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NEW CHANCERY FOR LUSAKA --

ATRIUM THERMAL ANALYSIS

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PREFACE

This report describes a portion of the work undertaken by Mr. Scott Matthews at the Botswana Renewable Energy Technology (BRET) project between December 15, 1984 and April 24, 1985. Mr. Matthews is an architectural consultant for Associates in Rural Development, Inc. (ARD), the contractor which is implementing the BRET project for the U. S. Agency for International Development (AID) under contract number 633-0209-C-00-1024-00.

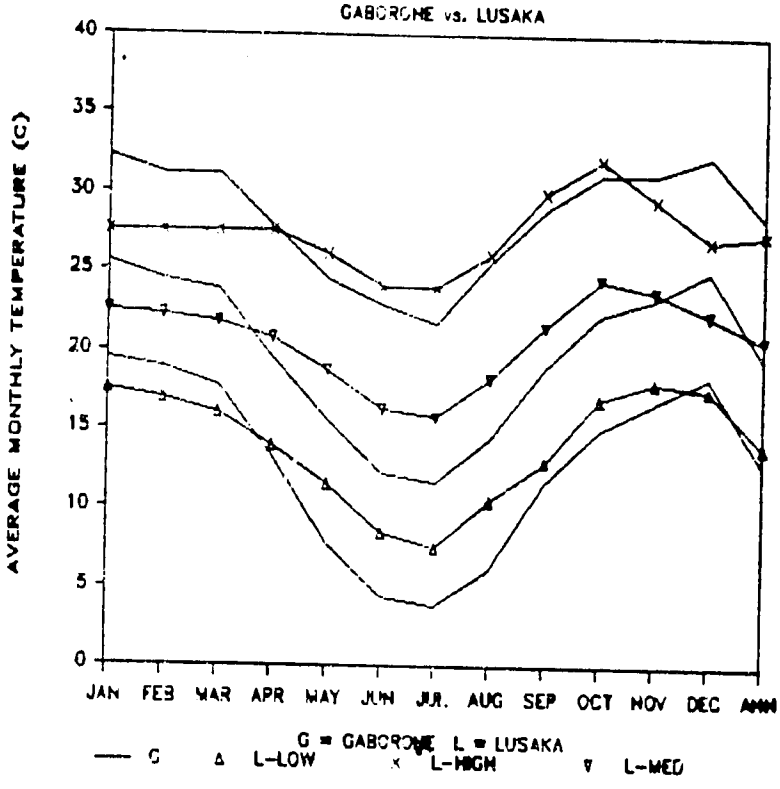
I. INTRODUCTION

The Government of Botswana (GOB) intends to build a new chancery for the Botswana High Commission in Lusaka, Zambia. The building is intended by its designer, Prof. Mihailov of the Buildings Department, to be a highly visible symbol of Botswana's vitality and national pride, and therefore is substantially more expressive architecturally than standard, tight-budget design practice. Among the unusual features of the design is a central courtyard or atrium intended to be covered by a steel space frame supporting a glass roof. Given that glass-covered atriums can develop thermal comfort problems, especially in sub-tropical climates, Mr. Kjell Kove, chief designer for the Buildings Department, asked the Botswana Renewable Energy Technology (BRET) project to analyze the thermal behavior of the atrium and make recommendations to the designer. This request was supported by Prof. Mihailov, and by Mr. Alastair Ritchie of Tswana Design, consulting architect for the preparation of contract documents and construction supervision.

II. CLIMATE COMPARISON

Lusaka's climate is somewhat more temperate than that of Gaborone, as it receives twice the annual rainfall and is at a higher elevation. Consequently, its maximum temperatures are less extreme, even though the annual averages are almost identical (see Figure 1). October, the warmest month in Lusaka, has temperatures similar to November in Gaborone, while July, the coldest, is five degrees warmer than Gaborone. Both cities have predominantly sunny climates, with very strong subtropical insolation during the hot months. Buildings in Lusaka should therefore be designed to provide some tempering of winter nighttime chills, but the primary requirement is for solar control and reduction in afternoon temperatures during the hot months.

Fig. 1: MONTHLY TEMPERATURE COMPARISON



III. THERMAL PERFORMANCE REQUIREMENTS FOR ATRIUM GLAZING

In the design that was analyzed (drawings dated April 14, 1983), the atrium is triangular in shape, narrowing from 22 meters on its northern side to four meters at the southern entrance. It is intended to be covered by a steel space frame which, in turn, supports a patent glazing system. The glazing would be laminated, combining a tinted and/or reflective outer pane and a clear inner pane with a vinyl interlayer. The glass, glazing system and space frame would be imported from South Africa or Europe.

The atrium is not a work area where people will spend a long time, but it does act as the circulation zone and organizing feature for the chancery. All employees and visitors will use it when going anywhere in the building, and all offices open onto it. As such, its thermal and light environment will dominate visitors' initial impressions of the building, and its conditions can either help or hinder working conditions in the offices.

Ideally, the atrium should have good daylighting, but people should be protected from direct sunlight. Its temperature should be warmer than ambient on winter nights, cooler on summer days, and otherwise temperate. Its daylight environment should not be so bright as to cause uncomfortable glare for those leaving offices, and the color of transmitted daylight should appear "natural" to those entering the building from outside. The glass roof, therefore, should neutrally transmit a significant fraction of incident daylight but very little near-infrared and ultra-violet radiation. The roof should also have a high thermal resistance on winter nights, and none on summer evenings.

IV. FACTORS AFFECTING GLASS CHOICE

Visible Versus Solar Transmission

Glass is naturally opaque to long-wave radiation (far-infrared), so it has some thermal resistance. Unfortunately, this property works against the atrium in summer, but can be offset by ventilation. The major variables in the choice of glazing, therefore, are its transmission of visible light and its shading coefficient. These are compared in Figure 2 (Table I provides key to figure) for the tinted and reflective glasses in one South African manufacturer's line of laminated glass products (Shatterprufe). Each labeled point on Figure 2's scatter plot represents the correlation of visible light transmission to shading coefficient for a glass type. The graph's scales correspond to the correlation for clear glass. That is, the visible transmission of a thickness of clear glass having a shading coefficient of 1 (3 mm) will have a visible light transmission of approximately 90 percent. The diagonal line drawn across the graph represents the divider between glass types that perform better than clear glass (greater light transmission per level of shading coefficient) and those which do not. For example, glass type 13 (light gold-coated reflective glass) transmits more light per unit of solar gain than clear glass, but glass type 4 (dark bronze-tinted glass) transmits much less, even though both types have almost identical shading coefficients.

The only glass types that perform better than clear glass are those which selectively reflect or absorb long-wave or ultra-violet radiation better than clear glass (e.g., gold- or copper-coated reflective glass, high-iron green tinted glass). All other glass types tend to absorb or reflect all wavelengths equally. In addition, tinted glass absorbs radiation, which in turn heats the glass, thus radiating long-wave radiation to the interior in place of short-wave visible light. For this reason most "high performance glass" does not perform as well as clear glass.

Psychological Issues

The level of performance required is relative to the need. For the chancery's atrium, as for many office buildings, the need for a low shading coefficient outweighs the desirability of high light transmission. In fact, a modest light transmission is desirable because the aperture is very large, and the likelihood of uncomfortable glare is certain on sunny days. Furthermore, inhabitants of warm-climate countries often associate high light levels with heat, and tend to prefer light environments which people from northern climates would consider dark or even gloomy. Since the climate is sunny and the sun is high in the sky during

Figure 2: LAMINATED GLASS PERFORMANCE

(DAYLIGHT vs. SOLAR CONTROL)

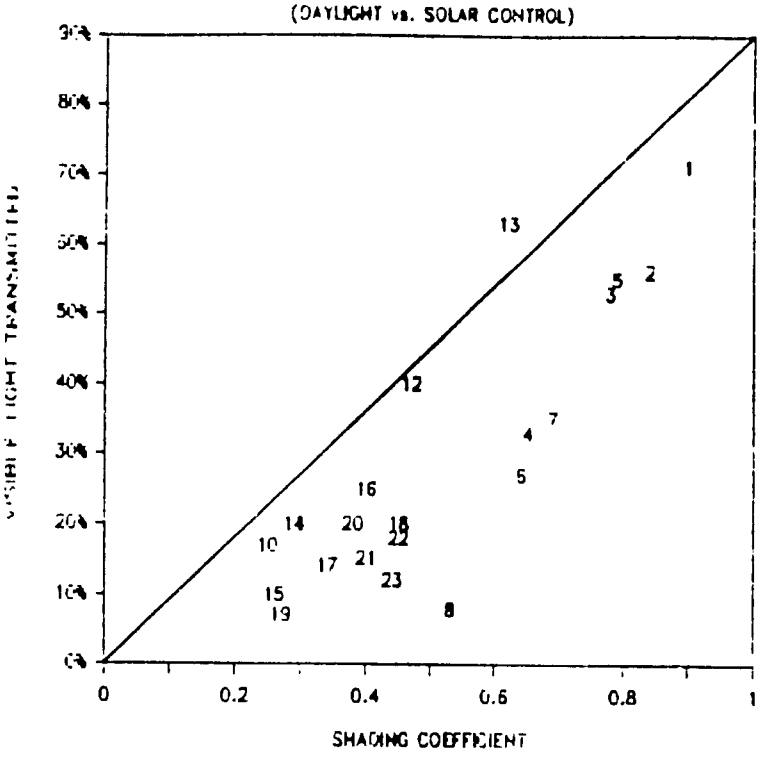


Table 1: LAMINATED GLAZING CHARACTERISTICS

GLAZING TYPE	CODE	VISIBLE TRANSMITTED	SOLAR REFLECTED	SOLAR ABSORBED	SOLAR TRANSMITTED	SHADING COEFFICIENT
DEEP GOLD	10	0.17	0.57	0.36	0.19	0.25
SILVER 2/10	15	0.10	0.35	0.52	0.23	0.26
SILVER BLUE 2/10	19	0.07	0.31	0.62	0.26	0.27
GOLD 2/20	11	0.20	0.47	0.42	0.25	0.29
BRONZE 2/20	14	0.20	0.45	0.47	0.25	0.29
C2/10	17	0.14	0.21	0.60	0.29	0.34
SILVER BLUE S/20	20	0.20	0.21	0.62	0.33	0.38
SILVER 2/20	16	0.25	0.23	0.56	0.35	0.40
SILVER BRONZE S/20	21	0.15	0.14	0.73	0.35	0.40
COOLRAY BRONZE	23	0.12	0.07	0.79	0.38	0.44
C2/20	18	0.20	0.24	0.59	0.39	0.45
BLUE 2/20	22	0.18	0.27	0.58	0.39	0.45
GOLD 2/40	12	0.40	0.33	0.42	0.41	0.47
S DEEP SPECIAL SR30	9	0.08	0.05	0.82	0.46	0.53
SHADOWLITE DEEP SPECIAL	8	0.08	0.05	0.82	0.46	0.53
GOLD 2/70	13	0.63	0.21	0.34	0.54	0.62
SHADOWLITE 25 (DARKER BROWN)	6	0.27	0.05	0.66	0.56	0.64
DEEP BRONZE	4	0.33	0.06	0.64	0.56	0.65
SHADOWLITE 25SR30	7	0.35	0.05	0.59	0.60	0.69
BRONZE	3	0.53	0.07	0.42	0.68	0.78
SHADOWLITE 50 (LIGHT BROWN)	5	0.55	0.07	0.40	0.69	0.79
DEEP BLUE	2	0.56	0.05	0.32	0.73	0.84
BLUE	1	0.71	0.05	0.25	0.78	0.90

most working hours, a relatively low level of light transmission will provide several thousand lux in the atrium during working hours.

In the case of the chancery atrium, these factors suggest glass types having a low shading coefficient, combined with good light transmission and a natural color rendition. "Natural" in this case means "expected." People are not very sensitive to the color rendition of a light source if there is no reference for comparison. For example, fluorescent light is usually accepted as "white," although its color varies from pink to blue depending on the type of tube. Its pinkness or blueness are not noticed unless there is a second light source (e.g., daylight, another type of tube or incandescent light) for comparison. Likewise, the apparent "color" of daylight in the atrium would not be an issue if no sources of comparison were available, but all users of the space will arrive from outside or from an office with very large, clear-glazed windows. The color of light in the atrium will therefore be noticed. In this situation, experience shows that people from northern climates tend to prefer a color shift toward the warm end of the spectrum if a shift is necessary. Those from warm climates could conceivably prefer a shift toward the blue, cooler side of the spectrum. There is no hard evidence either way, but a warmer-color light tends to enhance the appearance of both African and Caucasian skin tones and integrates well with the warm-color palette the designer intends to use in the building.

Glazing Recommendation

Combining all the factors discussed above, the choice of glass types is narrowed to those having:

- a low shading coefficient (less than 0.4),
- good light transmission (15 to 30 percent), and
- warm apparent color (neutral, bronze or gold).

The options that best satisfy the three conditions include:

Glazing Type	Code	Coating, Substrate	Light Color
"silver 2/20"	16	silver coating on clear	cool, neutral
"bronze 2/20"	14	gold coating on bronze	warm, brown
"deep gold"	10	gold coating on bronze	warm, brown

V. ANALYSIS OF GLAZED ROOF PERFORMANCE

The thermal performance of the atrium, as designed, was modeled by CALPAS-3 computer simulation to determine whether working comfort levels could be maintained using "high performance glass." The hour-by-hour weather used by CALPAS for its simulation is typical of Gaborone, so annual simulations would be somewhat misleading since Lusaka's conditions are less extreme. Simulations are useful, however, for determining hour-by-hour performance for individual days typical of weather in both locations. Two "Gaborone" days were chosen, one in May and one in November, as typical of average monthly weather and sun altitudes in Lusaka for July and October.

"As Designed" Performance

There is no doubt that a glazed roof would warm the atrium sufficiently in winter to provide working comfort. The critical time for the design is the hottest month, October. Figure 3 plots the outdoor ambient and atrium temperatures for a typical October day. The atrium was glazed with the silver version of the glass types chosen above. It was assumed to be continuously open to the outside air through the large entrance portico and the entire height of the glazed "slots" between the office wings and High Commissioner's suite (total vent area: 20 m^2). It is obvious from inspection of Figure 3 that either the venting is insufficient or glass shading coefficient too high: the atrium temperature is in the comfort zone (22-27°C) only until 9 a.m., after which time it climbs precipitously to 37°C at 2 p.m., 4°C higher than the outdoor ambient temperature.

Improving Ventilation

The heat load on the atrium is so great that it is unlikely that a lower shading coefficient will "fix" the problem. The primary needs are to remove heat as it is collected and, throughout the night, to cool the mass of the atrium's walls and floor. Figure 4 shows the results of lifting the space frame 0.7 meters above the wall parapet to provide a continuous ventilation slot along the entire perimeter of the atrium roof.

This design change increases the vent area 3.5 times, to 70 square meters. Predicting the effect of wind- and stack-driven ventilation by computer model depends on assumptions that can only be guessed at, so results are not necessarily accurate. It is likely, though, that increasing both high and low vent area by a large percentage will improve venting enough for the atrium to track outdoor ambient conditions. The atrium is slightly warmer at night as its mass gives off heat stored during the day, and

Figure 3: SILVER 2/20, LOW VENT

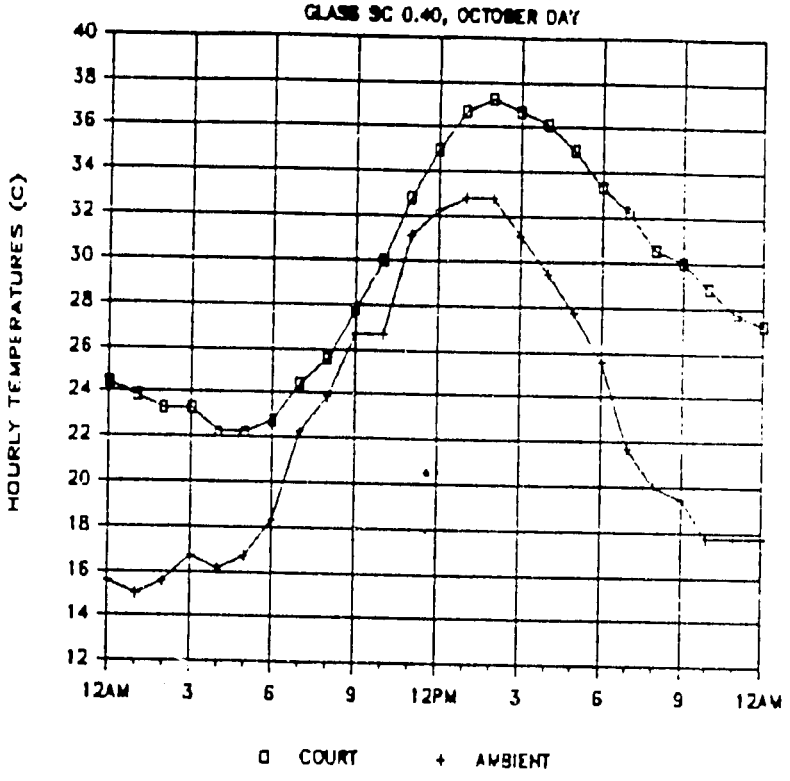
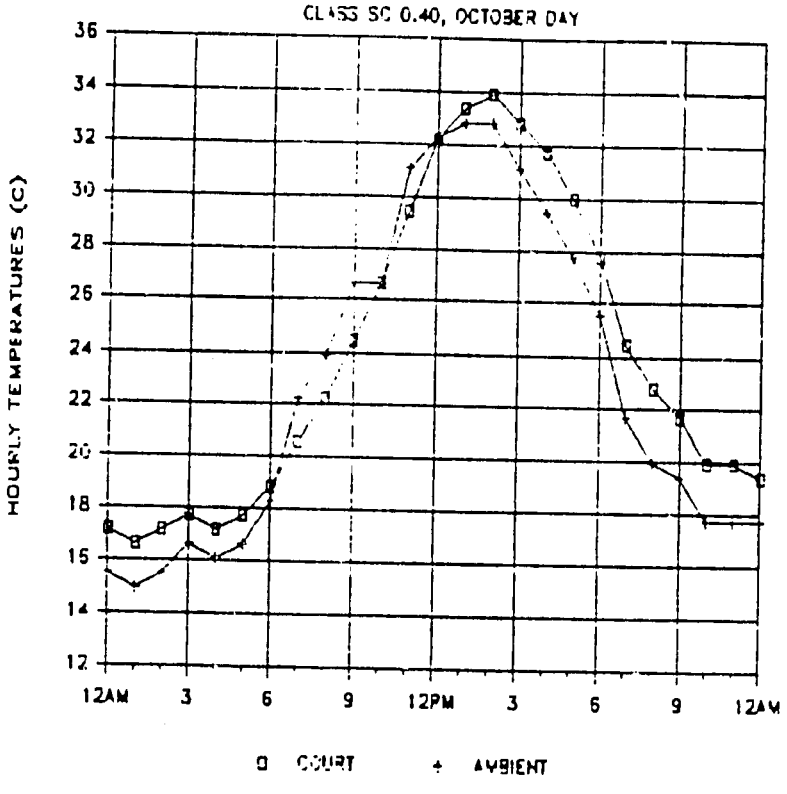


Figure 4: SILVER 2/20, FULL VENT



slightly cooler in the morning as the mass stores heat. Nevertheless, the atrium will always be warmer than ambient conditions in the afternoon as long as it receives direct solar gain and is not as well ventilated as a shade tree outside.

In winter, it would be desirable to control venting to reduce nighttime heat loss. The roof perimeter ventilation and the slot between buildings should probably be glazed, with horizontal, louvered windows that can be operated on a seasonal basis and provide some rain protection even when open. Ideally, the building's front entrance should be open for most of the year, but closed from May to July. A security grille is currently planned for the opening. Removable glass doors should be investigated for winter use.

Reducing Shading Coefficient Versus Radiant Effects

The minimum shading coefficient that can be achieved with laminated glazing is 0.25, that of "deep gold," which is 38 percent lower than that of the silver glazing in Figure 4. Deep gold transmits 19 percent of incident solar radiation and 17 percent of incident visible light. Using it would provide only a slight improvement to the atrium, if the atrium already had a large vent area. Figure 5 shows that atrium temperatures would be about 5°C below outside ambient conditions until noon, and about 5°C higher until midnight. These conditions are close enough to the silver-glazed atrium to indicate that the point of diminishing return has been reached. In fact, the situation is not as good as indicated on the CALPAS plots, since comfort in the atrium is affected by radiation from the surfaces of the "room" and direct sunlight, as well as the air temperature predicted by the simulation. This situation is indicated by Figure 6, which shows the temperature of the glass roof in addition to that of the atrium air. The glass is heated directly by the sun, and its temperature is relatively independent of its transmission or the ventilation rate. In short, any glass roof will exceed 50°C in the middle of the day. The downward long-wave radiation from this large, hot surface will raise the apparent temperature of the atrium 4-5°C above the air temperature. This effect is equivalent to that experienced when standing beneath a galvanized steel roof. For people standing in the middle of the atrium who "see" direct sunlight through the glazing, the effect will be even greater.

Summary

"High performance" glazing, if coupled with a large vent area around the entire perimeter of the space frame, can maintain atrium temperatues within a few degrees of outside ambient conditions during the warm months. On sunny days, however, the

Figure 5: DEEP GOLD GLAZING, FULL VENT

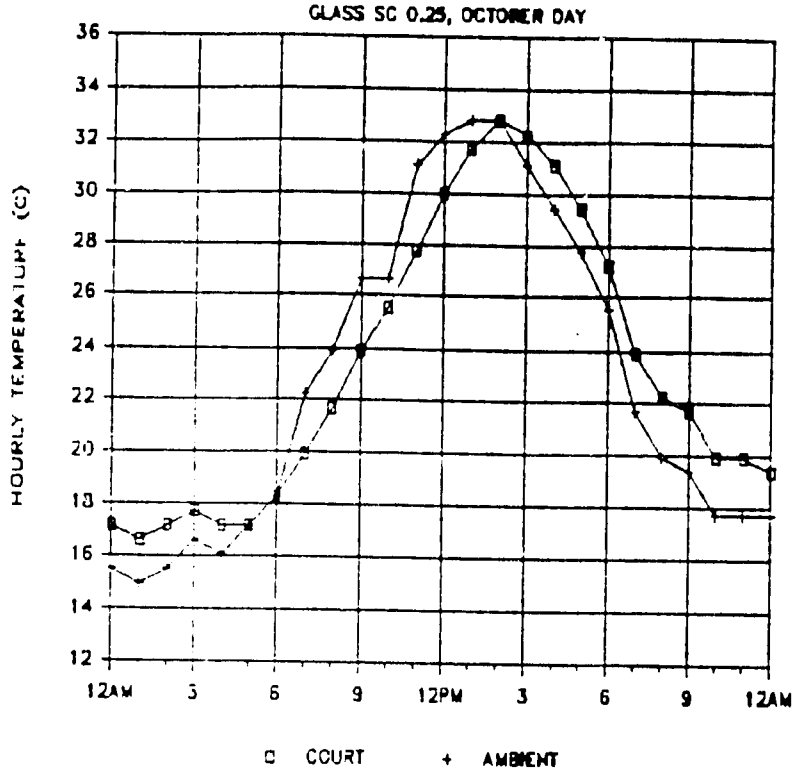
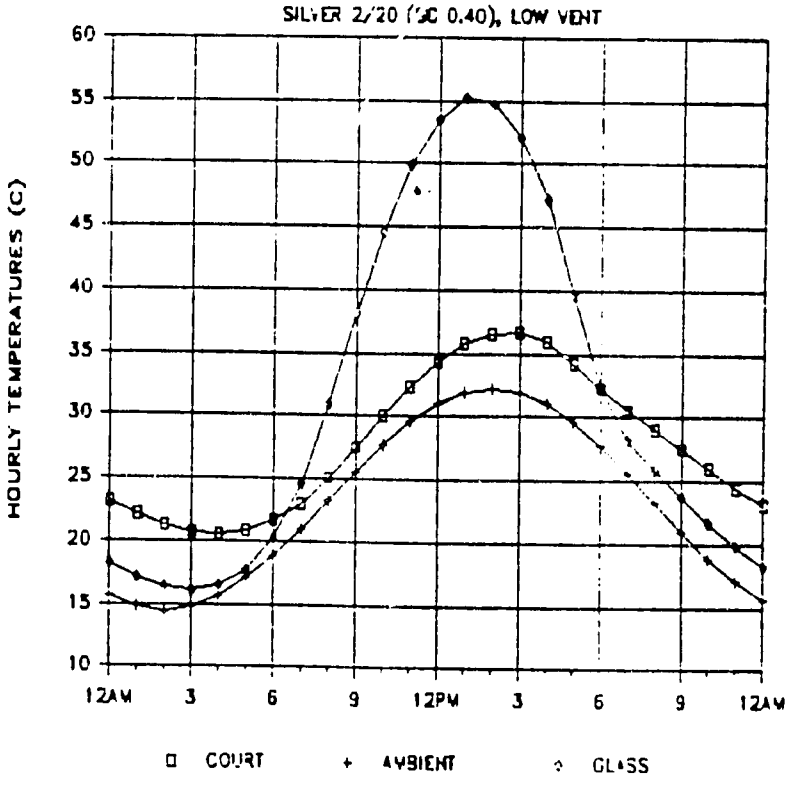


Figure 6 : GLASS TEMPERATURE, OCTOBER



atrium will feel much warmer than outside temperatures due to radiant heating from the hot glass surface and direct sunlight. On winter days, the atrium can be quickly heated above outdoor ambient temperature by controlling ventilation, and can retain much of this heat through the following night.

On an annual basis, the use of a glazed roof, coupled with seasonally or daily operated ventilation, is a reasonable strategy for tempering the atrium in winter, but cannot provide comfortable conditions on any sunny day when outdoor ambient temperatures are within or above the comfort zone (i.e., greater than 22°C). This limitation may be acceptable if workers and visitors only use the atrium as a circulation zone, but its size and location is such that it is likely to be used as an informal gathering place as well. If so, it should be designed to provide thermal comfort which is at least equivalent to, and certainly no worse than, that provided by a shade tree outdoors.

VI. ALTERNATE ROOF CONCEPT

A glazed roof supported by a space frame is architecturally exciting and is clearly the element that unifies the organization of the chancery. Its thermal performance, however, is poor, and the chancery is likely to be an expensive item to construct in that its elements are glass and steel, prefabricated and imported from South Africa. Therefore, it would be prudent to consider an alternate approach to the glazed roof if it becomes clear that its expense and performance liabilities outweigh its visual qualities.

The best way to retain the benefit of daylighting while reducing solar gain is by using relatively modest areas of vertical glazing, oriented north or south to simplify solar control. This describes the now-classic roof monitors and saw-tooth clerestories used in factory and warehouse designs before fluorescent lighting. Factory design might seem to be an unsuitable source for forms to be used in an embassy, but the dimensional requirements of monitors and clerestories result in distinctive and visually interesting forms which may integrate well with the bold expression of the Lusaka chancery. One example of how these forms might be used is shown in Figures 7 and 8.

Description

The concept illustrated in Figures 7 and 8 uses north- and south-facing vertical clerestories set in a series of five roof elements. A relatively small amount of direct sunlight can enter the atrium with this design, and then only when the sun is low in the sky. Most of the atrium's daylight is sunlight reflected from the white roof surfaces outside onto the sloped ceilings of the roof elements, then diffused throughout the atrium. The quantity of daylight in the atrium would be lower than that of the glazed-roof version, but its distribution would be even, with fewer contrasts and shadows. Most of the clerestory area faces south so that the amount of direct solar gain entering the atrium is reduced, and because this geometry allows the roof elements to step up to meet the high roof parapet of the High Commissioner's suite. Half of the east and west sides of the roof assembly are solid, to support the roof elements. The remaining area is glazed, but also shaded by the overhanging projections of the roof elements on the outside of the building. These clerestory windows could also be shaded by metal louvers in front of operable glazing.

All glazing in the roof structure is standard clear glass and is operable for ventilation, except the triangular clerestories at the ends of the roof elements. Standard, horizontal, louvered windows are used since they provide some

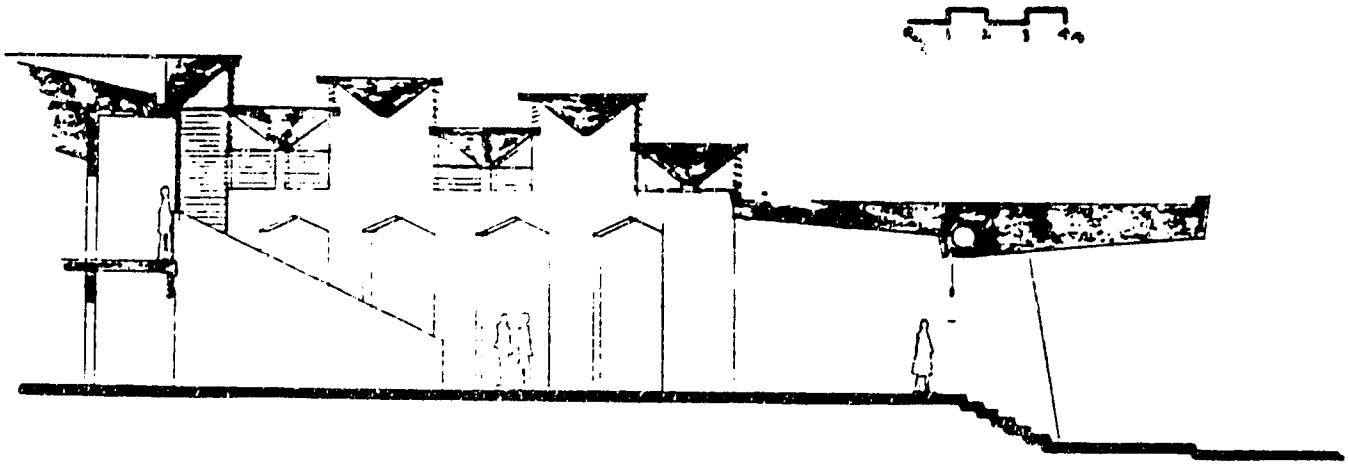


Figure 7. Section Through Atrium

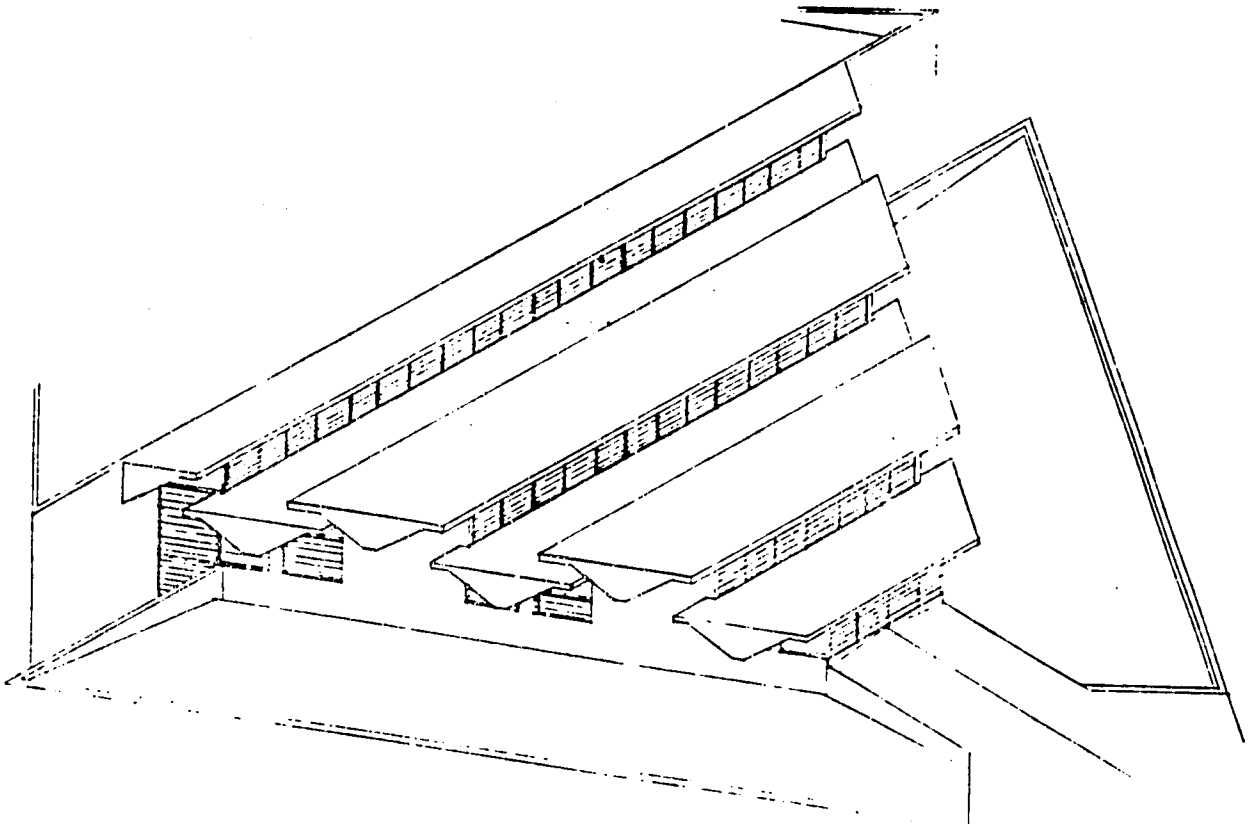


Figure 8. Isometric View of Atrium Roof

rain protection even when open, and do not greatly restrict air flow. They can be opened and closed, generally from the outside, on a seasonal or daily basis by one of the building staff. In addition to the roof ventilation, this design also requires the front entrance and "slots" between buildings to be open during the warm months.

A vertically glazed roof-lighting design may not be less expensive to build than a glazed space frame, but it is probably easier to build since most of the materials and connections required are commonly used in commercial-scale buildings. The roof elements' spanning structure could be either a single trussed steel girder or a triangulated pipe truss. The underside of the roof elements is covered with sloped, white ceilings to help diffuse light throughout the atrium.

Performance Comparison

The performance of the roof design illustrated in Figures 7 and 8 was simulated and compared to the simulated performance of the best version of the glazed roof (deep gold glazing, large vent area). Both versions were operated in an identical manner, with all windows and doors left open during the warm months and closed during the winter, except when indoor temperatures rose above the comfort zone. Both versions were assumed to have glass doors at the main entrance that could be operated by building staff to help regulate the atrium temperature, or left open throughout the warm season.

Figure 9 compares the two atrium designs' temperatures during a typical October day. As already shown above, the glazed roof closely follows outdoor temperatures as long as the sun is up. The roof monitor design, however, heats much more slowly since it transmits only a small fraction of the solar gain incident on the roof. Furthermore, the rate at which the thermal mass of the atrium's walls and floor absorb heat is closer to the rate at which it is introduced than in the case of the glazed roof, so its effect is more pronounced in dampening the atrium's temperature rise. The result is that the temperature in the roof monitor design does not exceed the comfort zone until 4 p.m., while the glazed-roof atrium has been too warm since 10 a.m. (including effect of radiant heating).

The difference in winter performance between the two design approaches is similar (Figure 10), with the glazed roof responding rapidly to the sun's heat, and cooling off just as rapidly. The roof monitor version receives enough solar gain to replenish the heat lost the night before, but not enough to substantially raise its temperature. Both versions store enough heat in the atrium's thermal mass to maintain a respectable temperature through the night.

Fig. 9: MONITOR vs GOLD REFLECTIVE

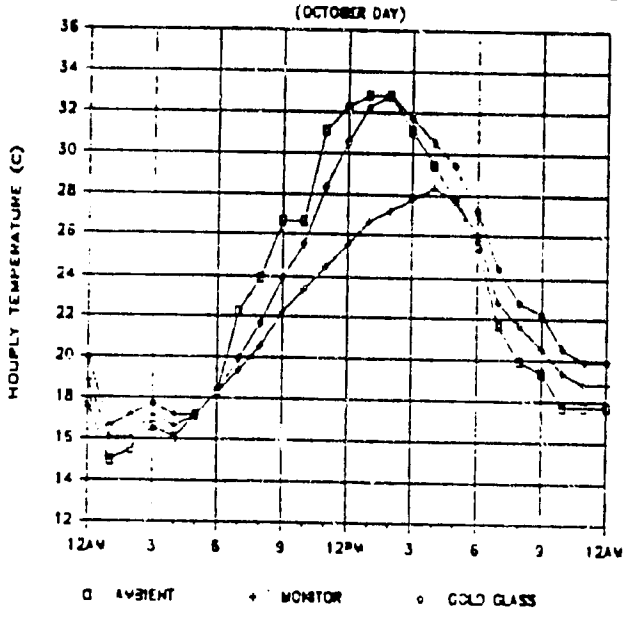
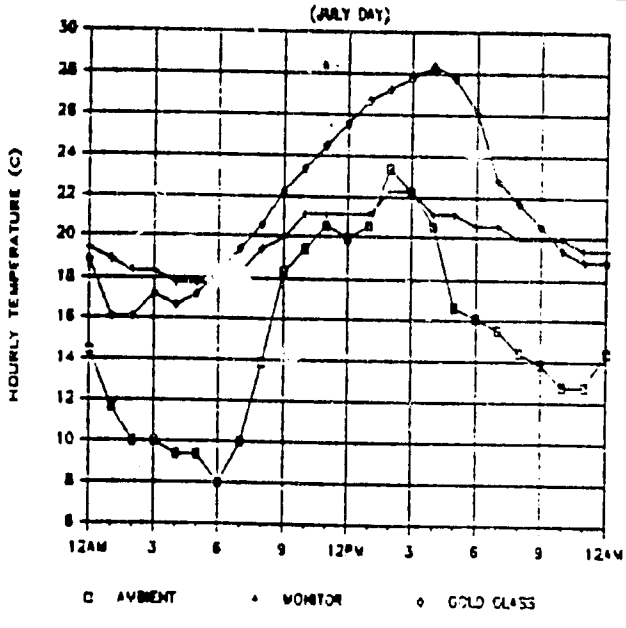


Fig. 10: MONITOR vs GOLD REFLECTIVE



Summary

Both the glazed and monitor roof options are likely to be expensive to design and construct. Long-term maintenance requirements of the glazed roof are unknown. For the monitor concept, they are similar to conventional roofs.

On an annual basis, a vertically glazed roof-monitor system will provide thermal comfort in the atrium for most of the year's working hours, if its ventilation is operated intelligently. A glazed roof can provide comfort throughout the working day only during the short cool season. For most of the year, comfort will be provided only in the early morning.

VII. RECOMMENDATIONS

The following recommendations are derived from the analysis described in the previous sections of this report.

First, a glazed roof will not reliably provide working thermal comfort in the chancery's atrium, which will generally be perceived as warmer than outdoors, even on hot days. The Buildings Department and consulting architect should investigate the feasibility of an alternate roof design using vertical, rather than horizontal glazing. A roof monitor or clerestory design probably would not be less expensive to construct, but would provide much better thermal comfort and equivalent daylighting. Long-term maintenance might also be simplified. One design example is included in the report for reference.

Second, if an alternate design is not practically feasible, it is imperative that the atrium's ventilation area be increased. A minimum improvement would provide a continuous vent around the roof's perimeter (0.7 meters high; 50 percent free area is a minimum) and provide for unobstructed ventilation through the chancery's entrance and the entire height of the glazed "slots" between office wings and the High Commissioner's suite.

Third, if a glazed roof is used, the glass choice should be limited to options having a low shading coefficient (less than 0.40), good light transmission (15 to 30 percent) and a neutral or warm color rendition.

Finally, north- and west-facing building facades would benefit from the addition of horizontal overhangs for solar control. The present design relies totally on vertical fins, oriented perpendicular to the walls, which are not effective when needed (i.e., midday on north, mid and late afternoon on west).