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PERFORMANCE SUMMARY OF NINETEEN PASSIVE SOLAR COMMERCIAL BUILDINGS IN THE UNITED STATES OF AMERICA

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1. Introduction

In 1979, the U.S. Department of Energy initiated the Passive Solar Commercial Demonstration Program to determine the potential of passive solar technologies for heating, cooling, and lighting in non-residential buildings. Nineteen buildings were designed, constructed, instrumented and monitored to determine the energy consumption, economic performance, and occupant impact. Table 1 summarizes the types of buildings, their location, size, and prevailing heating and cooling degree days.[1]

2. Energy Performance

The central question for this demonstration project was: "Can commercial buildings realize significant energy savings through the use of passive solar design strategies?" The results of the demonstration program indicates that these buildings use 45% less energy than their conventional counterparts -- the base cases. In comparison to the average commercial buildings the demonstration group consumed 60% less energy [2]. Figure 1 shows the aggregate decrease in energy consumption from the base cases, and Figure 2 shows the range of decreases for each building in the program. The Base Case is defined as the building which would have been built by the owners if the demonstration program did not take place. In the case of retrofit projects the base case was the existing building [2].

2.1. Performance Results

Heating, cooling and lighting energy was reduced by approximately 50%, while energy consumption in the "other" category actually increased. Figure 1 shows that all of the primary energy consumption categories were reduced by large amounts. Over half of the projects focused on daylighting strategies, however daylight strategies did not lead to increases in cooling or heating energy. This makes the energy reductions in heating and cooling especially significant. In addition, the use of solar heating strategies did not lead to a corresponding increase in cooling loads. Solar heating was

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the focus in over 50% of the projects. One might expect solar apertures to collect unwanted heat gain during the autumn months, however, as can be seen in Figure 3 this is not the case. One possible reason why daylighting designs did not experience cooling penalties is that auxiliary lighting energy (i.e. heat gain) was 22% lower in summer months than in non-summer months.[3]

2.2. Increases in Performance Predictions

In many of the demonstration projects energy use was actually higher than predicted. These increases were caused by changes in occupancy and use patterns, contributing to 20% higher than expected energy use, based on an area-weighted average. Figure 4 shows the breakdown of predicted and actual energy use by end use energy. Heating energy was higher by 31% than the original estimates. This change was accompanied by a decrease in heating degree days in almost all of the projects. In the case of cooling estimates the actual consumption was 47% less even though there was an increase in cooling degree days [2]. The two major explanations for the discrepancies between the actual and projected consumption are: (1) the buildings were used differently than the design programs, or owners, had indicated; and, (2) the design tools, used to develop the projections, were not designed to provide accurate estimates. Most of the design tools were initially developed for residential application and did not account for thermal mass effects and/or the dynamic interactions between heating, cooling and lighting.

3. Economics

The two key questions related to the economics of passive solar buildings are: (1) do passive solar buildings cost more to build?; and, (2) Do passive solar buildings reduce annual operating costs? These questions are answered only in general terms. B the analysis of the program data most passive solar commercial buildings do not cost any more to build than conventional buildings of the same type. In answer to the second question, passive solar commercial building cost significantly less to operate annually than conventional buildings of the same type. Cost was based on actual construction costs and compared to a range of typical building costs (for similar building types) provided by national construction cost data systems. Cost data was adjusted for building size and regional variations. Economic analysis was undertaken for 13 of the 15 new building projects. The results are presented in Table 2 showing that 75% of the buildings fell within or below the range of typical costs for conventional buildings of the same type.

Table 1
DOE's Passive Solar Commercial Building Projects

Project Code	Building Type	Location	Size S F	Heating Degree Days (HDD)	Cooling Degree Days (CDD)
NEW CONSTRUCTION					
TR	Two Rivers School	Fairbanks, Alaska	15 750	10 500	512
AS	Abrams School	Bessemer, Alabama	26 600	-	-
CU	Church Addition	Columbia, Missouri	5 500	5 100	1 353
CM	Colorado Mountain College	Glenwood Springs, Colorado	31 900	9 700	450
MA	Mt. Airy Library	Mt. Airy, North Carolina	13 500	4 550	1 824
SM	St. Mary Gymnasium	Alexandria, Virginia	9 000	4 720	1 370
JC	Johnson Control Office	Salt Lake City, Utah	15 000	5 730	1 090
PP	Princeton Office Park	Princeton, New Jersey	64 000	4 790	934
SB	Security State Bank	Wells, Minnesota	11 000	7 120	1 220
ED	Essex Dorsey Senior Citizen Center	Baltimore, Maryland	13 000	4 700	1 400
SR	Shelly Ridge Recreation	Philadelphia, Pennsylvania	5 700	4 700	1 050
RP	RPI Visitors Center	Troy, New York	5 200	6 700	1 105
GU	Gunnison Airport	Gunnison, Colorado	9 700	9 900	446
WF	Walker Field Airport	Grand Junction, Colorado	66 700	9 900	450
TG	Toulatos Greenhouse	Memphis, Tennessee	-	-	-
RETROFIT					
PA	Automobile Maintenance	Philadelphia, Pennsylvania	57 000	4 240	1 050
PS	Princeton School of Arch	Princeton, New Jersey	13 700	4 790	934
KI	Keiffer Retail Store	Wausau, Wisconsin	3 200	8 070	367
CO	Comet Workshop	Braunfels, Texas	4 800	683	4 095

Table 2
Base Case Primary Energy Cost and Project Cost

Project Code	Base Case Primary Energy Costs: Heat	DHW	Cool	Lights	Other	Project Costs: Base Case $/S F	Passive Solar Proj Cost $/S F
TR	***	*		**		NC	$ 149
AS	*		***	**		50/56	$ 36
CU	***		*	**		NC	$ 47
CM	***			*	**	55/69	$ 64
MA			*	***	**	79/90	$ 88
SM	**		*	***		NC	$ 74
JC	**		*	***		66/72	$ 57
PP	***		*	**		66/72	$ 46
SB			**	***	*	75/90	$ 64
ED	***		**	*		43/51	$ 85
SR	***	*		**		48/55	$ 85
RP	***			*	**	75/79	$ 81
GU	***			**	*	70/76	$ 80
WF	**			***	**	74/84	$ 60
TG	***		*		**	NC	$ 12
PA	***			**	*	NC	$ 9
PS	***			**	*	NC	$ 9
KI	**		*	***		NC	$ 18
CO	**		***	*		NC	$ 3

Key:
*** Highest energy cost
** Second highest energy cost
* Third highest energy cost
(Costs are based on local utility rates)

Base Case
0/0 Dodge Mean Average
\+ High average

NC Not comparable

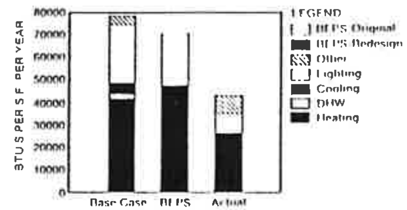

Fig. 1. Auxiliary energy use - aggregated results (1/31/85 JC, TR, MA, CU, GU, KI, RP, SB)

Table 3
Occupancy Changes, Utility Costs, and Heating Btu's/HDD

Project Code	Change in Building Use: TIMING OF OCCUPANCY	NUMBER OF PEOPLE	DIFFERENT LOCATION	DIFFERENT ACTIVITY	USE OF UNOCCUPIED SPACES	CHANGED OPERATIONS	Utility Cost: Passive Solar Annual Utility Cost $/SF	Conventional Utility Cost $/SF	Heating Btu's per HDD
TR	•	•				o			
AS									3.4
CU	•	•					15	45	3.3
CM	•	•	o	o	o		93	1.50	
MA	•	•					45	1.10	2.6
SM	•	•							
JC		–				o	56	1.00	3.5
PP	•	•	o	o		o			
SB		•	o	o	o	o	39	1.10	5.1
EO	•	•	o	o		o			
SR	•	•							
RP		•	o	o	o	o	1.20	2.30	2.5
GU		•		o	o	o	84	1.25	3.0
WF				o					
TG									
PA			o	o		o	89	1.50	18.0 (R)
PS				o		o			18.8 (R)
KI							25	65	8.8 (R)
CO	•	•				o	35	60	23.5 (R)

Key
• increase in hours occupied or increase in number of occupants
o occurred
– decrease
(R) Retrofit

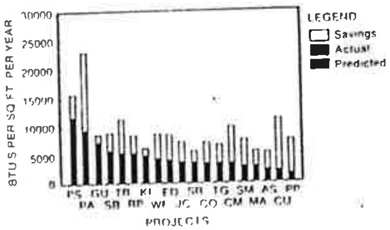

Fig. 2. Auxiliary energy use as a function of base case (1/31/85)

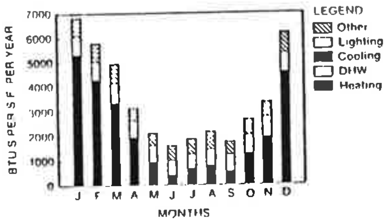

Fig. 3. Auxiliary energy use by function and month (1/31/85 JC, TR, MA, CU, GU, KI, RP, SB)

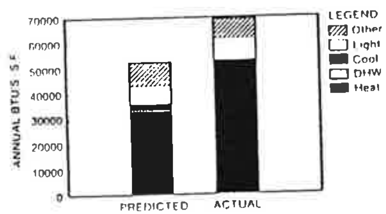

Fig. 4. Auxiliary energy use by function predicted and actual (1/31/85 for new and retrofit projects)

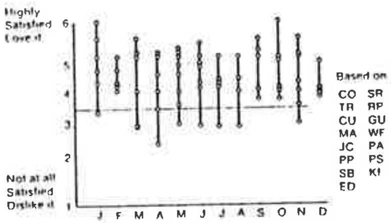

Fig. 5. Overall satisfaction by month

3.1. Operating Cost Comparison

Where comparisons could be made it is clear that annual utility costs for passive solar buildings are significantly lower than for conventional buildings. Ten of the 19 buildings have produced full-year utility costs as shown in Table 3. These are actual energy cost data, taken from monthly utility billings. They have been converted to a per square foot basis for comparison but have not been normalized to reflect regional climate differences. Of the ten buildings analyzed, the total annual utility cost for all of them fell well below its base case alternative. The best performing building was 68% below its base case. The poorest performing building was 8% below its base case. The average across all 10 buildings was 51% less energy cost than the base case.

4. Human Response Analysis

Under a separate contract DOE sponsored an occupant evaluation research effort related to the demonstration projects. The objective of this evaluation was to determine user satsifaction especially in those areas affected by the building energy systems. The research methodology included: use of occupant and building user questionaires (weekly and monthly); site visits, observations, and interviews; detailed inquiry with building managers, owners, and the design team.

4.1. Levels of Satisfaction

Figure 5 illustrates the degree to which satisfaction varied on a month by month basis using a six point scale.The overall pattern suggest a high degree of satisfaction based on 14 buildings within the program [4]. Table 3 suggests that the number and frequency of building changes, modifications in occupancy patterns, occurring after the design phase has an impact on the occupant satisfaction. On the issue of perceived thermal comfort the response was high averaging 74% (see Figure 6). Thermal Comfort satisfaction was highest during the Spring Season while most of the complaints occur during the morning hours of winter months. In some cases "being too cool" in the morning, and "too warm" in the afternoon occured in many of the buildings. Many of the buildings experienced thermal comfort problems through malfunctioning ventilation systems. Daylighting strategies were employed in all of the projects and occupant response to the environmental qualities was consistently high. Only 5% of the responses indicated "too dim" or "too bright" conditions as problematic. Glare problem was related to perimeter light sources rather than overhead light sources. In those buildings, where space modifications were made during the construction air quality problems arose. In many buildings infiltration problems occured right after occupancy. However, in most cases these conditions were corrected, and the complaints disappeared. In a majority of the buildings acoustical problems were identified resulting in loss of privacy. These problems

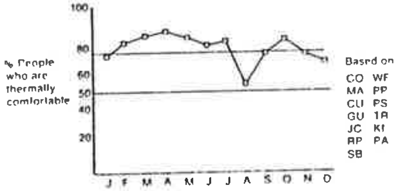

Fig. 6. Thermal comfort by month

were mostly due to: the non-absorptive surfaces of thermal mass; open office plans to enhance convective air movement and light distribution systems.

4.2. Impact of Occupancy and Use Modifications

A major cause for many of the occupancy problems was the changes made during or after the buildings were constructed. In almost all of the buildings actual occupancy patterns differed significantly from those predicted or specified. It is hypothesized that these changes contributed significantly to changes in actual energy use, as well as some of the discomfort conditions (see Table 3). Timing of occupancy changed. Because buildings were popular people used them many more hours than had been predicted, and additional uses for the buildings emerged. Spaces which were initially designed for one function, were modified to accomodated a different function. Changes in building operational patterns were also a problem. Each design team specified an operational pattern in their simulations. Such patterns included: summer/winter mode switching; Thermostat set points; and specific instructions to building users on what to do under specified conditions. In many cases procedures were modified, not followed, or not transferred to new personnel.

5. What Was Learned?

5.1. Daylighting

Six types of daylight strategies were utilized with the frequency of project occurance indicated in paranthesis: Windows to reduce artificial lighting needs (78%); Lightshelves (48%); Clerestories (39%) Roof monitors (35%); Sunspace and borrowed light (13%); and, skylights (13%) Daylighting contributed to significant energy and cost savings as well as environmental comfort for users. Base case lighting energy was reduced by 55% through the use of daylighting and tasklighting. Occupant satisfaction with daylighting strategies was quite high. Manual controls for artificial lighting are easily operated and controlled by occupant and provided the greatest potential for occupant participation in energy savings. Integration of daylighting and electric lighting, and its controls, are promising and critical strategies.

5.2. Thermal Mass Issues

The buildings and their thermal mass characteristics are classified in one of three groups: High mass buildings which use large amounts of thermal mass; Localized thermal mass (e.g. Trombe walls) where the location of the mass was designed to provide heating and cooling for a specified area; and, low mass designs based on specific occupancy pattern. The thermal mass analysis indicates that high mass does not appear to have been a contributing factor in the energy efficient functioning of these buildings. High mass does not necessarily solve thermal comfort problems and in some cases appears to have contributed to: acoustic problems; difficulty in regulating and timing heat delivery.; and, difficulty in integrating thermal mass system with mechanical systems. Moderate amounts of well distributed thermal mass appear sufficient to solve thermal problems. Localized mass can be an efficient strategy to provide delayed heat to specific building locations. Where daytime occupancy prevails early morning warm-up is more critical then delayed delivery.

5.3. Natural Ventilation

Natural passive ventilation was used as an integral part of the cooling strategy in several buildings. The evaluation did not analyze how well these systems worked. Assumptions about air currents, movement, and direction were sometimes inaccurate. Conflicts between shading devices and apertures impeded ventilation flows. Manually operated ventilation control strategies appear to work effectively when they are simple, close and familiar to the users.

5.4. Climate Dependency

The locations range from very cold regions such as Alaska and Upstate New York; to moderate areas such as Missouri; to Hot and humid areas like North Carolina and Texas (see Table 1). Solar buildings succeeded in a wide range of climates, from very cold to hot and humid. Energy performance was not dependent on climatic variables. There appears to be no pattern of heating energy performance by heating degree day. Btu/S.F. heating degree day is a good measure of the energy performance of solar buildings because it equalizes auxiliary energy without regard to size or building or climate. Data shows this performance parameter to be relatively independent of heating degree days. The range is between 2.6 and 4.0 Btu's/S.F./yr./HDD about half that of the base building values. There is essentially no variation of heating energy performance by solar insolation. The evaluation results show a fairly constant value near 3.5 Btu's/S.F./yr.HDD regardless of location (see Table 3).

5.5. System Integration

The most successful projects were those which integrated the passive heating, cooling, lighting techniques with conventional heating and lighting systems. Since both systems share the requirements for comfort the highest energy savings where realized where high level of integration, carefully designed control strategies and attention to detailing prevailed. In artificial lighting where dimming or shut off was not possible, during periods of adequate daylighting, energy savings potentials were lost. In some cases manual control were more energy conserving than automated devices.

6. Conclusions

On the basis of this effort it is clear that passive solar strategies are appropriate design strategies for commercial buildings; significant amounts of energy can be saved at very little, if any, extra cost; and, occupant satisfaction is above average. This research effort is also unique since it focuses on the "Whole Building" rather then a particular building aspect or subsystem.

7. References

(1) Kurkowski, T., The design of passive commercial buildings -- background and major lessons learned, Proceedings of US Department of Energy Passive & Hybrid Solar Energy Program Update Meeting, September 21-24, 1980, Washington, D.C., 3-4.

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(4) Kantrowitz, M., Occupancy analysis results: the DOE passive commercial experimental buildings program", 10th National Passive Solar Conference, Conference Proceedings, Raleigh, North Carolina, October 15-20, 1985, American Solar Energy Society, Inc., . 626-631.