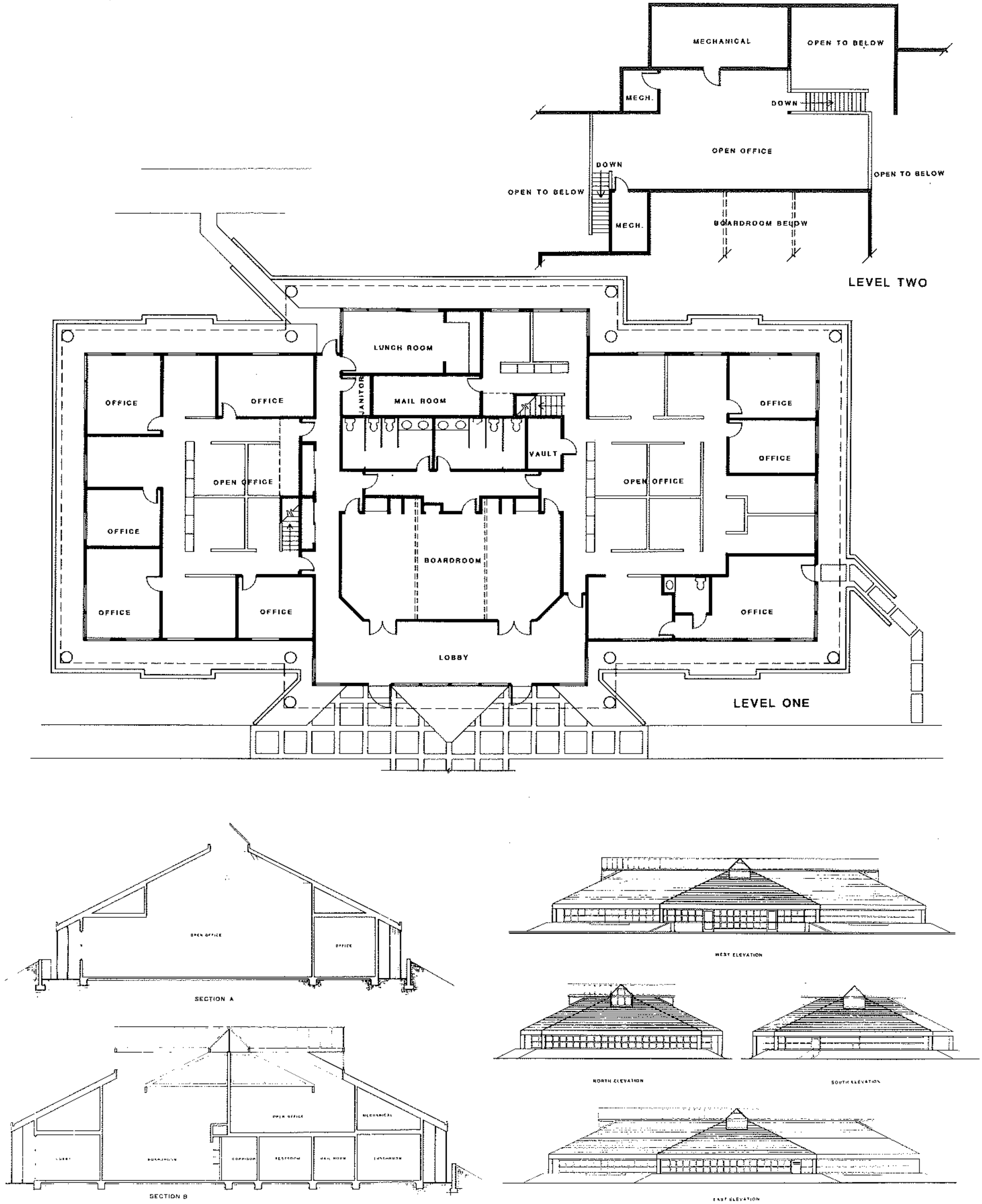

Figure 3. Plans, section, and elevation for Herbert Templeman Education Center

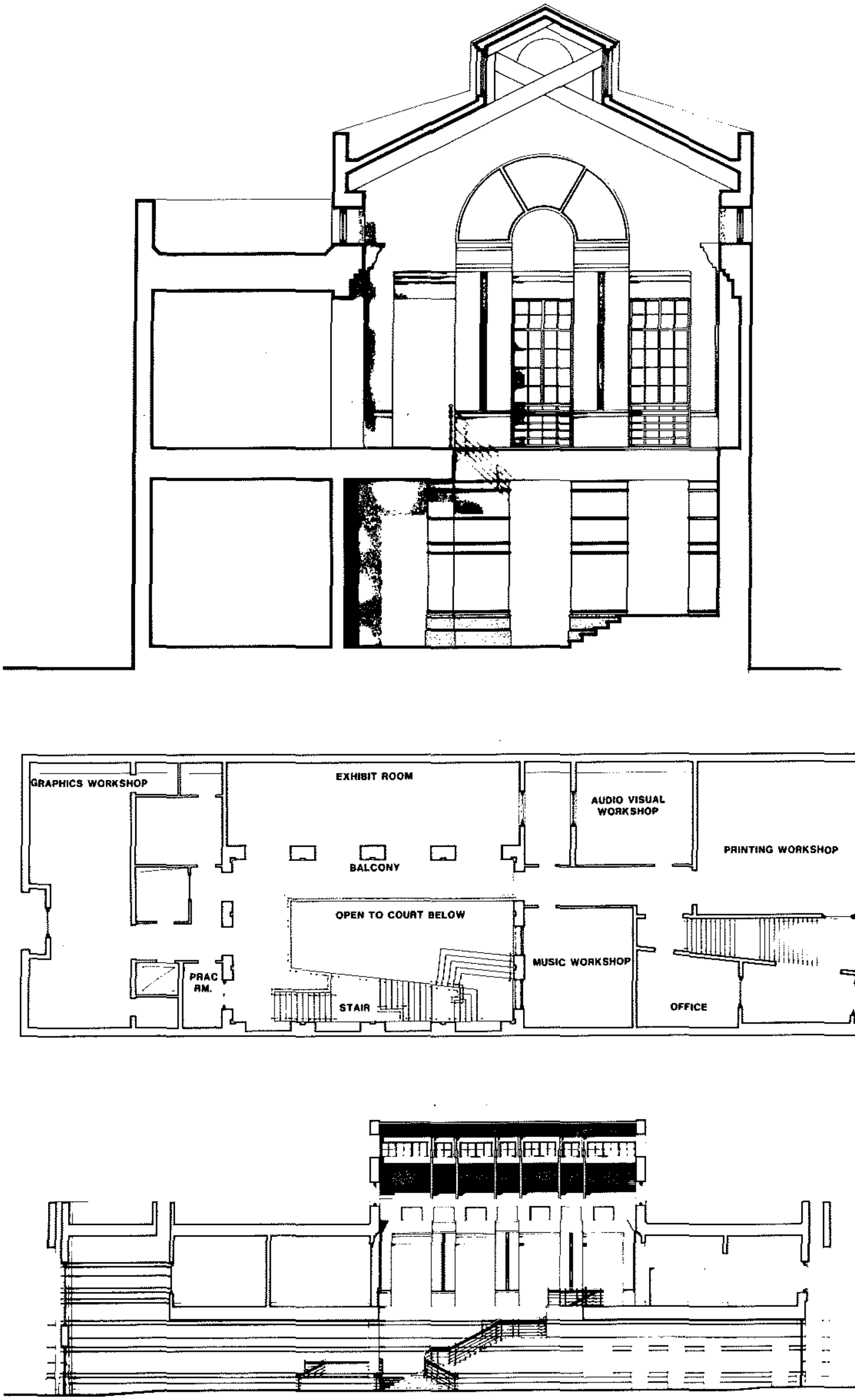

Figure 4. *Plan and sections for Crossroads School*

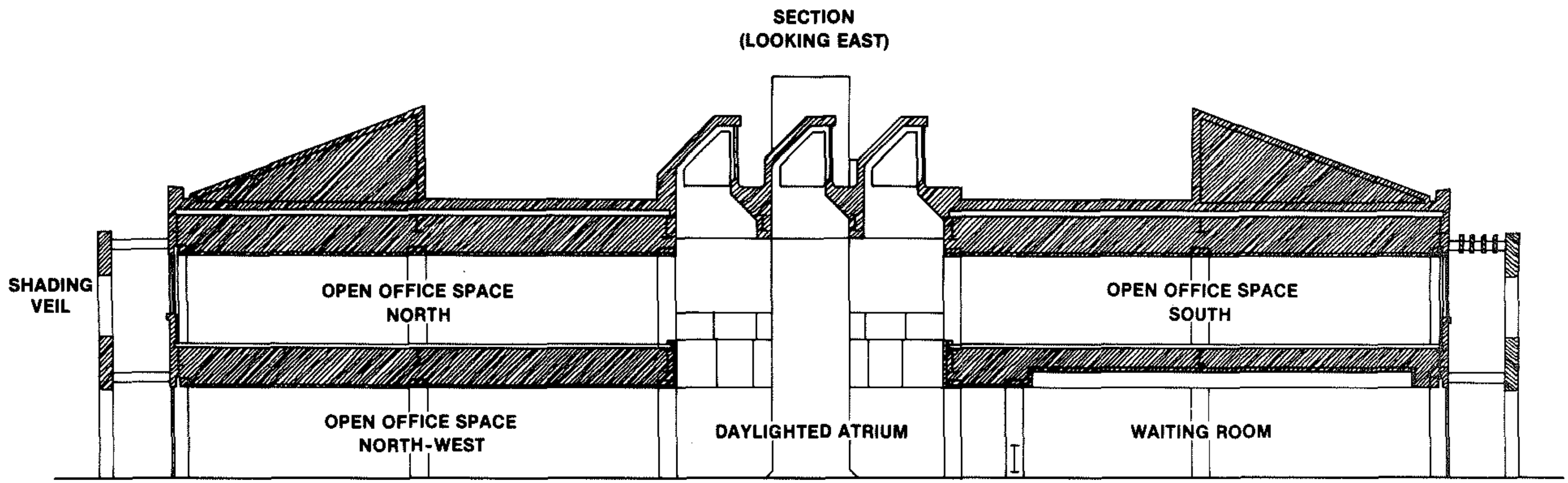

Figure 5. Section for Santa Barbara County Social Service Center

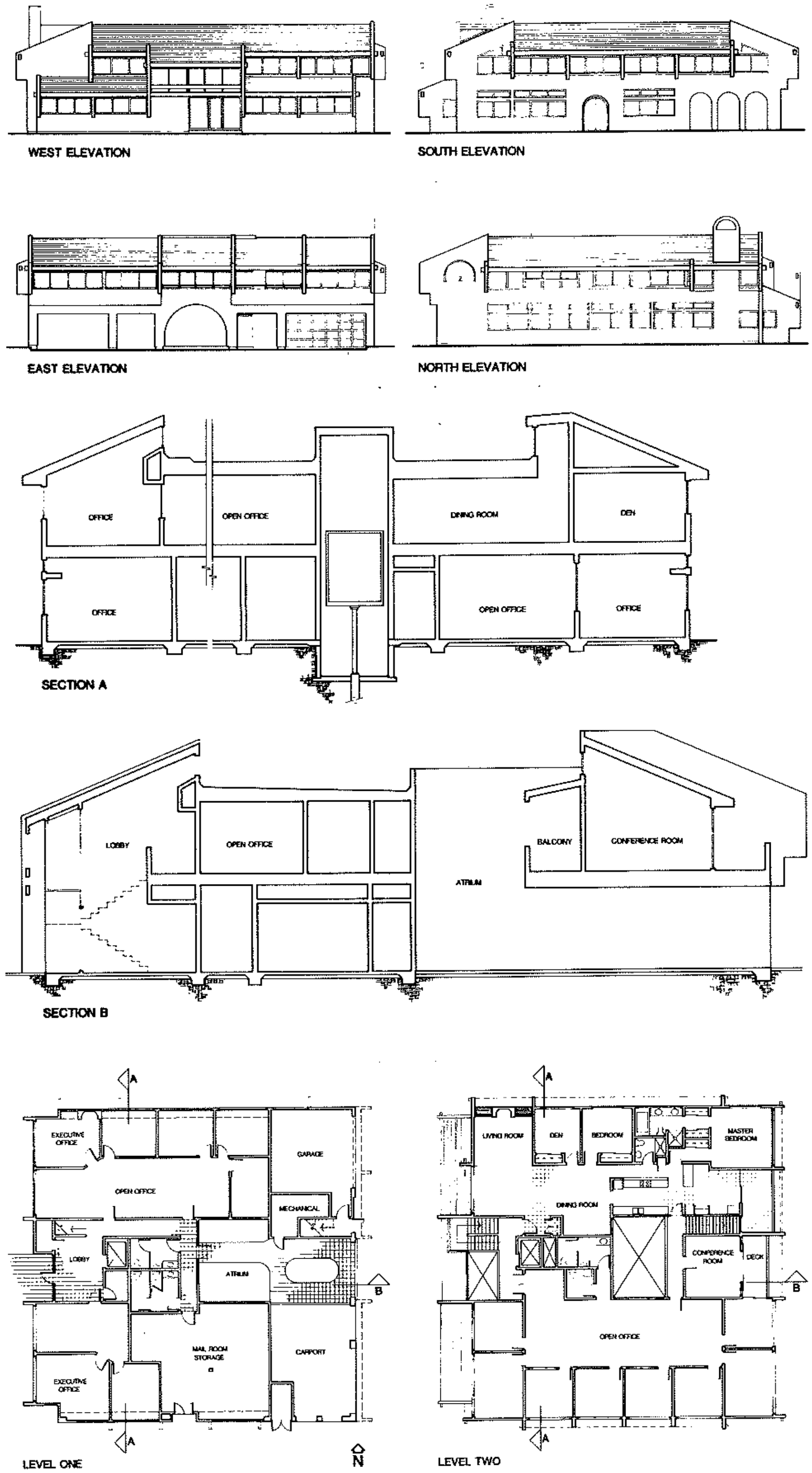

Figure 6. Plan, section and elevation for Truck Marketing Institute

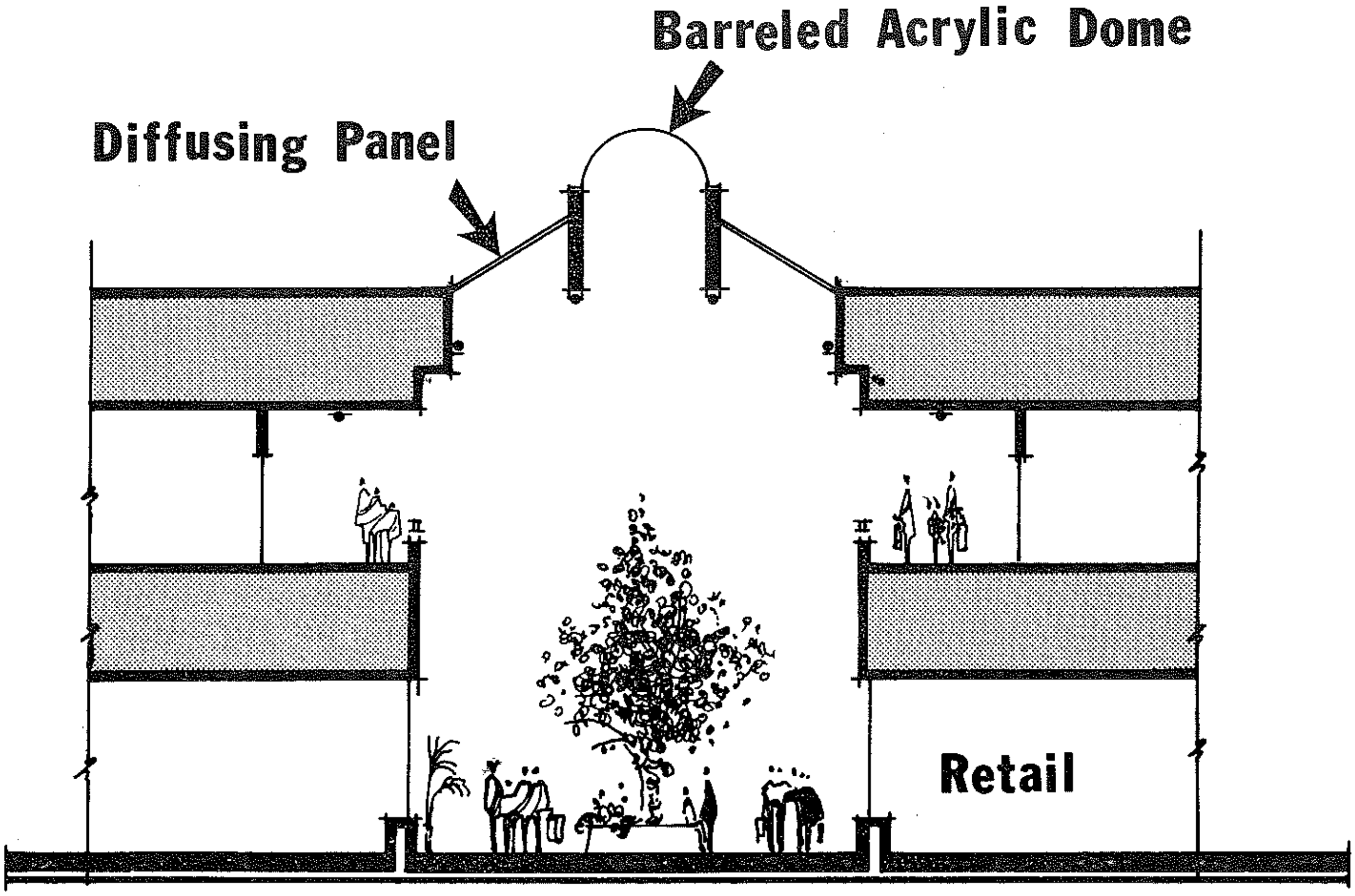

Figure 7. Section for Montebello Mall