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TOTAL BUILDING IMPACTS OF SOUTH-FACING ROOF APERTURES

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DISCLAIMER

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SOLAR BUILDINGS RESEARCH AND DEVELOPMENT PROGRAM
CONTEXT STATEMENT
November 21, 1985

In keeping with the national energy policy goal of fostering an adequate supply of energy at a reasonable cost, the United States Department of Energy (DOE) supports a variety of programs to promote a balanced and mixed energy resource system. The mission of the DOE Solar Buildings Research and Development Program is to support this goal, by providing for the development of solar technology alternatives for the buildings sector. It is the goal of the program to establish a proven technology base to allow industry to develop solar products and designs for buildings which are economically competitive and can contribute significantly to building energy supplies nationally. Toward this end, the program sponsors research activities related to increasing the efficiency, reducing the cost, and improving the long-term durability of passive and active solar systems for building water and space heating, cooling, and daylighting applications. These activities are conducted in four major areas: Advanced Passive Solar Materials Research, Collector Technology Research, Cooling Systems Research, and Systems Analysis and Applications Research.

Advanced Passive Solar Materials Research. This activity area includes work on new aperture materials for controlling solar heat gains, and for enhancing the use of daylight for building interior lighting purposes. It also encompasses work on low-cost thermal storage materials that have high thermal storage capacity and can be integrated with conventional building elements, and work on materials and methods to transport thermal energy efficiently between any building exterior surface and the building interior by nonmechanical means.

Collector Technology Research. This activity area encompasses work on advanced low-to-medium temperature (up to 180°F useful operating temperature) flat plate collectors for water and space heating applications, and medium-to-high temperature (up to 400°F useful operating temperature) evacuated tube/concentrating collectors for space heating and cooling applications. The focus is on design innovations using new materials and fabrication techniques.

Cooling Systems Research. This activity area involves research on high performance dehumidifiers and chillers that can operate efficiently with the variable thermal outputs and delivery temperatures associated with solar collectors. It also includes work on advanced passive cooling techniques.

Systems Analysis and Applications Research. This activity area encompasses experimental testing, analysis, and evaluation of solar heating, cooling, and daylighting systems for residential and nonresidential buildings. This involves system integration studies, the development of design and analysis tools, and the establishment of overall cost, performance, and durability targets for various technology or system options.

This report is an account of research conducted in systems analysis and applications research concerning passive solar technology assessment.

TOTAL BUILDING IMPACTS OF SOUTH-FACING ROOF APERTURES*

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ABSTRACT

The U.S. Department of Energy's Passive Experimental Non-Residential Buildings Program has resulted in the design, construction, and instrumentation of nearly twenty commercial buildings throughout the United States (Gordon 1982). Of these buildings, more than eighty percent employ south-facing roof apertures as a major component of their passive systems. These buildings provided an opportunity to investigate the impact of roof apertures with respect to such issues as occupant response to the naturally lit environment, effectiveness of electric lighting control, and secondary effects such as changes to the radiant and acoustic environments.

This paper will focus on a library building in Mt. Airy, North Carolina. It will investigate three topics related to the roof aperture design: the effectiveness of manual control of the artificial lighting; the changes in in energy use brought about by the inclusion of the roof apertures; and indirect impacts of the roof aperture design.

In addition to observation and measurement of the Mt. Airy Library, simulation using the building energy analysis program BLAST[†] analyzed these topics. Application of these techniques has shown that a situation exists which is conducive to the effective operation of manual lighting control; that the large apertures most directly affect lighting energy, and produce compensating effects on both heating and cooling energy use; and that thermal mass plays a role in a number of energy use and comfort issues, some of which are not easily reconciled.

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[†] BLAST (Building Loads Analysis and System Thermodynamics) is trademarked by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.

INTRODUCTION

Analyses of office buildings with continuous dimming of the electric lights, have shown that the optimal aperture glazing area is less than 10% of the building floor area over a wide range of U.S. climates (Place 1983). In the Department of Energy's Program, most of the buildings make use of south-facing roof apertures, typically with aperture areas above 20% of the building floor area. One can surmise that the two primary reasons for the use of these large glazing areas are (1) to improve heating performance; and (2) to provide daylight levels consistently above the minimum required for ambient lighting in order to avoid the need for continuous manual adjustment of the auxiliary lighting system. This paper will discuss the ramifications of this choice.

The Mt. Airy Library is a 1300 square meter public library servicing a rural community of 7000. The winters are generally mild, with about 2200 heating degree days (^{o}C), and summers are warm and humid. The library is typically open to the public from 8:30am to 8pm (shorter hours on weekends), with a staff of 3-4 on duty most of that time. There are usually 2-8 visitors in the building.

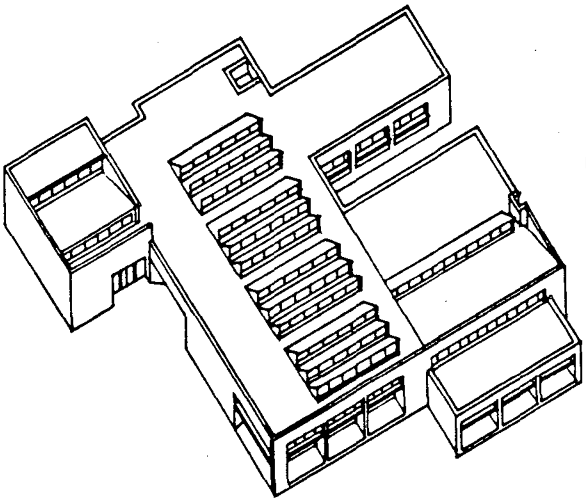

Fig. 1: Exterior Axonometric.

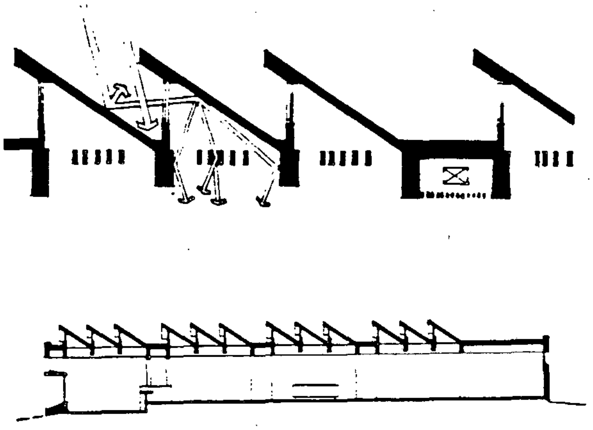

Fig. 2: Roof Monitor Section

There are a variety of daylighting techniques used (Fig. 1), but this analysis will concentrate on the dominant technique, the roof apertures (Fig 2) repeated along the main axis. This section of the library contains the circulation desk, card catalog, reading areas and work tables. Sunlight enters through vertical glazing on the south of the aperture (the aperture area is more than 20% of the floor area), then is reflected by the ceiling and by a set of baffles spaced to assure that no sunlight enters the space directly, thereby preventing glare and damage to materials. In this section of the library there are no interior partitions; sunlight therefore can be distributed evenly across the entire area. A concrete floor slab covered with paving tile provides thermal energy storage to absorb the diffused solar radiation from the roof apertures.

Four techniques have been used to develop information on the library's aperture system: direct observation of occupants and building operation, analysis of data measured continuously at the building for several winter months, illumination and solar measurements using scale models to test different solar and aperture geometries, and computer simulations with the building energy analysis program BLAST*. The methodology for this project is described in detail in (Andersson, 1984). Three topics are discussed below, and a fourth important issue, "Visual Environment", is dealt with in a separate report (Adegran, 1984).

MANUAL CONTROL OF ELECTRIC LIGHTS IN RESPONSE TO DAYLIGHT

The way in which electric lighting will be controlled is a major consideration in any daylighting design. Automatic controls are a significant expense, but they can provide more continuous, precise, and consistent control. Manual operation of the lights allows occupant involvement and adjustment for individual requirements, but can result in substantial artificial lighting when there is no need for it. Manual control is used in the Mt. Airy Library. Comparisons will be made between measured and predicted lighting energy use where the predictions assume automatic control strategies.

U.S. standards for lighting in offices and libraries are typically 550-770 lux. For the purposes of analysis, 550 lux was chosen as the minimum acceptable illumination level. Two automatic controls were simulated: "on/off" controls where the lights are fully powered whenever the illumination from daylighting drops below 550 lux; and "continuous" controls which add just enough artificial light to maintain the minimum 550 lux.

Table 1 indicates the number of hours in which different levels of illumination are provided by the roof apertures, and the amount of supplementary lighting energy required for the daylit building relative to a non-daylit building. The measured minimum work plane illumination level for each hour is used to define the bin into which the data for that hour is accumulated. The table summarizes experimental data for November and December, 1983. Manual control numbers are based on actual measurements at the building over that period. Results for automatic controls are based on simulations.

Table 1: Comparison of Auxiliary Lighting Control Strategies

Daylighting Illumination (lux)	25-220	220-330	330-550	550-1100	>1100	Total
Number of Hours	26	40	59	78	113	316
Relative Energy Use (%)						
-Manual Control	54	30	15	14	6	16.5
-Automatic Continuous Dimming	85	45	25	0	0	17.5
-Automatic On / Off Control	100	100	100	0	0	39.5

With manual control there are significant periods when no lights are turned on even though illumination levels do not meet the common standard. Comments from the occupants on the quality of light indicate that the lighting is nevertheless satisfactory. With a manual system, of course, there is a subjective judgment on the part of the person controlling the artificial light as to whether there is sufficient natural light for the task to be performed.

Switches at the circulation desk control the lights in the daylit area. The other occupants are typically visitors to the library spending a relatively short time there. Because of the concentration of responsibility, each full-time occupant can be instructed in proper operation of the system and more conscientious and consistent control can be exercised. The transient nature of visitors and their ability to move to different work areas reduces chances for inadequate lighting is provided to any individual. Responses from the occupants confirm that the lighting is acceptable. In this particular building, large apertures, good light distribution, centralized control, and transient use patterns combine to make manual control of electric lights not only inexpensive, but effective.

DIRECT ENERGY IMPACTS OF THE ROOF APERTURE SYSTEM

Identifying the energy contribution of a single element of a passive design is often difficult because each element affects many others. In trying to understand how the roof apertures contribute to overall performance, the energy use of the same building without roof apertures can be simulated to estimate heating, cooling, and lighting energy use for a non-daylit library which is otherwise identical to the real building. Although this cannot provide definitive results, it can provide insight into the magnitude of the effect and sensitivity to variations in design and operation parameters.

Impact of Roof Apertures on Lighting Energy Use

Table 1 provides the relationship between illumination available from daylighting and auxiliary lighting energy use. This relationship, based on two months of data, has been assumed to be valid throughout the year and serves as the basis for the annual estimate of energy use in Fig. 3. Without roof apertures, lights are required in the space during the 3500 hours that the library is occupied, resulting in electrical usage of 5700 kwh each year. However, the daylighting system allows lights to be turned off during a substantial portion of those hours. Regardless of the control strategy used, 75-80% of the lighting energy used in the area under the roof apertures can be saved. The results assume that the occupants are as conscientious throughout the year as they were in November and December, and that the automatic controls are never overridden. In buildings like this, the decision about what control strategy to use should be made on the basis of cost and convenience, since the differences in energy savings between the alternatives are not great.

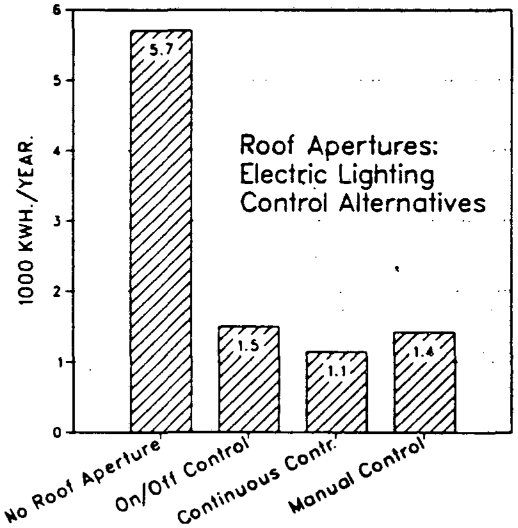

Fig.3: Lighting Energy Use.

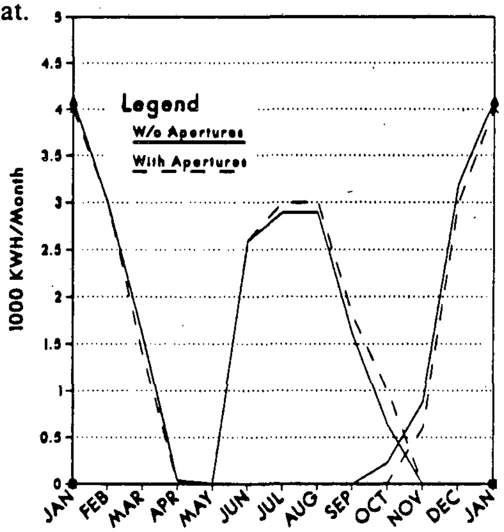

Fig.4: Heating, Cooling Energy Use

Impact of Roof Apertures on Heating and Cooling Energy Use

To identify the effect of roof apertures on heating and cooling energy use, issues which must be accounted for include changes in electric lighting use, solar gains through the south-facing roof apertures, and conduction losses through the double-pane glazing. In BLAST simulations all of these effects are accounted for by simulating a building without roof apertures which is otherwise identical to the actual building. The results of simulations of the actual daylit building and its non-daylit counterpart are shown in Fig. 4. (Simulation results for the actual building have been compared to measured energy use data to confirm that the simulation properly represents actual performance.)

Results in Fig 4. show that neither heating nor cooling annual energy use is dramatically affected by the roof apertures. In both cases, this is likely due to compensating effects. During the winter, the large solar apertures accept considerably more sunlight than is necessary for lighting purposes. Some of the excess heat is stored in the tiled concrete slab, while the rest heats the space immediately. This compensates for increased conduction of heat through the glazing, and decreases the heating load, especially in milder months like November. During the summer, beam radiation is virtually eliminated from the glazing by the fixed shades (Fig. 2). Diffuse light through the large windows provides daylighting much of the time, but is not so great as to cause overheating. Because natural lighting has a higher luminous efficacy (lumens/watt) than electric fixtures, if daylighting is used effectively to replace electric lights, less heat is admitted to the space, and, although some excess light is often admitted, the cooling loads are not substantially increased. Fig. 4 shows that in October, when the shading is less effective, beam radiation penetrates into the building, where it aggravates the cooling load.

INDIRECT THERMAL EFFECTS OF LIGHTING DESIGN OPTIMIZATION

The reasons for incorporating large south-facing apertures have been discussed above. Thermal mass is often used in buildings with substantial solar gains to store heat and to avoid overheating which would result in discomfort or unnecessary auxiliary cooling. However, the diffused, distributed radiation from the roof, required by the daylighting design, is probably one factor which resulted in the decision to distribute thermal mass over the entire floor, a concrete slab with paving tile as flooring. BLAST simulations were used to identify the effects of this decision.

In this building the typical occupancy is from 8:30am to 8pm. The thermostat is set back from 20.5°C during the day to 16.8°C between 7pm and 8am. There have been numerous comments by the occupants about the coldness of the building, especially in the morning. The lower heating and cooling energy use associated with the thermally massive floor and its moderating effect on daytime temperatures must be balanced against potential reductions in the effectiveness of the night setback strategy and against possibly deleterious impacts on comfort during the morning warm-up period.

Fig. 5 compares simulations of the building with its tiled floor against the same building with areas of the floor isolated by a thick carpet. The ability of the mass to absorb heat during the day, preventing rapid temperature increases and associated heat losses, outweighs any detrimental effect on performance of the setback. The advantage is modest, however, except when a fully carpeted floor is compared against the existing floor construction. There is little change in the cooling load, because a primary summer use of thermal mass, elimination of heat at night by ventilation, is of limited value in this climate. Summer night temperature and humidity are relatively high, making ventilation a marginal technique.

Fig. 6 shows simulations of a typical winter day's profile of effective temperature (average of air and mean radiant temperatures) for the tiled floor (solid curves) and one 2/3 carpeted (dashed curves) for both sunny (upper) and cloudy (lower) days. Effective temperature is generally considered a better indicator of thermal comfort than simple air temperature. These curves indicate the comfort level achieved with different mass levels by identifying those situations which fall outside the comfort envelope (boxed) during occupied hours (8:30-8).

There are clearly two potential comfort problems: coldness on cloudy mornings for both mass configurations; and overheating on sunny afternoons in the reduced mass case. Coldness in the building when there is little solar gain appears to result from a lag in mean radiant temperature which is only slightly improved by isolating the mass. The simulations indicate that the feeling of coldness is the result of the difference between air and radiant temperatures, and the effect of the thermostat to provide only sufficient heat to raise the air temperature, not the effective temperature, to comfort levels. The radiant temperatures of most interior surfaces, not just the floor, contribute to the problem. Excessive increase in effective temperature due to solar

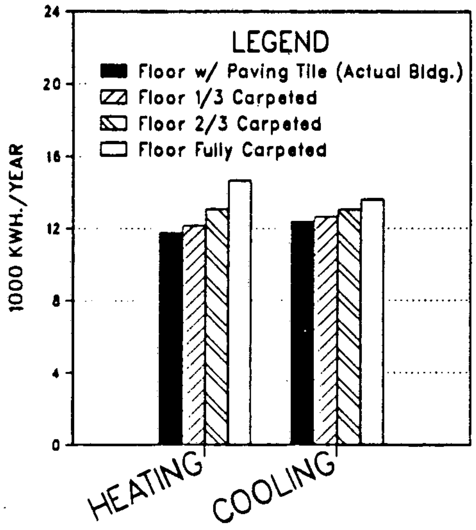

Fig. 5: Mass Effect: Energy

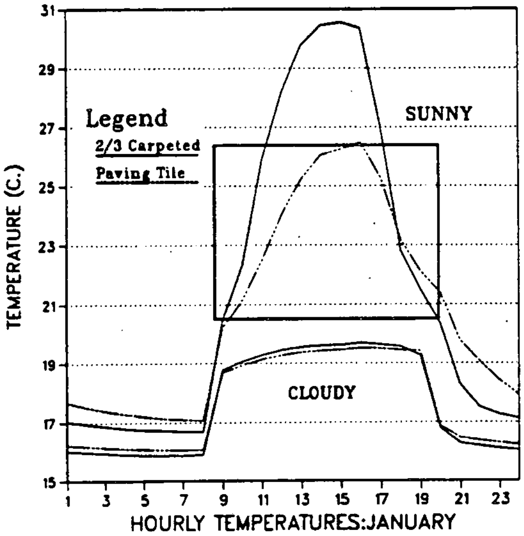

Fig. 6: Mass Effect: Comfort

gains on sunny days, however, is significantly reduced by the ability of the massive floor to maintain a relatively low radiant temperature.

These simulations indicate that the mass configuration used in the building provides a reasonable balance of heat storage for early evening hours, prevention of excessive solar heating, and allowance for sufficient drop in night temperatures, but a comfortable morning environment is not likely to be achieved without simply raising the thermostat, resulting in significant additional heating costs. Additional investigations should be made to better understand the numerous interrelated effects of thermal mass. Considerations such as ventilation to prevent overheating, reconciliation of energy, comfort, and acoustic requirements, and economics should be part of that investigation.

SUMMARY

A building in which roof apertures play important roles in lighting, heating, and architecture is affected in a variety of way. Observation, measurement, and simulation of the Mt. Airy Library has shown that (1) the daylighting design and the building function, occupancy level, and operation create a situation in which manual lighting control is very effective, (2) large, south-facing roof apertures can significantly reduce lighting energy, while only slightly affecting heating and cooling energy use, and (3) effective use of thermal mass depends upon evaluation of its effect on both energy use and occupant comfort.

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