~~DOE/ER~~
DOE/SF/11681--T1FINAL REPORT**PASSIVE-SOLAR-COOLING SYSTEM CONCEPTS
FOR SMALL OFFICE BUILDINGS**

- BEAM DAYLIGHTING
- MASS WITH NIGHT VENTILATION
- EVAPORATIVE COOLING
- INTEGRATED COOLING SYSTEMS

FEBRUARY, 1983

PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE-AC03-82SF11681

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Acknowledgements

W.I. Whiddon and G. Kimball Hart were the principal investigators for this work. However, the activities of the project involved a large number of firms and individuals. We would like to express our appreciation to each and all participants and especially to Ms. Janet Neville, Senior Programs Manager, Department of Energy, San Francisco Operations Office, and to Dr. Ronald Kammerud, Lawrence Berkeley Laboratories. In addition, special thanks goes to Ms. Rhonda Smith whose diligence and stamina made production of this report possible.

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EXECUTIVE SUMMARY

This report summarizes the efforts of a small group of building design professionals and energy analysis experts to develop passive solar cooling concepts including first cost estimates for small office buildings. Although estimated annual energy savings from passive cooling technologies range from modest (5-10% savings) to substantial (up to 40% savings), the first costs of these systems appears to be low (from 0 to 8% over comparable buildings). If these preliminary estimates are born out in real world applications, simple paybacks from 0 to 5 or 10 years could make passive cooling an attractive energy saving design alternative.

STUDY METHODOLOGY

Two design teams were brought together at each of two workshops held in the Fall of 1982. Each team included an architect, mechanical engineer, structural engineer, and energy analysis expert. The teams were briefed on a passive cooling concept which had already been simulated by either DOE2-1b or BLAST computer models. Each team was then asked to work independently to produce a schematic building design -- based on an agreed upon base case -- that incorporated the passive concept. Once concepts were drawn and materials specified, each was given to a team of independent cost estimators to develop a first cost estimate. In all, 9 concepts were developed for 3 passive cooling technologies and an integration of technologies:

- . Beam Daylighting -- 4 concepts
- . Mass with Night Ventilation -- 2 concepts
- . Evaporative Cooling -- 1 concept
- . Integration of Daylight & Mass with Night Ventilation -- 1 concept
- . Integration of Daylight & Evaporative Cooling -- 1 concept

All important drawings and a first cost estimate for each concept are contained in this report.

KEY FINDINGS

Bear in mind that findings presented in this report are limited to estimates of performance based on computer simulation and schematic design only and are also limited to a modest sized (10,000 sq.ft.) single story office building. It will be important to test other building types and sizes before these findings about passive solar cooling can be widely generalized.

Daylighting systems can be built in single story office buildings at no increase in first-cost over conventional design.

- . Mass with Night Ventilation and Evaporative Cooling are more or less cost effective depending on the utility rate structure in the area where they are to be applied. First costs of applying these technologies tend to be low but annual energy cost savings vary widely (depending on utility rates), thus creating a wide range of possible paybacks.
- . Electricity for cooling and lighting is the key energy issue in non-residential buildings. The importance of cooling in office buildings is likely to increase as strategies for reducing lighting become more common.
- . The thermodynamics of heat transfer at low temperature differences (low T) are not yet well understood and not well modeled. Wide acceptance of storage dependent cooling concepts will likely be delayed until the design professions gain greater confidence that building mass can be used as an effective heat "sink" in passive cooling systems.
- . Although investigation of individual passive cooling systems is instructive, design professionals require much more information about the interactions of passive cooling systems and the interaction of passive systems with conventional HVAC equipment.

At the conclusion of the workshops, both the energy research community at the national laboratories, and the professional building designers from the private sector expressed strong feelings that the opportunity to meet and exchange views about important research issues was extremely valuable and ought to be continued.

I. INTRODUCTION

In June, 1982, the Systems Analysis Working Group (including researchers from Lawrence Berkeley Laboratory and Los Alamos National Laboratory) completed an assessment of passive cooling technologies assessment sponsored by the Federal Government. The assessment used simulation tools (BLAST and DOE-2) to make preliminary estimates of the energy savings that could be achieved with individual passive cooling technologies. These analyses were, by definition, theoretical and not limited by any existing materials or design solutions. As a result of the assessment, research priorities for the passive cooling technologies were rank ordered according to their estimated energy saving potential:

- . Priority 1: Natural lighting and cooling load control
- . Priority 2: Evaporative cooling and ventilative cooling
- . Priority 3: Dehumidification

Because of the limited scope of the cooling assessment, no estimates of first cost were made for any of the technologies (and could not have been, based only on theoretical concepts).

In order to test the possibility of translating these theoretical concepts into schematic building designs suitable for drawing rough first cost estimates, two design workshops were held in November and December, 1982. At each workshop, practicing professionals -- including leading architects, mechanical engineers, structural and civil engineers, energy analysts, and cost estimators -- were asked to apply their knowledge and judgement to design problems based on the theoretical work carried out in the technology assessment, and develop a series of passive cooling system design concepts.

The workshops presented the design teams with unusual situations. Almost never does extensive thermal analysis precede design work. In addition, in order to fit the needs of comparability across a number of technologies to be studied, the process has to be much more highly constrained than would a normal design process. The fact that the design effort for each problem was compressed into only a matter of hours was also unusual.

On the otherhand, it was realized that in order to take greatest advantage of the experts collected for the workshops, it would also be necessary to allow as much freedom as possible in the process. As a result, it was decided to address two problems in each workshop -- the first highly constrained and the second much less so. In fact, problem definition itself became an important topic of the workshops. The results of the collective effort to hone a number of issues into meaningful problems is reported here.

This report presents the passive cooling system concepts resulting from the workshops. It summarizes the design problems, solutions and first-cost estimates relating to each technology considered, and documents the research needs identified by the participants in attempting to implement the various technologies in an actual building design.

Each design problem presented at the workshops was based on the reference (base case) small office building analyzed as part of LBL's Cooling Assessment. Chapter II summarizes the thermal performance, physical specifications and estimated first-costs of the base case design developed for this work. Chapters III - VI describe the passive cooling system concepts developed for each technology:

- . Chapter III - Beam Daylighting
- . Chapter IV - Mass with Night Ventilation
- . Chapter V - Evaporative Cooling
- . Chapter VI - Integrated Passive Cooling Systems

Within each of these chapters, the following information is presented in sequence:

- . A Description of the Technology - energy and cost savings
- . The Design Problem Statement(s) - physical and thermal constraints on design solutions
- . Resulting Design Concepts -
 - The teams' understanding of the problem
 - A brief discussion of the process or approach used to address the problem, including major themes addressed.
 - The solution proposed.
 - Ideas rejected and issues left unresolved.
- . First-cost comparison between design concepts and the base case building.

The final Chapters, VII and VIII present the preliminary implications for economics of passive cooling technologies (based on review of the design concepts) and recommendations of workshop participants for future research in passive cooling for commercial buildings.

Appendices provide backup information on each chapter as indicated.

Readers should realize that this exercise was organized as part of an overall research and development activity and was limited to a single building type, a single building size, and a single climate. Although the work presented here suggests valuable new lines of inquiry, it should be applied to other buildings with healthy amounts of professional judgement.

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II. BASE CASE (REFERENCE) SMALL OFFICE BUILDING

The goal in defining a base case building is to provide a benchmark for comparison of improvements in both energy performance (Btus/sf-yr) and energy costs (\$/sq.ft.) that result from the application of a passive cooling technology. Improvements in energy performance are based on analysis of the whole building, with the technology under study included. Improvements in energy costs are measured by comparing the typical annual energy bill for the base case building to the bill result for the building as modified by the technology.

The base case building is configured to represent currently "typical" new construction. It is presumed to have been designed by a competent and conscientious designer, but one who has no special incentive or mandate to achieve significant energy/cost savings. The building is also configured to be flexible in its design and specifications, to make it suitable for various clients and generally acceptable to a speculative builder. It is intended that the building be neutral to both climate and regional building characteristics -- that is, not violate regional design practice significantly, although it clearly cannot be "most typical" of construction or all regions simultaneously.

THERMAL SPECIFICATIONS

The base case building was originally specified to meet the requirements of the simulation programs used in the analysis (BLAST and DOE-2). The complete set of specifications is in Appendix A-1. These specifications were sufficient to meet the needs of the simulation program but not complete enough to specify a real building (e.g., massless exterior walls, no doors, no shading, return air ducts in the ceiling plenum, and no differentiation of interior spaces).

Based on these original thermal specifications, base case energy performance and typical utility bills were computed for eleven climate regions in the U.S. Results of this analysis are shown in Appendix A-2. The design workshops were largely limited to consideration of only one climate (Northeast -- including New York and Washington, D.C.). This assumption was changed to Denver in the final workshop problem -- testing integrated solutions -- because Denver was seen as equally beneficial from the point of view of all technologies.

Portions of the original base case specifications were, and continue to be, questioned in terms of conventional design practice:

- . Relatively high connected wattage (including specification of a high number of lighting fixtures)
- . Return ducts in the plenum

it was a general feeling of the workshops that the building as specified was of slightly higher cost (and perhaps quality) than a true speculative office building. If one takes the extreme view that the lowest priced speculative office building should be the base against which all cost increases are calculated, this base case building should be stripped back somewhat further.

BASE CASE ENERGY USE

BLAST and DOE-2 simulations for the base case thermal specifications in the Northeast/Washington, D.C. climate resulted in the following annual energy requirements, displayed in Figure 6:

- . Fuel: 0.04 MCF/sf-year
- . Electrical consumption total:
 - lights and equipment: 9.8 kWh/sf-year
 - cooling: 1.9 kWh/sf-year
 - fans: .975 kWh/sf-year
- . Demand: (summation of monthly peaks): 0.054 kW/sf-year.

ONE PHYSICAL SOLUTION

In order to begin the process of trying to specify real physical solutions for the theoretical passive technologies under study, it was necessary to develop a base case building design to a level of detail that would support a cost estimate. As part of the preparation for the workshop, one possible physical solution was prepared to meet the thermal specifications. Figures 1-5 illustrate a hypothetical site plan, elevation, floor plan, section, and reflected ceiling plan.

While defining this base case building, it was necessary to address real architectural choices for both space allocation and system selection. The result is obviously only one of a great number of possible solutions, but it does provide sufficient schematic detail to arrive at a first-order cost estimate.

BASE BUILDING COST ESTIMATE

Detailed cost estimates for the base case building were developed only for the greater Washington, D.C. area -- in keeping with the limited focus of the workshop. Based on a cost estimate by Scharf-Godfrey Associates, the base case building will cost \$50.89/sq.ft., not including site work. The cost estimators feel that this cost is somewhat high but within 5-10% of average costs for a speculative office building in the Washington, D.C. area. A summary of the cost estimate, by system category, is shown in Figure 7. A complete breakdown with detailed back-up is provided in Appendix A-3.

FIGURE 1

- Notes:
- ~24,000 sq.ft. asphalt parking
 - Quartz iodine lighting (3 poles, 3,600 W)
 - ~3,250 sq.ft. concrete walkway
 - 20' setback, street utilities

FIGURE 2

BASE CASE
SMALL OFFICE BUILDING
FLOOR PLAN

FIGURE 3
BASE CASE

SMALL OFFICE BUILDING

ELEVATION & SECTION

NOTES: ~315 SF. GLAZING ON EACH FACADE

FIGURE 4

BASE CASE

SMALL OFFICE BUILDING

SECTION THROUGH EXTERIOR WALL

FIGURE 5

BASE CASE
SMALL OFFICE BUILDING
REFLECTED CEILING PLAN

- Notes:
- 317 1' x 4', 2 lamp troffers
 - Shaded troffers - emergency lighting

FIGURE 6

BASE CASE

SMALL OFFICE BUILDING

ANNUAL ENERGY USE

ANNUAL ENERGY USE

	NORTHEAST (NY)
LIGHTS & EQUIPMENT (MBtu)	336
FANS (MBtu)	33
DX UNIT (MBtu)	65
TOTAL ELECTRIC CONSUMPTION (MBtu)	443
BOILER FUEL (MBtu)	394
TOTAL ENERGY USAGE (MBtu)	837
Peak Demand (kW)	53.6

FIGURE 7

BASE CASE
SMALL OFFICE BUILDING

COST ESTIMATE

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BASE CASE

PROJECT RECAPITULATION (NOT INCLUDING SITE WORK)

SYSTEM DESCRIPTION	TOTAL COST	\$/SF	%
GENERAL REQUIREMENTS @ 10%	41,638	4.16	9.09
FOUNDATIONS	7,200	0.72	1.57
SLAB ON GRADE	13,100	1.31	2.86
SUPERSTRUCTURE	50,275	5.03	10.98
ROOFING	44,113	4.41	9.63
EXTERIOR WALLS	27,807	2.78	6.07
EXTERIOR GLAZED OPENING	36,648	3.66	8.00
INTERIOR PARTITIONS	23,219	2.32	5.07
DOORS	13,655	1.37	2.98
CEILING FINISHES	11,288	1.13	2.46
FLOOR FINISHES	16,252	1.63	3.55
SPECIALTIES	1,300	0.13	0.28
EQUIPMENT	1,500	0.15	0.33
PLUMBING	16,753	1.68	3.66
HEAT, VENTILATION & AIR CONDITIONING	82,280	8.23	17.96
ELECTRICAL	70,990	7.10	15.50
TOTAL COST	458,018	45.81	100.00
GENERAL CONTRACTOR'S OVERHEAD & PROFIT @ 10%	45,802	4.58	
SUBTOTAL	503,820	50.39	
BOND @ 1%	5,038	0.50	
TOTAL ESTIMATED CONSTRUCTION COST - OPEN SHOP	508,858	50.89	
FACTOR TO REPRESENT UNION SHOP CONDITIONS - 8%	40,709	4.07	
TOTAL ESTIMATED CONSTRUCTION COST - UNION SHOP	549,567	54.96	

CHAPTER III.

BEAM DAYLIGHTING

The first design workshop was devoted entirely to investigation of beam daylighting for a small office building. The two design problems presented were to build on energy analyses already performed by the national laboratories. Summaries of the daylighting investigation at Lawrence Berkeley Laboratory are presented in Appendices 5 and 6.

For a number of reasons, work to date by the researchers investigating passive technologies at the laboratories, has focused on the use of direct beam daylight for illumination. At least in single story buildings, this application is possible over the whole roof and is independent of building orientation. It is also desirable because capturing an intense beam of light can result in maximum illumination with minimum amounts of glazing and minimum negative effects due to thermal conduction. However, the difficulty of dealing with beam daylight architecturally can be substantial -- "like trying to drink from a firehose."

Acknowledging the bias toward beam daylight for illumination, the analyses and modeling performed to date imply a number of physical constraints on the design solutions to be considered by the design teams:

- . South facing roof aperture
- . Glazing tilted up 60° from horizontal (representing the best trade-off between ideal angle for overcast conditions -- horizontal -- and a good angle for clear conditions -- vertical)
- . Total aperture (tilted) to be 2-3% of floor area.

These basic requirements were further refined in defining the two problems to be addressed at the Beam Daylighting workshop.

BEAM DAYLIGHTING - PROBLEM STATEMENT #1:

BEAM DAYLIGHTING THROUGH MODIFICATION OF ROOF SYSTEMS ONLY

In this problem, the design teams were to focus only on the roof "system sandwich" -- from roof to ceiling as shown in Figure 8. While ignoring the effects of perimeter lighting, the design team was to get 50 foot candles of uniform light at the height of work surfaces throughout the building. As stated above, roof glazing was limited to a 60° tilt and a total of 2-3% of the gross floor area (250 square feet).

The suspended ceiling plenum was to be retained and the roof system was to be "punctured" as required to achieve proper lighting. It was assumed that 1 foot candle of sunlight could replace 1 foot candle of artificial light. (In fact, simulations

FIGURE 8
SMALL OFFICE BUILDING
BEAM DAYLIGHTING

SYSTEMS "SANDWICH"

STRUCTURE	BASE CASE COSTS (\$/SF)
• beams/joists/precast deck	\$ 7.92
• vermiculite topping	
ROOF	
• built-up/insulation/flash	5.30
INTERIOR WALL	
• decorative face	3.01
CEILING	
• acoustical/drywall	3.30
MECHANICAL	
• roof drains/rooftop unit/exhaust fans	3.50
• ductwork, insulation/evap coils	0.04
• temperature control	.76
• miscellaneous mechanical	.34
ELECTRICAL	
• fixtures/branch conduit and wiring	0.30
Total "Sandwich"	\$29.00
Total Ref. Building	\$3.00
	<u>\$51.00</u>

BEAM DAYLIGHT

indicate that replacing 1 foot candle of artificial light with 1 foot candle of sunlight actually reduces the thermal load on the occupied space and thus reduces cooling loads.)

Modifications were to be made for the lowest net increase in total building cost over the base case total.

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #1

Understanding the Problem

Team one made the following assumptions based on the problem statement:

- . The volume could be changed, but the mechanical and structural systems must remain in the ceiling.
- . The distribution of lighting elements can change.
- . The amount of glazing (250 sq.ft.) cannot change.
- . Uniform light must be delivered to the work surface at 50 foot candles.
- . Glazing tilt must be 60° up from horizontal.

Process and Key Themes

First the constraints of the problem were defined and agreed to by the team. Next, utility costs were reviewed for possible cost savings. Assuming a \$.50/sq.ft. saving due to the use of daylighting, the team estimated saving approximately \$5,000 per year in utility costs. Since a 5-year payback was desired, there was potentially \$25,000 to spend on the daylighting system. Potential cost savings by changing the structural and mechanical systems were explored and initially rejected. The size of the mechanical system had to be left largely intact because of peak load capacity.

The first approach was to try 100 holes of 1.6' x 1.6' on a 10' by 10' grid. The concept that some areas did not need daylighting was mentioned at this point, but a per zone requirement of 2.5% of floor area in roof glazing eliminated the possibility of modifying the potential daylighting system on the basis of functional space relationships.

The concept of using exposed ducts to eliminate the hung ceiling was discussed, but rejected because of cost. (Exposed ducts are usually very expensive because of finish and fit requirements.) Several other alternative proposals for integrating structural and mechanical systems were discussed and rejected because of cost implications.

At this point the team summarized these various options into three categories: the "grid," "the strip," and the "one big skylight" approach. The requirement for uniform distribution of light on the work surface eliminated the "one big skylight" option from further consideration.

- . Alternative #1 - "The Grid": A modular 1.5' x 1.5' coffered skylight. The team estimated they could build a skylight and coffer at a 33% increase over the cost of the drop ceiling replaced or about \$125 per fixture. At this price, all 100 would be within the budget of \$25,000. The team thinks it would be possible to save money in ductwork with this system compared to the base case. Reducing the number of light fixtures was discussed as another cost savings approach appropriate for both the grid and strip designs.
- . Alternative #2 - "The Strip": Two approaches were discussed: A) a repetitive "v" form of sloped drop-in tiles alternating ductwork with strips of glazed daylighting; and B) a similar system of flat strips coffered evenly in both directions. The first strip alternative was judged not only to be cheaper, but to have better light distribution. Costing for the first strip option was based on a 20% increase in ceiling tile area, extra labor and special hangers. Since fixtures could be suspended in the openings of the "v" and directed upwards, inexpensive fixtures were a possible cost saving.

Solution:

Because of flexibility in integrating with lights, partitions, and ducts, the "grid" seems preferable to the "strip" -- assuming costs turned out equal. Therefore, the team reviewed the costs of both the "grid" and "strip" alternatives:

- . The estimated "grid" cost was \$6,250 in ceiling components and \$12,500 in skylights, less \$750 because of elimination of return air light fixtures. At a total of \$18,000, this was within budget. The main advantages of the system were:
 - cost effectiveness compared to the base case
 - flexibility.

The disadvantages were a large number of boxes extruding up from the surface of the roof and a lot more surface area exposed. Insulation on the opaque areas of the daylighting modules was not initially included in the teams' cost estimate, but was judged to be expensive.

. The estimated "strip" cost was less than the "grid" system. At \$900 for the ceiling components and \$15,000 for low cost apertures, minus a savings of \$11,000 on light fixtures, a total added cost of \$13,000 was estimated. This was \$5,000 better than the "grid" system. Despite the apparent cost advantages of the "strip" system, it would be difficult to integrate the required pattern with interior partitions. This was considered a significant disadvantage to this system.

The team returned to the "grid" at this point. Design questions such as "how to finish the box" and "how to put a lid on the box" were discussed in detail. Clear vertical glazing was compared to tilted diffusing glazing. Various internal configurations for box design were considered. Decisions were based on patterns of light diffusion, cost of materials and construction, drainage considerations and quality of light expected to be delivered by each alternative. The final solution (see Figure 10) proposed 1' x 2.5' of clear glazing tilted and set in a wooden frame. The frame extended far enough above the roof to insure adequate flashing to avoid leakage. The lightwell coffer beneath is square through the roof and then slopes to a 5'x5' opening in the hung ceiling. This "daylight fixture" is made entirely of accoustical tile held in place by metal channels.

Unresolved Issues

- . The shape of the lightwell received considerable dicussion. This concept assumes that beam daylight will bounce off the well cavity in such a way that light will be uniformly distributed. Further study of lightwell configuration is needed to confirm this major assumption.
- . The team's concept of forming the lightwell with tilted acoustic tile was thought to be innovative. There was some concern, however, regarding maintenance and durability of such an assembly.

FIGURE 9

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #1

FIGURE 10

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #1

FIGURE 11

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #1

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #2

Understanding the Problem

After reviewing the base case and problem constraints, the design team agreed that the basic issue was how to penetrate the roof to get distributed illumination. Two key questions to be addressed were the frequency of punctures and the geometry of each puncture. The drain plan and structural plan were critical to the location of the punctures.

The high number of required lighting fixtures was likely to be a problem. The HVAC system, including VAV boxes, could probably be reconfigured so as not to present a limitation on the solution.

Process and Key Themes

The team started by investigating a number of different modular schemes as a way of determining the number and size of punctures required. Three systems were reviewed: 10' square modules at 100/10,000 sq.ft. suggested a large puncture; 7' square modules at 200/building suggested a considerably smaller puncture; 5' square modules at 400/building also suggested a small puncture.

Smaller modules would be more flexible for the speculative office building situation. Smaller modules also suggested the possibility for simply alternating daylight "fixtures" (or punctures) with standard fluorescent fixtures in a "checkerboard" pattern. The smaller module was accepted early as the best way to proceed.

The team then spent a considerable amount of time investigating the possible geometry of a possible "daylight fixture." Presuming that it would probably not be a problem to cut a hole in the roof, the size of the hole to be cut and the size of the hole in the ceiling became determining factors.

A square fixture (in cross section) was considered briefly and rejected largely because of the likely inefficiency of a deep and square coffer. It then became an interesting problem to see whether or not a triangular fixture (in cross section) could be designed that was broad enough at the base to provide a good opening in the ceiling, while high enough at the peak to provide enough room for both glazing and flashing without creating a drainage problem. Sketches suggested that a solution was possible so the triangular cross section was selected. It was presumed to be square (not sloped) on the ends to provide enough area for the required glazing.

With an approximate fixture in mind, the team turned again to the approximate number of fixtures required. With a 5' square module (25 sq.ft.) a total of 400 modules resulted for the 10,000 sq.ft. building. With a checkerboard design, available modules was reduced to 200. Omitting 24 modules (about 600 sq.ft.) for the mechanical room left 176. At this point, the team took the position that illumination from wall glass would be sufficient to illuminate perimeter offices up to 10' from the exterior wall. By eliminating skylight fixtures in the first 10' from all exterior walls, the team eliminated another 72 modules and concluded that 104 daylight fixtures would be sufficient for the building as shown in Figure 12. It could be argued that recognition of perimeter lighting was a violation of the strict definition of the problem. It is, nevertheless, reasonable.

The Solution

As shown in Figures 13 and 14, the team settled on a triangular skylight "fixture" with a 3' x 4' opening at the base. The frame of the fixture uses readily available metal rigging. It is designed so it could be built as a unit in the shop and simply bolted or shot into place. The strength of the frame also provides solid support for drywall used on the interior of the coffer and a rigid joint for butting ceiling tile to the fixture. The steel framing also provides enough space for insulation.

The dimensions of the triangle allow enough of the fixture to be exposed above the roof so there is room for both 6-8" of glazing and a minimum of 10" of gutter to prevent leakage. The "fixtures" are located, as shown in Figure 12, in a checkerboard pattern, alternating with fluorescent fixtures. Because of this arrangement, it is necessary to run duct work on a diagonal (in relation to exterior walls) over the light fixtures.

The team rejected the idea of continuous strips of glazing because of the increased difficulty of puncturing the roof and related problems of working out a drainage pattern given the current structure of the roof. As explained previously, the square coffer hole was rejected because of a presumption that it would be less efficient than a sloping coffer.

Unresolved Issues

The design team was concerned about the quality of light and the potential for uncomfortable light and dark spots with the checkerboard pattern. It might be possible to investigate this issue by building physical models.

FIGURE 12

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #2

FIGURE 13

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #2

DAYLIGHT MODULE CONCEPT
SECTION

FIGURE 14

BEAM DAYLIGHTING SYSTEMS (ROOF ONLY)

CONCEPT #2

FIGURE 15

COST COMPARISON: BEAM DAYLIGHTING BY ROOF MODIFICATIONS ONLY

CONCEPTS #1 & #2

OPEN SHOP NOT INCLUDING SITE WORK)

SYSTEM DESCRIPTION	BASE CASE	CONCEPT #1		CONCEPT #2	
	SYSTEM COSTS \$/SF	COST DIFF. \$/SF	REASON	COST DIFF. \$/SF	REASON
GENERAL REQUIREMENTS @ 10%	4.16	+0.24	• increased cost -1 of systems costs below/before OH&P	+0.28	• same
FOUNDATIONS	0.72	--		--	
SLAB ON GRADE	1.31	--		--	
SUPERSTRUCTURE	5.03	+0.08	• angles around 100 daylight roof units	+0.10	• angles around 104 daylight roof units
ROOFING	4.41	+0.50	• increased labor around units	+0.27	• increased labor around units but larger opening/less roofing
EXTERIOR WALLS	2.78	+0.18	• walls around roof units	+0.65	• more wall per unit, used steel framing to bottom of lightwell
EXTERIOR GLAZED OPENING	3.66	+0.62	• 250sf skylight glazing	+0.63	• 250sf skylight glazing
INTERIOR PARTITIONS	2.32	--			
DOORS	1.37	--			
CEILING FINISHES	1.13	+0.97	• more tiles & labor for lightwells up to roof decking	+1.31	• drywall & labor for lightwells
FLOOR FINISHES	1.63	--		--	
SPECIALTIES	0.13	--		--	
EQUIPMENT	0.15	--			
PLUMBING	1.68	--		--	
HEAT, VENTILATION & AIR CONDITIONING	8.23	--		+0.31	• added complexity of HVAC ducting on diagonal
ELECTRICAL	7.10	+0.04	• photo cells for light switching	-0.56	• added photo cells for switching • reduced # of fixtures by using
TOTAL COST	45.81	+2.63		+2.99	2'x4' 4-lamp troffers
GENERAL CONTRACTOR'S OVERHEAD & PROFIT @ 10%	4.58	+0.26	• increased OH&P 10% of above	+0.30	• same
SUBTOTAL	50.39	+2.89		3.29	
BOND @ 1%	0.50	+ .04	• increased bond 1 % of above	+ .03	• same
TOTAL ESTIMATED CONSTRUCTION COST - OPEN SHOP	50.89	+2.93		+3.32	
		53.82		54.21	

Modeling might also be useful in addressing the issue of the design of the coffer (square vs. angular) and the possible reduction of efficiency caused by having light enter at the peak of the triangle.

The team did not seriously address the issue of forcing in additional light fixtures simply to meet the required number. It was believed that 4 lamp troffers in the 96 modules of the checkerboard that did not have skylight fixtures would be adequate -- even though it was considerably below the original requirement of the problem.

COMPARISON OF CONCEPTS FOR BEAM DAYLIGHTING THROUGH MODIFICATION OF ROOF BUILDING

- . Without collaboration, both teams chose solutions that "punctured" the roof with a "daylight fixture" much like an artificial lighting installed on a grid pattern.
- . Both teams also investigated continuous strips of glazing but rejected them because of perceived difficulties in integrating the strips into the proposed building:
 - difficult to match with interior partition layout
 - difficult to integrate with roof drainage system
- . Both teams agreed that approximately 100 fixtures would be adequate to daylight the entire building uniformly.
- . Concept #1 is a lower cost option principally because the coffers (boxed lightwell between glazing and suspended ceiling) are made very cheaply out of accoustical ceiling tile and aluminum channels.
- . Concept #2 is more costly because it is higher quality construction. The "daylight fixture" has a rigid steel frame and is covered with drywall. This design would facilitate shop fabrication and could make it applicable as a retrofit strategy.
- . Concept #2 was also judged to be more costly because of the diagonal fixture layout. This layout is not common practice and may require additional fittings and/or labor.
- . Both systems included the cost of photo cell switching used to reduce artificial light when daylight is adequate. This ensures the cost savings in electrical energy use estimated by the simulation programs.

Beam Daylighting - Problem Statement #2:

Beam Daylighting Through Limited Building Redesign

In the second, less constrained problem, the design teams had to accomplish the same levels of uniform illumination using beam daylight but they were free to investigate trade-offs in the roof and wall systems or to do a complete redesign from the foundation up.

In order to retain some comparability between teams and with the original thermal analysis supporting the work, a number of constraints remained:

- . Maintain the same building program
 - 10,000 sq.ft. in a single story
 - same aspect ratio (100' x 100')
 - 55 occupants doing office work
- . Maintain the same U-value as the base case (but trade-offs between glass area and insulation could be made)
- . Balance relationships between glass area and shading coefficients to equal the base case.

As before, the teams were to accomplish this at the lowest net increase (or maximum decrease, if possible) in total building costs.

Resulting physical solutions to the problems by each team are presented, together with modified cost estimates, in the next two sections.

BEAM DAYLIGHTING SYSTEMS (BASECASE BUILDING REDESIGN)

CONCEPT #1

Understanding the Problem

The team made the following assumptions based on the problem statement for beam daylighting through building redesign:

- . 55 occupants
- . 10,000 square feet
- . Wall glass may be substituted for roof glazing if desired
- . The U value must be balanced
- . Interior materials and structure can change
- . Toplighting the core is possible
- . View amenity must be greater than or equal to base building.

The purpose of this problem was taken to be: How to design the lowest cost building that meets these criteria.

Process and Key Themes

After some general discussion on the tradeoffs between clear and low transmissive glazing, the team decided that the first priority would be to reorganize the layout of the space to take advantage of a perimeter sidelighting zone. Another alternative was to move the mechanical room to the perimeter to act as a thermal buffer. This would also facilitate the design layout of the mechanical system.

The size of daylight apertures necessary to deliver the desired quantity and quality of light on the work surface was discussed in general. Because of cost considerations, the team decided to look for the minimum possible opening in the roof.

Two alternative structural schemes (20'/25'/15'/25'/20' and 15'/15'/20'/15'/15') were discussed. Both allowed a central unlit mechanical core, a daylit perimeter, and an intermediate area that could be daylit both by borrowed light from the perimeter and by roof daylight of some type.

Solution

The solution arrived at focuses on three daylighting strategies:

- . Do not daylight the mechanical core
- . Daylight perimeter offices with vertical wall glazing (diffuse daylight)
- . Daylight "intermediate" spaces (between perimeter and core) with "borrowed light" from the perimeter and a two beam daylight clerestories.

The team started with a redesign of the building site plan and entry (Figure 16). The entrance was moved to the west side of the building to serve as a "buffer" zone. Trees were added to the site to reduce unwanted solar gains during summer months (using shade trees). Interior space planning was redone (Figure 17) so that private offices were located next to perimeter glass and all interior office space was converted to an open plan -- to enhance daylight distribution. All bathrooms, kitchen facilities, and mechanical equipment were condensed into a small central core.

All building elevations (Figure 18) were redrawn to take advantage of less costly pre-manufactured wood windows. The south elevation was changed (Figure 19) so that daylight aperture (above) could be separated from view glazing (below). Light through the daylight aperture was controlled by using separate blinds on both top and bottom window assemblies.

FIGURE 16

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)
CONCEPT #1

SITE PLAN

FIGURE 17

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #1

FIGURE 18

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #1

FIGURE 19

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #2

FIGURE 20

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #1

FIGURE 21

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #1

FIGURE 22

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #1

Two clerestory designs were developed (Figures 20 and 21). One used ceiling baffles to diffuse incoming light (A). The other used an adjustable blind just behind the clerestory glass to control and diffuse beam daylight. Both concepts located fluorescent lamps to shine upward onto the sloped roof of the clerestory to diffuse artificial light when it was required. Concept A was eventually chosen, in part because it required less user interaction (with the blind) in order for the system to work properly.

Once the roof daylight problem was solved, the team redid the location of fluorescent fixtures to accommodate it (Figure 22). In general, the team objected to the high number of fixtures required in the base case but, under duress, "shoe-horned" in the full number of required fixtures in order to insure comparability with the other concepts developed.

The structural plan was revised to accommodate the clerestories as shown in Figure 23. The mechanical system (not shown) consisted of a central dead zone, supply from the mechanical room on the west to the east, distribution both north and south through the open plan office, and return along the perimeter of the building.

Unresolved Issues:

- . Selection of perimeter (diffuse) daylighting strategy lead to costly control problem, two sets of blinds per window.
- . Concern was expressed about glare problems in interior (beam daylight area). Baffle arrangement was viewed as critical, requiring physical model studies.
- . In general, the team was uncertain about balancing view and illumination glazing on the south wall. Mirror glass was offered as an additional solution worth investigating.

BEAM DAYLIGHTING SYSTEMS (BASE CASE BUILDING REDESIGN)

CONCEPT #2

Understanding the Problem

The overall goal of the problem, according to Team #2's view, is to reduce lighting wattage and cooling tonnage using daylight. This is to be accomplished in a building with roughly the same thermal skin as the base case at the lowest total building cost possible. The building proportions (especially aspect ratio) cannot be changed. From this team's point of view, this is basically a roof-vs-wall trade-off or integration problem. It suggests a top-down approach.

Process and Key Themes

The team started with a review of the building structural system and floor plan. It was agreed that if a core space was run the length of the building, it would be much easier to organize the HVAC system -- with trunk lines in the central core and feeder lines running parallel to a proposed daylighting system. Going to a full ceiling daylight scheme suggested to the team that they might want more flexibility in HVAC system layout than was required to simply punch holes -- as in the previous problem. Figure 24 illustrates a modest revision of the base case floor plan to accomplish this central core concept.

The team then addressed the issue of glass orientation. For this problem, the team viewed the building in three zones (note that these are not HVAC zones).

- . South Zone: The building to a depth of 15' from the south wall. For this zone there is good resource of south light which, with design help, would likely be sufficient to illuminate the whole zone.
- . North Zone: The building to a depth of 10' from the north wall. In this zone there is a good diffuse light source (north light) which could provide a high percentage of natural light with little more than the installation of clear glass.
- . Central Zone: The remainder of the building from the east to the west walls, including the central core. At the east and west facades it is very difficult to control beam daylight -- venetian blinds are the common solution to the problem, but require a great deal of user interaction. The team's decision was to leave reflective glass in place on both walls and address this zone as the key area for daylighting -- with the possible exception of the mechanical room.

At this point, the team returned to a review of structural options. Pre-cast concrete tees were considered briefly until a preliminary estimate of cost was made by the cost estimator. Although the tees would complement a linear daylighting scheme, there were concerns raised about movement in the tees due to temperature variations.

Having rejected tees, the team began an extended investigation of various folded plate roof options -- which might also be referred to as "sawtooth." The folded plate offered the option of using the roof itself as support with savings in structural bar joists. Preliminary investigations of an idea to use manufactured wood trusses looked promising and was continued. A wood truss, as shown in Figure 25, was eventually chosen (see solution).

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

[illegible]

FIGURE 24

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #2

While the team awaited a cost estimate on the wooded truss system, alternatives for its application were investigated. Should the proposed new roof system be more expensive than the base case, it would be best to limit its application to the central zone of the building, excluding the central core -- as shown in Figure 26. In this case, it would be necessary to develop a section for the south wall that would enhance use of daylight in the space. The recommendation, shown in Figure 27, was an independently suspended light shelf made from plywood hung in front of a combination of clear and reflective glass held in a wooden or metal frame and separated with a neoprene gasket -- possible as long as the distance between mullions did not exceed about 3'.

If, on the other hand, the wooden folded plate roof proved to be less costly than the base case building, it would be advantageous to use it over as much of the roof as possible, as shown in Figure 28. In this scheme, the central core was not daylit.

Finally, the folded plate roof suggested the possibility of eliminating the hung ceiling -- as long as duct work could be exposed. Elimination of the closed plenum space suggested that the roof could be dropped up to 2' without seriously affecting the office space below. If the core roof was not dropped, it creates an opportunity for carrying the trunk lines and VAV boxes of the HVAC system in the core with feeder ducts running through the walls around the core and directly in the space under each sawtooth.

Solution

The solution chosen applied the wooden truss (Figure 25) in the maximum application (Figure 28). Preliminary cost analysis suggested that the folded plate wooden roof could be very cost competitive. The trusses would be manufactured out of 2" x 6" material with internal structure as required. They would be plywood top and bottom and be filled with fiberglass batt insulation with a plastic vapor barrier. Trusses would be bolted to an angle iron at the base which, in turn, would rest on structural beams. The trusses would be fastened at the top with mullions leaving space for glazing. Framing and neoprene gaskets would be used to hold glazing.

The HVAC feeder ducts would run parallel to the sawtooth and would either be square ducts enclosing the beams at the foot of each folded plate, or would be continuous round ducts suspended in the space created by each fold. Trunk lines and VAV boxes would be in the central core as discussed above. Lighting would be provided by 1' x 4' 2-lamp troughers hung in long rows beneath the duct work. They would be wired in series to reduce the cost of wiring, ballasts and switches.

The interior of the folded plate would be sprayed with light colored acoustical material to enhance light distribution and to provide noise control.

FIGURE 25

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #2

FIGURE 26
BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)
CONCEPT #2

FIGURE 27

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPT #2

FIGURE 28

BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)
CONCEPT #2

ROOF STRUCTURAL
PLAN

EAST/WEST ELEV.

OPTION "B": Full plate & brace

The maximum use of the folded plate would eliminate the need for special glass treatments on the north and south glass, although clear glass on the north would cost less than reflective glass and would increase view in that direction.

It was decided to drop the roof in all areas, using the folded plate, leaving a higher ceiling in the central core as discussed above. Besides fitting well with the HVAC distribution strategy, the lower ceiling height would mean 15-20% savings on the interior and exterior facade and modest reductions in steel costs because of shorter columns. Partitions would end at 9' with the space above open into the sawtooth.

Unresolved Issues

Leakage is a major concern in any folded plate roof. Flashing and drainage details would need serious attention in final drawings but were not completed for the exercise. Pre-cast gargoyles at the outside end of each sawtooth trough and properly located piles of rock as a landscaping feature were briefly discussed as solutions to the drainage problem.

A closer specification of the HVAC system would also be required to determine which ducting option would be the least costly and would result in the least potential penalty from sub-contractors for being out of the ordinary.

COMPARISON OF CONCEPTS FOR BEAM DAYLIGHTING THROUGH BUILDING REDESIGN

The concepts proposed were very different in approach, but were quite close in terms of first-costs.

- . Both concepts proposed natural lighting solutions less costly than the base case (while using the same number of installed fluorescent lamps as the base case).
- . However, the approaches are distinctly different:
 - Concept #1 has only 2 large roof apertures and uses baffles in the ceiling to distribute light in the space.
 - Concept #2 uses smaller apertures distributed across the roof to get distributed light.
- . Note that by more extensive redesign, both teams overcame their objection to strip glazing in the "roof only" design problem (Statement #1).

FIGURE 29

COST COMPARISON: BEAM DAYLIGHTING SYSTEMS (BUILDING REDESIGN)

CONCEPTS #1 & #2

(OPEN SHOP NOT INCLUDING SITE WORK)

SYSTEM DESCRIPTION	BASE CASE	CONCEPT #1		CONCEPT #2	
	SYSTEM COSTS \$/SF	COST DIFF. \$/SF	REASON	COST DIFF. \$/SF	REASON
GENERAL REQUIREMENTS @ 10%	4.16	-0.22	•decreased cost-10% of systems costs below/before OH&P	-0.08	
FOUNDATIONS	0.72	+0.90	•smaller bays, more foundation, more but lighter columns, beams, joists--net decrease of \$8355	--	
SLAB ON GRADE	1.31	--		--	
SUPERSTRUCTURE	5.03	-1.73		-0.25	•replaced deck and joists with manufactured wood trusses (folded plate)
ROOFING	4.41	+0.16	•increased labor around roof opening	-0.90	
EXTERIOR WALLS	2.78	-0.45	•selected brick veneer/metal drywall system	-0.44	•reduced wall heights
EXTERIOR GLAZED OPENING	3.66	-0.80	•selected wood windows (stock size), clear glass	+0.72	•250sf roof aperture glazing, gasket, flashing
INTERIOR PARTITIONS	2.32	+0.20	•added acoustic panel	--	
DOORS	1.37	--		--	
CEILING FINISHES	1.13	+0.02	•increased labor on sloped ceiling	+0.07	•sprayed acoustic
FLOOR FINISHES	1.63	--		--	
SPECIALTIES	0.13	+0.25	•separate shade for daylight aperture on wall	--	
EQUIPMENT	0.15	--		--	
PLUMBING	1.68	--		--	
HEAT, VENTILATION & AIR CONDITIONING	8.23	--		+0.22	•more complex duct layout to track roof plate ridges
ELECTRICAL	7.10	-0.58	•2'x4', 4-lamp fixtures, industrial lamp	-0.25	•cheaper ballast reduced conduit and wire
TOTAL COST	45.81	-2.25		-0.90	
GENERAL CONTRACTOR'S OVERHEAD & PROFIT @ 10%	4.58	- .23	•decreased OH&P @ 10% of above	- .09	•same
SUBTOTAL	50.39	-2.48		-0.99	
BOND @ 1%	0.50	-0.02	•decreased bond @ 1% of above	-0.01	•same
TOTAL ESTIMATED CONSTRUCTION COST - OPEN SHOP	50.89	<u>-2.50</u> 48.39	•net reduction cost	<u>-1.00</u> 49.89	•net reduction cost

- . Concept #1 is the less costly solution because:
 - Daylight is used on the roof only to light the center of the building -- thus reducing roof glazing by 1/2 and relying on diffuse daylighting of perimeter areas (no reflective glass).
 - Focusing attention on lower cost alternatives for all parts of the redesign:
 - .. lower cost (lighter) structure
 - .. lower cost (stock) exterior wood windows
 - .. lower cost light fixtures -- a mix of 4-lamp (rather than 2-lamp) and industrial fixtures.
- . Concept #2 is slightly more costly than Concept #1 because it retains the full amount of roof glazing (250 sq.ft.). It was made less costly than the base case by replacing the deck/joist system with less costly manufactured wooden trusses and using the new layout to reduce light fixture and wiring costs. The cost estimators felt that duct layout might be more costly in this configuration than in the base case, even though the team did not agree.
- . Concept #2 achieved significant cost savings by eliminating the plenum and reducing overall building height 2 feet.

CHAPTER IV

MASS WITH NIGHT VENTILATION SYSTEMS

Description of Technology

In simulating the energy saving potential for mass with night ventilation, the national laboratories took an "ideal" technology approach (100 air changes in the simulation). The simulations assumed that:

- . A high rate of ventilation could be employed at night to bring interior temperature down to exterior conditions with no energy penalty (i.e., additional fan power = 0).
- . The building was of very high mass (over 30,000 sq.ft. of 2" thick concrete exposed on one side).

With these assumptions, the following energy savings would result from using the technology in the Northeast (the climate chosen for this problem):

- . Fuel consumption - 0.039 MCF/sf-yr
- . Electricity consumption - 11.6 kWh/sf-yr
- . Demand - 0.045 kW/sf-yr (sum of monthly peaks)

The "ideal" application of this technology reduced electrical energy consumption for cooling 23% (from the base case), and reduced the total annual demand requirements (summation of monthly peaks) 14%. Energy consumed for heating was reduced 7%, but was not considered in the following design problem. Two major variables were fixed in investigating the "ideal" systems:

- . mass thickness: 2" minimum
- . mass exposure: 33,500 sq.ft. (including 2,700 sq.ft. in base case specifications)

Mass with Night Ventilation - Problem Statement

The design teams were asked to develop a physical solution that would approximate, as closely as possible, the lab's thermal assumptions for mass with night ventilation. In discussing the thermal and physical constraints of the problem, several issues were resolved:

- . Basic architectural and mechanical specifications to achieve 90-95% of ideal potential were fixed:
 - mass specific heat: 0.2 Btu/LB-F
 - mass density: 140 LB/CU.FT.
 - mass/air heat transfer coefficient based on still air
 - climate: Northeast (New York/D.C.)
 - night ventilation rate: 25 ACH in unoccupied space
 - air velocity: 50-100 FPM
 - floor covering: 7,500 sq.ft. carpeted (R-3)
 - cooling mass isolated from conduction to exterior

Criterion for evaluation of solutions would be lowest simple payback. This suggested two possible design approaches:

- Accept the highest possible ventilation rate (set at 25 air changes per hour at night by the group) and exposed mass (33,000 sq.ft. at 2" thickness); then redesign the base case to achieve least first cost
- Look for a practical combination of ventilation rate and mass exposure, to be determined by team. That would achieve the best simple payback (first cost divided by annual energy savings).

MASS WITH NIGHT VENTILATION

CONCEPT #1

Understanding the Problem

The team began with a brief discussion of the problem and some thoughts to focus attention. They agreed that locating the problem in Washington, D.C. -- which has both a temperate climate and modest energy costs would not seriously skew the solution to any one region of the country, but would likely be about "average." Early thoughts on the nature of the problem included:

- . Sizing the HVAC System -- Proposed HVAC systems would be significantly different depending on whether they were sized for daytime HVAC needs or for high nighttime ventilation rates. Probably no single system is optimum for both. Where is the best tradeoff?
- . User Comfort -- The strategy of high air changes could be especially uncomfortable to users if it occurred during occupied periods. Also, using building mass either as a heat sink or heat source could cause uncomfortable surface temperatures on building walls. In either case, user comfort will have to be watched carefully.
- . Amount of Mass to Use -- Lab analysis to date does not indicate an optimum amount of mass for either thermal or economic performance of a mass with ventilation strategy. Maximum mass may not be the "best" solution. The team thought it would be useful to investigate other than the full-massed option.

- Specifications for a Speculative Office Building -- Although not specified in the problem definition, the team agreed that if a building is to be truly a speculative office building it must have carpet on the floor, movable partitions (eliminating the proposed lab solution), and unobstructed windows.

PROCESS AND KEY THEMES

The team used a "brainstorming" session to generate ideas worth pursuing in-depth. A wide variety of issues were covered including suggestions to:

- Reduce loads wherever possible. Look especially at reducing heat gains due to heat-of-lights and solar gains.
- Shift energy demands off peak. For example, the chiller might be used to pre-cool the building mass during night and morning hours to cut down afternoon cooling load. This option would increase energy use for the chiller but would reduce costs by reducing peak demand (and resulting costs).
- Reduce HVAC system costs. An obvious approach is to find ways to reduce duct costs by reducing length of runs. A more interesting option might be to go to a constant volume system. Unless the building layout is so complex as to include several zones and mixing of air temperatures across zones, there is no need for the complexity (and cost) of a VAV system. Also, a two-speed fan could solve the problem of high air change requirements at night (up to 15 - 20 ACH) and low air changes during the day (about 1 or 2 ACH).
- Improve HVAC system performance. Increase the efficiency of heat transfer in the building (the heat transfer coefficients in the equation) by better use of mass in wall construction or in the structure.
- Use pre-cast concrete tees in the plenum as duct work. This could enhance the interaction of mass with the HVAC system.
- Isolate air flow in the plenum from air flow in the occupied spaces. This increases the number of air changes that can occur without causing occupant discomfort.

With these preliminary ideas in mind, the team proceeded into a series of analyses aimed at determining which ideas were likely to be worth carrying into design. The team started with an analysis of HVAC system costs in the base case and determined that equipment costs of \$22,000 and distribution costs of about \$25,000 were worth further analysis for possible reductions. Distribution costs, especially, seemed high.

FIGURE 31
MASS WITH NIGHT VENTILATION SYSTEMS
CONCEPT #1

RECOMPATATION OF ANNUAL BASE CASE ENERGY BILL
TYPICAL WASHINGTON, D.C. RATE STRUCTURE

	<u>Average Monthly</u>	<u>Average Annual (Monthly x 12)</u>	<u>% of Total Bill</u>
<u>Electric Bill</u>			
Basic Customer Charge:	\$ 5.45	\$ 65.40	
Consumption:			
1st 6200 kWh/mo	\$306.00	\$3,672.00	
Remaining 4378 kWh/mo*			
x \$.015/kWh	65.67	<u>788.00</u>	
		\$4,525.40	
Tax (6%)		<u>271.50</u>	
Total Consumption & Tax		\$4,796.90	60%
Demand:			
1st 25kW free			
Remaining 19/kW/mo* x \$4.85/kW	\$ 92.15	\$1,105.80	
Tax (6%)		<u>66.30</u>	
Total Demand & Tax		\$1,172.10	15%
TOTAL ELECTRIC BILL (Average = 5.89¢/kWh)		<u>\$5,969.00</u>	
<u>Gas Bill</u>			
No Basic Charge or Demand Charge			
Consumption:			
383.3 MBtu/yr* x \$5/MCF or MBtu	\$159.71	\$1,916.00	
Tax (6%)		<u>115.00</u>	
TOTAL GAS BILL		<u>\$2,031.00</u>	25%
TOTAL ENERGY BILL (Average 80¢/sq.ft.-yr)		<u>\$8,000.00</u>	100%

*Average monthly energy use from lab simulations

FIGURE 32

**MASS WITH NIGHT VENTILATION SYSTEMS
CONCEPT #1**

**ANNUAL ENERGY COST SAVINGS DUE TO NIGHT VENTILATION
AT VARIOUS LEVELS OF INCREASED MASS**

(BASED ON TYPICAL WASHINGTON, D.C. UTILITY RATES)

		CONSUMPTION	DEMAND	TOTAL
FULL MASSED (32,000 sq.ft. exposed)	AMOUNT SAVED/YR	12,936 kWh/yr ¹	89.8 kW/yr	
	RATE	\$.015/kWh	\$4.85/kW	
	\$ SAVED/YR	\$ 194	\$ 436	
	WITH TAX - 6%	\$ 206	\$ 462	\$ 668
HALF MASSED (15,000 sq.ft. exposed)	AMOUNT SAVED/YR	5,836 kWh/yr ²	42 kW/yr	
	RATE	\$.015/kWh	\$4.85/kW	
	\$ SAVED/YR	\$ 88	\$ 204	
	WITH TAX - 6%	\$ 93	\$ 216	\$ 309

1. Based on BLAST simulation analysis (LBL)
2. Estimated by interpolation among BLAST runs

Next, the team did an analysis of the annual base case energy bill in order to get some sense of the most important energy cost problems to be addressed. As shown in Figure 31, based on Washington, D.C. prices, the base case energy bill was estimated to be about \$8,000 per year (\$.80/sq.ft.) -- a reasonable U.S. price but less than half of New York City prices. The analysis showed electrical consumption as about 60% of the total bill, electrical demand about 15%, boiler fuel about 25%, including taxes and fees. Although electrical consumption is clearly the greatest single cost, demand charges are significant enough to be worth attention by the team.

Finally, the team did an analysis of the likely costs and potential savings due to the application of various amounts of mass to the building. As shown in Figure 32, lab analysis indicated that a very high amount of mass (about 32,000 sq.ft. exposed) would save approximately \$670 per year. Based on further analysis of the lab figures, the team estimated that using approximately half the maximum amount of mass (in the range of 15-16,000 sq.ft. exposed) would reduce annual savings to approximately \$310 -- all based on the Washington, D.C. utility rates. Clearly these relatively low total annual savings dictated very cost effective (low cost) mass in order to get any kind of reasonable payback. An innovative wall system under consideration which included thin concrete panels (built in place and tilted up) was quickly eliminated when costs were estimated to be \$9/sq.ft. Pre-cast concrete tees at about \$1.20/sq.ft. looked far more cost effective than even brick veneer at approximately \$5/sq.ft.

Based on these calculations and preliminary cost estimates, the team defined a basic set of strategies to guide the design of their proposed solution:

- . Reduce first cost of the HVAC system
 - high probability of cutting distribution costs
 - look for opportunities to cut central chiller capacity (and peak) costs
- . Reduce energy operating costs (to off-set any increase in first cost due to increased use of building mass)
 - reduce cooling loads by rejecting heat-of-lights and shading or insulating the building skin as required
 - use building mass like it was chilled water storage in order to shift peak cooling loads to lower cost times of day
 - use the cheapest source of energy (not necessarily the lowest total use) to meet building loads.

With these concepts in mind, the team proceeded to work out their solution to the problem.

THE SOLUTION

The solution arrived at is affectionately called the "half-massed" solution. The goal of the solution is to put approximately 15,000 sq.ft. of exposed mass into the building -- rather than the 32,000 sq.ft. which the labs presumed to be about the maximum possible in a building of this size (10,000 sq.ft.).

First, the team replaced the open-web joists and metal deck in the base case solution with pre-cast concrete "double tees" (Figures 33 & 34). The 24" tees are 50' in length and rest on a pair of bearing walls forming a central spine of the building. The two bearing walls of 8" concrete blocks are 100' in length, and approximately 1-1/2' - 2' apart.

The concrete tees themselves add 15,600 sq.ft. of exposed mass to the structure when all under surfaces of the tees -- including the legs -- are considered. The increased amount of bearing wall in the center of the building adds another 900 (or so) sq.ft. of mass. The north and south walls of the building also become bearing walls, although their mass was not considered to be a significant addition over the base case. Taken together, the exposed mass in this solution is about half that of the proposed maximum, but considerably greater than the base case.

Interaction between the mass and HVAC system is accomplished by making the channels between tees serve as both HVAC ducts and light troughs. As shown on Figure 33, every third channel is either a supply duct, a return duct, or a light trough. Main supply ducts are hung below and perpendicular to the concrete tees. The space between the central bearing walls is used as a large return duct.

Combining the structural and HVAC systems creates the possibility of reducing ducts by an estimated 20-25% and eliminating 2 feet from the plenum space. Thus, the height of the building -- including the facade could be cut 2 feet. It was hoped that resulting cost savings could offset the slightly increased cost of using concrete tees.

Because this building, as conceived, would have at most three zones (south, core, and north), the variable air volume system was replaced by a less costly constant volume system. This eliminated the need for VAV boxes but did call for the addition of several in-line fans to pull air across the double-T's.

This solution also applied a number of strategies to cut cooling loads -- especially peak loads. First, the team vented light troughs directly to the outside, making it possible to "dump" heat-of-lights directly outside when it would be likely to cause overheating problems. This solution required the addition of dampers in the building facade and a large fan to assist in flushing out the light troughs. The team also reduced the amount of north, east and west glass to the amount needed for view only, and reduced south glass to 6' x 6-1/2' foot panels. The team decided to continue to use gas heat so as not to aggravate electrical costs -- especially peak demand costs.

FIGURE 33

MASS WITH NIGHT VENTILATION SYSTEMS
CONCEPT #1

FIGURE 34

MASS WITH NIGHT VENTILATION SYSTEMS

CONCEPT #1

FIGURE 35

MASS WITH NIGHT VENTILATION SYSTEMS

CONCEPT #1

ESTIMATED ENERGY COST REDUCTIONS

HVAC SOLUTIONS INCLUDING ADDED MASS, NIGHT VENTILATION,
AND LIGHT TROUGH FLUSHING

(BASED ON TYPICAL WASHINGTON, D.C. RATE STRUCTURE)

STRATEGY & (LOAD REDUCED)	ELECTRICAL CONSUMPTION			ELECTRICAL DEMAND		
	ENERGY SAVED PER YEAR	RATE	\$ SAVED PER YEAR	ENERGY SAVED PER YEAR	RATE	\$ SAVED PER YEAR
• NIGHT VENTILATION & ADDED MASS (COOLING LOAD REDUCTION)	-5836 kWh/yr ¹	\$.015 + tax	-\$88	-42kW ¹	\$4.85 + tax	-\$204
(FAN POWER INCREASE)	+15000kwh/yr ²	same	+\$225	NA ³	NA	NA
• DAY VENTING - HEAT-OF-LIGHTS ONLY (COOLING LOAD REDUCTION)	+164kWh/yr ²	same	-\$135	-60kW ²	same	\$291
COLUMN TOTALS:	+164 kWh/yr		+\$2	-102kW		-\$495
NET ENERGY COST SAVINGS:	-\$493/yr					

1 See Figure 32

2 Rough estimates by engineers at workshop

3 Not computed at workshop - could be significant

The net effect of all these strategies is estimated to be an annual energy cost savings of about \$500 (Figure 35). This is significantly less than the \$800-\$1,000 savings per year hoped for by the team, and is due largely to the increased cost of operating the additional in-line fans. Still, savings of this magnitude would result in an 8-10 year payback based on estimated increases in construction first cost of \$4,000-\$5,000.

Unresolved Issues

The addition of in-line fans ended up costing more than the team had hoped, both for first cost and for operating costs. The increased cost of several small fans more than offset savings by reducing chiller size. It appeared that the goal of cutting HVAC distribution costs was correct, however. Further analysis would be necessary to arrive at a solution that would not require the use of so many in-line fans.

The innovative thin concrete "tilt-up" wall system was attractive until it had to be eliminated because of cost. It would be interesting to pursue this line of thinking further to see if a "light" but massive wall solution -- along the lines originally proposed by the labs -- is possible. If such partitions could be installed and removed nearly as easily as current dry-wall construction, it would make mass wall solutions possible. Presumed owner requirements would no longer restrict high mass solutions to the plenum, as was presumed here.

MASS WITH NIGHT VENTILATION

CONCEPT #2

Understanding the Problem

The team agreed that the goal of the design problem statement was to cost-effectively introduce sufficient mass and air flow into the building to satisfy the laboratories' thermal analysis assumptions. To achieve over 90% of the savings potential for the technology the team would need:

- . 25 air changes per hour ventilation rate at night
- . 33,000 square feet of exposed mass
 - 2" thick concrete; single exposure, or
 - 4" thick concrete; double exposure

Twenty-five air changes per hour was thought to be feasible -- as long as pressure drop across the fan could be kept low. The team felt that the key to the problem was the amount and location of thermal mass. From the outset, the team agreed to pursue only those solutions that would provide the required amount of mass and night ventilation.

Process and Key Themes

Design team review of the thermal analysis results showed that the solution would need to be very cheap -- current Washington, D.C. utility cost savings were projected to be less than \$.20/sq.ft.-yr for the technology, and savings in areas with more expensive energy prices would not be more than double that. Location of mass would also be an important issue. According to the researchers, the mass was presumed to be entirely in 4" thick concrete interior partitions exposed on two sides. However, after a quick analysis, the team rejected both exterior and interior wall locations for the mass for the following reasons:

- . Hollow-core exterior walls and floor were certainly feasible but thought to be both very expensive and difficult to couple with the ventilation flow. Also, only 26,000 sq.ft. of exposure was possible.
- . Massive interior partitions were even less appealing. Not only were they likely to be expensive, but, more importantly, massive interior partitions were highly inflexible for future space planning needs. This was not in keeping with "speculative" or "owner-occupied" design approach. Furthermore, simple analysis showed that to achieve the required mass in interior partitions would demand 100 10'x10' cubicles -- without doors. As a result, the team decided to focus on solutions that increased mass in roof/ceiling systems.

The team sequentially investigated four alternatives, schematically presented in Figure 36. Each option was evaluated for pros and cons -- with successive options based on ways to improve the fundamental concept of increasing roof/ceiling mass and exposure to ventilation flow.

- . Alternative #1 - Linear or coffered pre-cast "double-T" roof deck exposed to interior spaces:
 - pros: concept yields approximately double the potential mass exposure of flat deck (17,000-20,000 sq.ft.)
 - cons:
 - .. mass thicker than needed for single exposure on underside of roof deck
 - .. integration with mechanical and electrical systems is difficult
 - .. less exposed mass area than required to achieve thermal performance goals.
- . Alternative #2 - Linear "double-T" deck with drop ceiling for concealing mechanical/electrical systems:
 - pros: much easier integration of systems -- can use channels between "tees" as plenums and eliminate supply and return ducts if partitioned properly
 - cons: added expense without achieving mass exposure required.

FIGURE 36

MASS WITH NIGHT VENTILATION SYSTEMS

CONCEPT #2

OPTION #1:

ALTERNATIVE
CONCEPTS

OPTION #2:

OPTION #4:

OPTION #3:

- . Alternative #3 - Since deck thickness is sufficient for double exposure, but not used in options 1 and 2, invert T's with a drop ceiling beneath to obtain two-layer plenum:
 - pros: approaches mass exposure requirements while still eliminating supply and return ducts
 - cons: very expensive; viewed as awkward approach by team.

- . Alternative #4 - Replace double-T's with two concrete slabs separated by open web joists (all site fabricated) to form a supply air plenum. Suspend a drop ceiling below the bottom slab to create a return air plenum:
 - pros: achieves mass/exposure requirements (30,000 sq.ft. in ceiling alone) at much less cost than inverted double T's. Plenum is unobstructed by T's allowing, as with all previous alternatives, flexible partitioning of air flow as required. This approach also does not interfere in any way with interior space planning below ceiling.

After review of alternatives, the team selected #4 for further development, since it was the only solution that both satisfied all requirements for exposed mass and appeared to be a low cost approach.

The Solution:

The team focused on the mechanical system aspects of the design. They first looked at HVAC system requirements and then used them as the basis for modifying other aspects of the base case building design:

- . The team's underlying theory was to separate the thermal mass heat sink from the occupied space so that it could be used for cooling only when and in the amount needed. This approach was felt to provide much more control and flexibility in use than would be possible with the mass directly connected to interior spaces. The matter of control of the technology was an overriding issue to the team. The mass in the plenum would be mechanically charged (cooled) as much as possible at night by flushing only the plenum with outside air. Large amounts of air (at least 25 ACH) would be needed to insure that the air temperature within the plenum approximated outside conditions throughout the night cycle. With this approach, the mass temperature could be brought down to 40°F-50°F, as needed for cooling, most seasons of the year.

- . During the day the mass would be discharged by circulating inside air and required ventilating air through the supply (upper) plenum; introducing the cooled air into the space; and pre-cooling recirculated air in the return air (lower) plenum. It was felt that normal air circulation rates would be sufficient to allow cooling of the air during daytime operation.

- . For the HVAC system to accomodate night ventilation at the level required, (25 ACH) the system would have to be able to operate in two distinct modes -- one mode for high air changes at night and one mode for the lower air change rate during the day. This will require additional controls. The HVAC schematic, Figure 37, presents the control strategy selected. Six dampers are required to adequately control operation of the system. The building is pressurized during normal (daytime) operation. During the night ventilation sequence, outside air is circulated within the "mass plenum" (between slabs) with the return air damper in the closed position. The system requires a two speed fan, the high speed used only for nighttime charging of the mass.

The pressure drop across the fan and consequent fan power requirements were of major concern to the team. Channeling the air flow rate required through a system of supply and return ducts would create a sizable fan load. The conceptual approach chosen, however, (i.e. eliminating the duct system by employing a stacked mass plenum with extremely large cross sectional area to accomodate the flow of air) eliminated the concern. The maximum air velocity within the plenum was calculated to be quite low, less than 6'per second.

- . Distribution of air to VAV boxes in each of the five HVAC system zones of the building was somewhat more complex, however. A central core was selected as most efficient in terms of access to each zone. Plenum partitioning and distribution parallel to the structural system did not present a problem, but getting perimeter VAV boxes across the open-web steel joist system and intervening wide flange beam structural members was more difficult. The team solved the problem by changing the direction of the joist layout in the core area, shown by the dotted line on Figure 38, and running 3"x4' cross-section ducts over the top of the structural beams in the 3-inch gap created by the joist end-condition figuration, as shown in Figure 39 and 40.

- . The final problem was to connect the supply air plenum to the conditioned space below. The team punctured the bottom slab of the supply plenum, as shown in Figure 40, and used 10" flex duct connectors to 24"x24" lay-in diffusers in the suspended ceiling. The design calls for 45 such diffusers on a 15' grid, as shown in the figure, to allow highly flexible space layout below.

CONCEPT #2

HVAC SYSTEM SCHEMATIC

• NORMAL SEQUENCE

- ZONE STAT CONTROLS D_1 TO MAINTAIN TEMP.; D_2 CLOSED
- T_1 CONTROLS V_1 , D_3 & D_4 IN SEQUENCE TO MAINTAIN DISCH.
- T_2 OVERRIDES T_1 CONTROL AT O.A. TEMPERATURES OVER 65°F
- P_1 CONTROLS D_5 TO MAINTAIN BLDG PRESSURE
- P_2 CONTROLS D_6 TO MAINTAIN STABLE FAN OPERATION

• NIGHT VENTILATION

- D_1 , D_2 , D_3 & D_5 OPEN, FAN ON HIGH SPEED
- D_4 & D_6 CLOSED

HVAC SYSTEM ZONING

FIGURE 38
 MASS WITH NIGHT VENTILATION SYSTEMS
 CONCEPT #2

FIGURE 39

MASS WITH NIGHT VENTILATION SYSTEMS

CONCEPT #2

FIGURE 40

MASS WITH NIGHT VENTILATION SYSTEMS

CONCEPT #2

Redesign of the base case structural system to meet HVAC system needs resulted in a more flexible system at lower cost:

- . First, it was clear to the team that the base case structural system was more expensive than necessary, employing only 9 structural bays. It would get more expensive with the addition of the concrete roof deck and mass plenum. A 20' grid (25 bays) was investigated and found to require less steel than the base case, even with the additional mass. As mentioned above, the structural layout was tailored to HVAC distribution requirements in the core area (Figure 40).
- . The 20' grid also allowed convenient separation of HVAC zones and little or no revision to the architectural plan. If anything, the team felt that the solution was even more flexible than the original base case because 300 linear feet of masonry partitions were eliminated. The solution reduced the mechanical core to a 400 sq.ft. central module accomodating the boiler room, duct work from the roof top unit, telephone equipment, and electrical closets.

Unresolved Issues

While the team was excited about the solution, a few nagging questions remained.

- . The solution is a "clever idea" but the team had real concern about whether or not the result was at all practical for a real building. For example, once in place, the mass plenum is entirely inaccessible
- . The solution relies on a degree of tightness in construction that may not be achievable. How well the suspended ceiling or even the concrete decks will hold in and channel airflow is questionable.
- . The team was confident that the night mass "changing" cycle would work. The labs had essentially based their simulation on "still-air" convective heat transfer at outside temperature conditions -- to change the mass -- a conservative approach. The "discharging" cycle was not as well understood. Forced air discharging may or may not work, depending on the thermodynamics involved.
 - The temperature differences (40°F-50°F mass vs 78°F return air from occupied spaces) appear to be sufficient but,
 - the amount of air needed for efficient heat transfer is unknown.
- . The complexity of the ceiling plenum ("Do not make any mistakes while you are building it - Please!") was a direct result of the desire for flexible interior space options. Other less complex and less costly systems could be designed if flexibility in space planning was not such a critical issue.

- . In discussions following the workshop, it was pointed out that the solution may operate quite well without forced air discharging. In this approach, louvers would replace acoustical sections of the ceiling, allowing control of the convective rise and fall of inside air into and from the plenum space. This approach would allow indirect charging of the mass at night (separate from the interior spaces) and direct discharging during the day. The concept requires research to confirm its potential, however.

COMPARISON OF CONCEPTS FOR MASS WITH NIGHT VENTILATION SYSTEM

Though quite different in approach and solution configurations:

- . Both concepts are very close in cost to the base case -- about 1% increase in each case.
- . The concepts are surprisingly close in cost, given that Concept #2 includes about twice the mass of Concept #1.
- . Both solutions focused on adding mass to the building above the ceiling tiles as the only reasonable location in a speculative office building.
- . Both solutions achieved significant cost savings in the HVAC system over the base case.
- . Concept #1 is the lower cost solution because it uses low-cost pre-cast concrete tees to add mass to the building.
- . Concept #1 could have been considerably less costly had there been sufficient design time to look for a more cost-effective structural system (especially footings), and a low-cost method for finishing the ceiling and connecting it to the double-T's.
- . Concept #2 is slightly more costly than Concept #1 because the high cost of significantly increased mass could not be completely offset by cost savings from a careful structural redesign and the elimination of almost all duct work in the HVAC system.

FIGURE 41

COST COMPARISON: MASS WITH NIGHT VENTILATION SYSTEMS
CONCEPTS #1 & #2

(OPEN SHOP NOT INCLUDING SITE WORK)

SYSTEM DESCRIPTION	BASE CASE	CONCEPT #1		CONCEPT #2	
	SYSTEM COSTS \$/SF	COST DIFF. \$/SF	REASON	COST DIFF. \$/SF	REASON
GENERAL REQUIREMENTS @ 10%	4.16	+0.04	• increased overall cost	+0.05	• increased overall cost
FOUNDATIONS	0.72	+0.62	• linear footing for bearing walls	+0.06	• heavier pier footings
SLAB ON GRADE	1.31				
SUPERSTRUCTURE	5.03	+0.53	• double-T's	+2.39	• two mass decks, heavier columns/ beams, extra joists
ROOFING	4.41				
EXTERIOR WALLS	2.78	+0.10	• direct, bond beams, masonry walls		
EXTERIOR GLAZED OPENING	3.66	-0.30	• reduced area, clear glass		
INTERIOR PARTITIONS	2.32	-0.07	• eliminated glass block, added bond beam	-0.33	• reduced CMU partitions, eliminate glass block
DOORS	1.37				
CEILING FINISHES	1.13	+0.35	• drywall replaces acoustic tile		
FLOOR FINISHES	1.63				
SPECIALTIES	0.13				
EQUIPMENT	0.15				
PLUMBING	1.68				
HEAT, VENTILATION & AIR CONDITIONING	8.23	-1.05	• constant volume system, removed ducts and VAV boxes	-1.58	• use 25 ton multizone, eliminated almost all ducts
ELECTRICAL	7.10	+0.19	• additional wiring for in-line fans	-0.07	• removed air handling bonnets
TOTAL COST	45.81	+0.39		+0.52	
GENERAL CONTRACTOR'S OVERHEAD & PROFIT @ 10%	4.58	0.04		0.05	
SUBTOTAL	50.39	+0.43		0.57	
BOND @ 1%	0.50	0.01		0.01	
TOTAL ESTIMATED CONSTRUCTION COST - OPEN SHOP	50.89	+0.44 51.33		+0.58 51.47	

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CHAPTER V

EVAPORATIVE COOLING SYSTEMS

Description of Technology

Los Alamos National Laboratory researchers developed two "realistic" evaporative cooling systems for simulation as part of the Cooling Assessment work: a direct evaporative system, Figure 42, and a direct/indirect system, Figure 43. Each system was comprised of readily available (off-the-shelf) mechanical system components.

Although the sizing of the evaporative cooling equipment varies with climate, for the purpose of establishing a cost, the following component specifications for a California coast site were provided:

Direct Evaporative Cooling

- . 19 ton air washer delineating 7,347 cfm of air
- . Ductwork and dampers to bypass 7,347 cfm of air around the washer.

Direct/Indirect Evaporative Cooling

- . 19 ton air washer delivering 7,347 cfm of air
- . Ductwork and dampers to bypass 7,347 cfm of air around the heat/cool recovery coil and air washer
- . Return fan exhausting or recirculating 7,347 cfm of air
- . Heat/cool recovery coil -- see Appendix 7.

DOE-2 simulation of the single story base case building equipped with the combined direct/indirect evaporative system produced the following results, shown in Figure 44, for the California coast (Los Angeles) climate region:

- . Fuel consumption: 0.004 MCF/sf-yr
- . Electricity consumption:
 - lights & equipment: 9.8 kWh/sf-yr
 - cooling 1.2 kWh/sf-yr
 - fans and pumps: 0.9 kWh/sf-yr
- . Annual electric peak: 4.9W/sf-yr

FIGURE 42
SMALL OFFICE BUILDING
EVAPORATIVE COOLING

DIRECT EVAPORATIVE COOLING SCHEMATIC

FIGURE 43

SMALL OFFICE BUILDING
EVAPORATIVE COOLING

DIRECT/INDIRECT EVAPORATIVE COOLING SYSTEMS SCHEMATIC

FIGURE 44

SMALL OFFICE BUILDING

EVAPORATIVE COOLING

ANNUAL ENERGY SAVINGS
FOR CALIFORNIA COAST

Base Case

With Evap. Cooling

The evaporative cooling system specified resulted in a significant reduction in the cooling energy consumed over the base case and a minor reduction of demand:

- . 45% reduction in electricity consumed for cooling
- . 7.2% reduction in demand

Evaporative Cooling - Problem Statement

The cost-estimating team was asked to develop an estimate of the approximate first-cost of the proposed system if added to the reference building design. No benefit was estimated for the potential elimination of the primary mechanical cooling equipment. A recent unpublished investigation by Los Alamos National Laboratory indicates that the mechanical cooling can be entirely displaced by evaporative cooling in the Pacific Northwest, Fresno/El Paso, and Central Mountain climate region of the U.S. It was presumed that no significant modifications would be required to base case architectural systems to apply this technology, so it was not necessary for the design teams to address evaporative cooling as a workshop problem. Incremental increases in first cost of the mechanical system alone would be sufficient for providing all upper bound on the cost of evaporative cooling technology. The maximum cost for implementing this technology is then compared to the potential costs of implementing the other technologies evaluated.

Evaporative Cooling System concept:

A comparative cost estimate for the direct/indirect system vs base case mechanical system costs is presented in Figure 45. The total cost for the direct/indirect system option is 1/3 higher than the base case HVAC system. Major cost differences include:

- . Air washers: \$5,160.00
- . Z Duct System: \$9,320.00
- . Return air Fan: \$2,750.00
- . Additional ductwork: \$1,650.00
- . Additional controls: \$2,150.00

Depending on performance of the system in a particular climate, the incremental cost for both evaporative systems might be reduced through elimination of conventional mechanical chillers. In addition, variations in the design of other building systems, in the same manner as solutions to design problems involving application of beam daylighting and mass with night ventilation technologies, could reduce system total incremental costs even further. A reasonable estimate of the net incremental cost over the base case for the evaporative cooling system is \$.80-\$1.20/sq.ft.

PASSIVE SOLAR COOLING SYSTEM & CONCEPT STUDIES

DESCRIPTION	QUANTITY	UNIT PRICE	TOTAL LABOR	TOTAL	DESCRIPTION	QUANTITY	UNIT PRICE	TOTAL LABOR	TOTAL
BASE CASE HVAC -----					*DIRECT/INDIRECT EVAPORATIVE COOLING SYSTEM HVAC -----				
EQUIPMENT					EQUIPMENT				
ROOF TOP A.C. UNIT (20 TONS)	1 EA	15,000.00	15,000		ROOF TOP AIR CONDITIONING UNIT	1 EA	15,000.00	15,000	
BOILER (306 MBH) GAS	1 EA	2,500.00	2,500		BOILER (306 MBH) GAS	1 EA	2,500.00	2,500	
PUMP (IN-LINE)	2 EA	1,050.00	2,100		PUMP (IN-LINE)	2 EA	1,050.00	2,100	
EXPANSION TANK W/TRIM	1 EA	443.00	443		EXPANSION TANK W/TRIM	1 EA	443.00	443	
AIR SEPARATOR	1 EA	470.00	470		AIR SEPARATOR	1 EA	470.00	470	
WALL FIN RADIATION	400 LF	18.00	7,200		WALL FIN RADIATION	400 LF	18.00	7,200	
BOILER/HVAC FLUE	1 EA	225.00	225		BOILER/HVAC FLUE	1 EA	225.00	225	
CEILING EXHAUST FANS W/ROOF JACK	5 EA	185.00	925	28,863	CEILING EXHAUST FANS W/ROOF JACK	5 EA	185.00	925	
					*AIR WASHER	1 EA	5,160.00	5,160	
					*2" DUCT SYSTEM	1 EA	9,320.00	9,320	
					*RETURN AIR FAN	1 EA	2,750.00	2,750	
					*DAMPERS (W/OPERATORS)	6 EA	260.00	1,560	47,653
AIR DISTRIBUTION					AIR DISTRIBUTION				
GALV. SHEET METAL DUCTWORK	7,500 LB	2.00	15,000		GALV. SHEET METAL DUCTWORK	8,325 LB	2.00	16,650	
DUCT INSULATION	3,500 SF	0.90	3,150		DUCT INSULATION	3,663 SF	0.90	3,297	
VAV BOXES:					VAV BOXES:				
800 CFM - CORE	6 EA	537.00	3,222		800 CFM - CORE	6 EA	537.00	3,222	
600 CFM - PERIMETER	8 EA	451.00	3,608	24,980	600 CFM - PERIMETER	8 EA	451.00	3,608	28,777
ROUGH-IN					ROUGH-IN				
PIPE & FITTINGS	960 LF	6.70	6,432		PIPE & FITTINGS	960 LF	6.70	6,432	
VALVES & SPECIALTIES	20 EA	39.62	792	7,224	VALVES & SPECIALTIES	20 EA	39.62	792	7,224
AUTOMATIC TEMPERATURE CONTROLS	1S		5,200	5,200	AUTOMATIC TEMPERATURE CONTROLS	1S		7,350	7,350
MISCELLANEOUS					MISCELLANEOUS				
PERMITS	1S		80		PERMITS	1S		80	
TEST & WARRANTY	1S		1,040		TEST & WARRANTY	1S		1,040	
AIR BALANCE	1S		920		AIR BALANCE	1S		920	
WATER BALANCE	1S		260	2,300	WATER BALANCE	1S		260	2,300
SUBTOTAL				68,567	SUBTOTAL				91,304
SUBCONTRACTOR'S OVERHEAD	PROFIT @ 20%			13,713	SUBCONTRACTOR'S OVERHEAD & PROFIT @ 20%				18,261
TOTAL HVAC				82,280	TOTAL HVAC				109,565

FIGURE 45
EVAPORATIVE COOLING SYSTEM
INCREMENTAL SYSTEM COSTS

CHAPTER VI

INTEGRATED PASSIVE COOLING SYSTEMS

Description of Technology:

In systems analysis of passive cooling technologies to date, no attempts have been made to evaluate the potential of combined systems either as combined passive heating and cooling systems, or as multiple passive cooling systems in a single building. As a result, only guesses can be made concerning the energy and cost savings potentials of combined systems approaches. Analysis of such concepts has been proposed as a logical and necessary next step in the evolution of the federal research program.

Integrated Passive Cooling - Problem Statement:

In order to provide the research community with some understanding of the physical design considerations that must be dealt with in proposing and evaluating integrated system solutions, the design teams were asked to develop a schematic design solution that would satisfy the following constraints:

- . 2-story, owner-occupied, 10,000 sq.ft. office building
- . Rocky Mountain (Denver) climate conditions
- . Application of 2 or more passive cooling strategies from among:
 - daylighting (beam and/or diffuse)
 - night ventilation (with or without mass)
 - evaporative (direct, indirect, or direct/indirect)
- . \$55.00/sq.ft. construction budget

The teams were required to:

- . Develop schematic concepts to sufficient detail for first-cost analysis
- . Describe assumed rationale for building operation and interaction of systems
- . Estimate potential energy cost savings of the derived solution using professional judgment and available tools.

Note that the 1-story base case used for comparison in previous problems does not apply directly here. Base case energy use and building first cost would be different in going to a multi-story solution. The arbitrary \$55/sq.ft. budget used to guide this problem does not reflect any analysis of the likely increase in

first cost in going from the base case used previously, to one appropriate for this problem. The cost estimating team agreed that a 2-story solution similar in quality to the given base case could increase in cost as much as 10-15% (up to \$60/sq.ft.), due to added costs for the 2nd story, such as elevators, stairs, fire protection, HVAC expansion, added facade, etc. These increased costs would be offset somewhat by reduced costs of land area, had they been considered as part of the cost estimates used at the workshops. New multi-story base cases would have to be developed before truly comparative results are possible.

The climate condition for this problem was switched from the Northeast (Washington, D.C.) climate (used previously) to the Central Mountain (Denver) climate so that all technologies considered might have an equal opportunity of success. The Denver climate was presumed favorable for both night ventilation and evaporative cooling.

The two design teams involved took radically different approaches to the problem.

INTEGRATED PASSIVE COOLING SYSTEMS

CONCEPT #1

Understanding the Problem

The team quickly addressed the fact that this is an integration problem and, as such, has many more potential solutions than any of the previous problems. In order to be efficient, the team decided to build on the best ideas of their mass with night ventilation solution, while revisiting ideas that had not worked to see if a more integrated approach might lead to better solutions.

The team agreed that because this is a speculative office building, the floor must be carpeted, partitions must be movable, and perimeter glass must be unobstructed. Given these constraints, any use of mass would probably be confined to the plenum and a few walls which need not be movable -- as in the core.

In recognition of the fact that this problem had a specified utility rate schedule, the team decided to revisit the lab analyses of energy use to recheck all potential areas of savings. The team also estimated the magnitude and cost of monthly demand charges to use as a yardstick for measuring potential reductions in peak energy costs.

The team's overall approach to the problem was to let areas of significant energy savings suggest strategies to be pursued while, at the same time, building on lessons learned in the mass with night ventilation solution.

Process and Key Themes

The team began with a review of lab findings of potential energy savings and developed a list of strategies worth investigating, the load to be reduced, and the approximate maximum reduction possible:

<u>STRATEGY</u>	<u>LOAD REDUCED</u>	<u>APPROXIMATE MAXIMUM REDUCTION</u>
DAYLIGHTING:	COOLING	-40%
	LIGHTING	-40%
EVAPORATIVE COOLING:	COOLING	-42%
DAYTIME VENTILATION: (SUPER ECONOMIZER)	COOLING	-34%
ADDED MASS:		
- WITH NIGHT VENTILATION:	COOLING	-44%
- WITH PASSIVE HEATING:	HEATING	Unknown
WINDOW MANAGEMENT:	COOLING & HEATING	Unknown
SIMPLIFY HVAC SYSTEM:	FAN POWER	Unknown

Based on this preliminary analysis, the team decided to pursue roughly three basic strategies in parallel. No single strategy was to be primary. Tradeoffs among strategic options were largely to be settled by lowest first cost considerations. The three strategies were as follows:

(1) Maximum Use of Daylighting

The team unilaterally decided not to puncture the roof in order to daylight the upper floor of the proposed building. In marked contrast to the findings of the daylighting workshop, this team was unwilling to believe that the roof could be punctured cost effectively without "tricks" like a wood truss system. Instead, the team revised the building aspect ratio to a maximum width of 50', which the team believed could be daylit from north and south glass using known daylighting techniques. (Recall that the option of a narrow building was not allowed in the daylighting solutions discussed previously).

The decision to go with a longer and narrower building raised the first interesting tradeoff in strategy integration. While the long and narrow building would reduce lighting costs, it also was likely to increase HVAC system costs (due to somewhat longer HVAC runs) and also increase the cost of the building exterior skin (building skin having been increased by going to the longer shape). Pending further analysis, the team made a heroic assumption that savings in energy costs were worth the increased costs and proceeded.

(2) Reduce HVAC System Costs

The team suggested going to a non-ducted return to save on duct costs. The team also wanted to review their previous solution to see if there was some way to reduce both duct and fan costs while still using the mass with night ventilation strategy.

(3) Use Building Mass to Reduce or Shift Peak Energy Loads

Although common HVAC systems use heat gains on the south of a building to supply heating needs on the north, the team was interested to see if building mass could be used either to assist this process or to reduce HVAC system costs.

A related, and even more interesting, question was whether or not building mass could be used as a part of a cooling strategy to shift daytime heat gains later in the day when they could be dealt with after occupants had left and when energy costs were lower (at off-peak rates).

With these three strategies in mind, the team proceeded to do several analyses to see if even approximate numbers supported their three basic strategies. Analysis techniques varied from "back-of-the-envelope" calculations by hand to an on-line computer terminal accessing the energy conservative design (ECD) program.

First, the team did a brief calculation to find the annual amount of excess heat generated in the south and central zones and the amount of heat needed in the north zone. Results for each lineal foot of one story (a slice 1' wide by 12' high through the entire 50' width) on a typical winter day were as follows:

	<u>Heat Gains and Losses (BtuH)</u>		
	<u>South Zone 12' deep</u>	<u>Central Zone 26' deep</u>	<u>North Zone 12' deep</u>
Ventilation:	-109	218	-109
Exterior Wall:	-192 (added glass)	-0-	-144
People, Lights, & Equipment:	+41	246	+41
Solar Gain:	<u>+1200</u>	<u>-0-</u>	<u>+160</u>
Total:	+940	+28	-52

This preliminary calculation suggested that the key problem would not be meeting the heating needs of the north zone but preventing overheating in the south zone. If it could be stored, this heat could be a resource. South shading strategies also seemed appropriate to consider.

Second, the team investigated the differences in temperature that were likely to occur above and below the plenum given the calculations above. Although only estimated, it was presumed that the difference in temperature (ΔT) would be too low to use the modestly heated room air from the south zone to heat-up the building mass. On the other hand, the team presumed that pre-cooled mass could probably be used to cool supply air to the south zone thus replacing some costly air conditioning. It was also presumed that heated south air could be used either to warm the north zone directly or as pre-heated supply air which could be "bumped-up" to the necessary temperature with the gas heating system.

Third, the team used the computer thermal analysis to check the potential for pre-cooling the mass using outside air in the Denver climate. Based on a high number of air changes (15 air changes per hour in the plenum), the mass temperature would range from a low of 36°F. in winter to a summer peak of 72°F in summer. This analysis suggested that at all times of the year the building mass would be available as a heat sink, although it would be least available in summer.

With these basic strategies and analyses in hand, the team turned to the task of trying to design a building.

The Solution

As shown on the building Floor Plan (Figure 46), the team settled on a building 50' x 110' -- 10' longer than necessary to meet program requirements in order to have room for stairs and elevators. These dimensions seemed to be a reasonable balance between a narrow building desired for daylighting design and increased HVAC run costs -- although the issue did not get serious cost analysis. Pre-cast concrete double-T's run the full 50' width of the building (4'o.c.) and rest on pre-cast beams in the north and south walls.

All glass is on the north and south of the building. South glass is expanded to the maximum that can be fit between structural members. North glass is held to the minimum possible for both view and daylighting.

Note that the main HVAC distribution channels (running below the double-T's) are offset to the north. This accomplishes a number of things. First, it makes possible a central circulation spine (should one be desired) in the final configuration of internal spaces. Second, a clear span is provided to the south zone so daylight can more easily be reflected into the central part of the building from the south. Third, the long run to the south creates a longer duct to the south for greater potential pre-cooling of supply air.

A combination elevation and section (Figure 47), illustrates many of the key features of the solution. Starting at the right (or south), the large amount of south glass is shown (6' x 6-1/2' panels). Above each window 6' permanent awnings (with a reflective upper surface) are used both to reflect light into the clerestory above and to shade south glass below. The clerestory is 2' high and runs the length of the building in front of the double-T's. Light is reflected into channels created by the double-T's and is used to illuminate much of the south and central zones below. This solution is highly controversial with opponents suggesting that significant penetration of light will occur only under optimum conditions.

Private offices are located on the south wall and are supplied with conditioned air through insulated round ducts installed in the channels created by the double-T's. Electrical supply cables are also in this space.

Main supply and return ducts are shown located in a central corridor. In this area, the ducts reduce ceiling height from 9' to 7'4". Finally, the less "punctured" north wall is shown at the far left.

As shown in detail, (Figure 48) the double-T's serve as structure, HVAC channel, and light troughs. Across the ceiling, two light troughs alternate with a single HVAC and power channel. The light troughs are covered with prismatic light diffusers at the bottom. HVAC channels are covered with sheet rock. Light troughs are connected directly to the outside for dumping excess heat-of-lights directly to the outside. HVAC channels carry insulated ducts only where required to supply south offices.

Combining structure and plenum reduces floor-to-floor height two feet, while maintaining a nine foot ceiling height. Although resulting savings in building skin and HVAC runs are modest in a 2-story building, in a multi-story building a two foot savings per floor would allow six stories to be built in the space typically used by five.

The proposed HVAC system is the most ambitious -- and least certain -- part of the team's solution. Figure 49 presents a simple schematic diagram of two operating modes for the proposed system. The upper diagram illustrates nighttime summer cooling. In this case, cool night air is pulled into the building, drawn through the concrete tee ducts into the building, and exhausted through the main return ducts. This mode cools the unoccupied office spaces and pre-cools the building mass.

FIGURE 46

INTEGRATED PASSIVE COOLING SYSTEMS

CONCEPT #1

FLOOR PLAN

FIGURE 47
INTEGRATED PASSIVE COOLING SYSTEMS

CONCEPT #1

FIGURE 48

INTEGRATED PASSIVE COOLING SYSTEMS

CONCEPT #1

DOUBLE-T CONFIGURATION

FIGURE 49

INTEGRATED PASSIVE COOLING SYSTEMS
CONCEPT #1

OPERATION CYCLES

During summer days (not shown), light troughs are vented directly to the outside to cut heat gains from lights. Massive HVAC "ducts" are used to cool supply air, thus reducing the load on air conditioning equipment. It is hoped that overall heat build-up in the space is thus delayed until unoccupied hours when cooling can be accomplished either by ventilation or mechanical cooling.

In the lower diagram (winter overheat situation), air flows follow two separate loops. Referring to the diagram, a portion of the warmed return air (1) is supplied into the exposed double tee ducts (2) and is thus cooled (3) before being supplied into the overheating south zone of the building (4). Mixing (5) cools the overheating space and warms the return air. A portion of this return air (6) is returned to the boiler or fan coil where it is heated and sent via insulated ducts (7) to the north zone of the building (8). Mixing heats the north zone (9) and cools the return air (10) which returns to the central air handlers and is exhausted. If room temperature air could be counted on to heat the building mass, the north duct (7) would not be necessary. Heat from solar gains could be carried via room air and stored in the concrete plenum -- a truly passive solution. Unfortunately, low temperature differences (ΔT) are likely to make this solution impossible.

In the early morning start-up phase the cooled mass of the building is isolated from the occupied spaces, and gas heat is used to make offices comfortable until solar and internal loads supply enough heat to replace mechanical heating. When overheating begins, the building mass is used in the manner described above to reduce or shift loads.

In effect, we have created a very "light" building inside a very massive or "heavy" building. When quick heating is required the light building is isolated from the heavy one. When mass is useful to shift cooling loads, the light building is then connected to the heavy building via the HVAC system. The net result is a building which uses less heat during the morning start-up and requires less cooling during peak utility rate hours.

Unresolved Issues

Although the team decided early in the analysis that temperature differences between the occupied zones and the massive plenum were not great enough to use room air to actually "heat-up" the plenum space for later use as a heat source, the team did presume that enough heat transfer would take place in the plenum so that the mass of the building could be used to pre-cool supply air to overheating spaces. This assumption, unfortunately, cannot be substantiated based on research to date. Lab simulations, to date, have directly coupled mass and occupied spaces so that heat exchanges can occur by convection alone and rely little on air flow rates over the mass. It is simply not clear whether or not room temperature air can be cooled sufficiently, while in a concrete plenum (even at high turbulence), to make it useful as cooled supply air.

It was the judgment of the team that investigations into the basic physics of the type of low heat transfer in confined spaces proposed here be given the highest priority by the research community as they are the key to building mass plus ventilation strategies in speculative buildings. If pre-cooling is possible as proposed, cooling loads could be shifted in such a way as to eliminate mechanical cooling altogether in many climates where mechanical cooling is now routinely required. Attendant savings in both operating costs and first costs are obvious.

In addition to the key unresolved issue of thermodynamics, several other interesting issues remain. For example, the reflective awnings appear likely to become major snow collectors in northern climates. What this will do structurally as well as to the proposed daylighting resource was not specified.

Attaching alternate rows of sheet rock and plastic prisms to the bottoms of pre-cast concrete tees was not adequately resolved. The potential for movement in the tees due to variations in temperature could be a major problem.

Direct exhaust of the light troughs could create problems of dirt and dust in the light troughs. The combination of clerestory, double-T's and dampers could prove to be expensive details.

Finally, a cost effective skin for the north and south faces of the building needs to be developed. A proposed curtain wall, which simply left the concrete structure exposed behind glass, proved vastly too expensive. Some use of low cost metal walls similar to the base case was presumed for cost purposes but details of how to connect metal and glass to the more massive structure have yet to be worked out.

INTEGRATED PASSIVE COOLING SYSTEMS

CONCEPT #2

Understanding the Problem

The team saw the problem clearly as one of passive system integration -- much different from previous workshop problems which were all single-focused in applying a single technology. In the team's view, this design problem was much more complex:

- Multiple stories always result in more complex architectural design problems:
 - Vertical transport and access becomes a primary physical problem, and
 - Energy system design and integration are also necessarily more complex because no single building element (such as the roof) is accessible to all areas.

The full "menu" of technology options also complicated choice and selection. For example, the team asked:

- Should daylight, if used, be employed in part or all of the building? Should it be beam or diffuse? Both?
 - Should ventilative cooling be used with or without mass? At night only?
 - Could the high potential of evaporative cooling in the Denver climate outweigh higher fixed costs of primary equipment and storage? Justified for use in a small building? If no, how should direct or indirect/direct systems be used?
 - All technologies have potential worth investigating, but how can they be made to work together well?
- . The specific utility rate schedule added yet another constraint in this design problem. The schedule suggests a need to reduce both electricity consumption and demand.

The team agreed early about the importance of the utility rate structure and focused on the dominance of electricity consumption and demand charges -- 80% of total utility costs. They decided to focus on lighting and cooling (electricity cost reductions) rather than heating, even though heating energy use in Denver is over 30% of the total use for the base case building. Still faced with so many options, the team wanted to narrow choices as quickly as possible.

Process and Key Themes

- . The team reviewed previous workshop results:
- Solutions for distributed beam daylight and mass with night ventilation all involved primary modification of roof systems for cost effective solutions. Previously proposed solutions are reduced by at least half in a two-story building.
 - Mass costs extra dollars.
 - Systems (daylighting, evaporation, and HVAC) typically cost extra dollars.
- . Analysis of the problem statement suggested the need for more program information:
- Equipment energy requirements and heat output are increasingly important in office design. The number of minicomputers and word processing stations and their potential effect on comfort requirements had to be decided.
 - Architectural image was also important. Could offices be open space or private?

Client opted for mix of open and private offices, including 20 word processing stations and a reduced ambient lighting level in the area of their use.

- . The team then set goals for technology performance. They wanted to reduce total energy cost by \$.50/sq.ft.-yr -- a 50% decrease in total utility costs. According to the team, this goal would:
 - make possible an increase in building first-cost
 - be sufficient to cause the owner to pay attention and seriously consider the importance of energy conscious alternatives.
- . Based on this review and analysis, the team selected the following directions for their investigation:
 - Cooling, a big factor in both electrical consumption and demand, would be the team's primary focus. Ventilative and/or evaporative cooling may be able to eliminate the mechanical chiller. With evaporative cooling, the team felt they would be able to go to light construction (dry processes), which they believed would reduce building first cost.
 - Lighting, the other half of the electrical consumption and demand problem, required a combination of approaches:
 - .. Use beam illumination on the second floor: probably in the core and north zone using either a clerestory or distributed light wells.
 - .. Use diffuse illumination on the first floor: by limiting building depth and employing reflective light shelves to throw light into the interior of the building.

THE SOLUTION

The team focused initially on the mechanical system requirements and selected direct/indirect evaporative cooling with water storage for primary investigation.

- . The practical dynamics of the cooling cycle were investigated to ensure that the indirect/direct evaporative cycle would achieve desired comfort conditions within the building.
- Figure 50 displays a schematic representation of the psychrometric path followed by the cycle.

In the indirect half of the cycle, at outside conditions of 88° DB and 64° WB, (the 95% design condition for Denver) outside air is introduced to the indirect evaporative cooling coil. Sensible cooling lowers the air temperature to 73 DB and 59° WB, still not sufficiently "cold" to maintain comfort within the space. The air is then passed through a water spray (water taken from storage) in the direct half of the cycle. The spray provides a moderate amount of dehumidification because the water sprayed is colder than the dew point temperature of the air being conditioned. The wet bulb temperature depresses slightly as the conditioned air saturates. From this point, at 59° DB and 58° WB the supply air is introduced to the space. Within the space the supply air picks up both heat and moisture up to inside design conditions of 78° DB and 65° WB. One important advantage of the process is that 100% outside air is delivered during the cooling process. This suggests that the moisture gain in the space could have been drastically reduced by pressurizing the building and eliminating building infiltration. This would have allowed higher supply air delivery temperatures rather than the 59F air provided. This fact has important significance when applying this concept to more humid climates.

Once satisfied that the process would achieve the desired results, the team turned to the physical configuration of the mechanical systems, also presented schematically in Figure 50. Important considerations were:

- Size and Operating Temperature of the Water Storage Tank: a 20,000 gallon tank (approximately 20'x10'x12') provided sufficient storage if cooled by evaporation at night to 45-48° F. However, the team found that location, configuration, and material composition of the tank were much more important than size to the building design because of cost.
- Cooling Tower Size: a key decision that could only be "ball-parked" (in the time allowed) for the solution. It was estimated that the cooling cycle could eliminate mechanical chillers and reduce peak demand by 20-25kW, even with the additional pumps and other components needed for the evaporative system. It was proposed that a 10 ton tower might be sufficient for the system, but 20 tons was selected to be conservative.

Architectural, structural and cost-based decisions followed development of the mechanical system concept:

The architectural solution, Figure 51, was driven largely by daylighting requirements. In order to employ diffuse daylight (i.e. vertical wall aperture) throughout the first floor, the depth of the building had to be limited. The team looked at 50' and then 45' depths. The 45' option allowed less expensive structure (see below). Penetration of daylight then became the issue. Through-the-wall light shelves were selected to increase reflective surface area and

FIGURE 50

INTEGRATED PASSIVE COOLING SYSTEMS
CONCEPT #2

Direct/Indirect Evaporative Cooling Process

HVAC System Schematic

FIGURE 51

INTEGRATED PASSIVE COOLING SYSTEMS

CONCEPT #2

FIGURE 52

INTEGRATED PASSIVE COOLING SYSTEMS
CONCEPT #2

Building Section

South Wall Section

shade view glass simultaneously. The shelves, together with blinds on lower glass area, were used to reduce glare problems within the space.

- . The daylight solution required increased ceiling height for perimeter spaces (Figure 52). HVAC duct work was therefore arranged along the central spine of the building with registers on interior walls of the perimeter zones.
- . Beam daylight in the second floor core zone was introduced through a narrow clerestory band, conforming to the laboratories' 2-3% solution requirement discussed as part of the beam daylighting workshop solutions.
- . The structural solution was driven by a least cost approach. The building could be very light (no mass required for energy reasons). The 12.5' north and south bay depth permitted private offices and the use of extremely light-weight structure, while the 20' spine was generous enough for an open office planning approach, satisfying the client's requirement for both.
- . Once the general outline of the building was agreed upon, several alternative details were selected on the basis of cost consequences:
 - The team initially wanted a stainless steel storage tank but thought it too expensive. A site fabricated alternative beneath the slab was investigated but found to be even more expensive than the steel. Finally it was decided to bring a stainless steel tank away from the structure.
 - Significant first-cost savings were envisioned by eliminating the chiller, but no off-the-shelf direct/indirect evaporative cooler was available. It would have to be assembled by a manufacturer from available components at a significant cost increase. The net result was no significant savings in first cost for the system.

Unresolved Issues

Though the "integration" problem had been solved, the team was unsure about the solution on several counts:

- . Elimination of the Mechanical Chillers -- there was substantial concern and discussion about what happens under extraordinary climate conditions?
- . Fine Tuning, Sizing of Mechanical System Components -- more time and information were needed to do an adequate analysis. Many decisions were necessarily "ball-parked" and might change under more thorough scrutiny.

- . Through-the-Wall Light Shelves -- Questions regarding structural integrity, installation and maintenance, and cost were raised.
- . Lighting Controls -- the team had no practical experience of fully tested and accepted off-the-shelf, inexpensive and highly reliable systems.

COMPARISON OF CONCEPTS FOR INTEGRATED PASSIVE COOLING SYSTEMS

- . A 2-story base case was not prepared for the workshops. Comparison to the 1-story base case is of limited value because variations in cost due to the 2-story design (for example, added costs for elevators, plumbing and duct work vs reduced costs for slab and roof), tend to mask the costs of applying the passive cooling technologies under study. Multi-story applications and integrated solutions require further analysis to achieve "reasonable" cost comparisons.
- . Both solutions exceed the 10,000 sq.ft. program specification in order to add room for stairs and elevators.
- . Concept #1 is the least costly alternative because cost increases due to added mass (pursuing the mass with night ventilation strategy) are offset by HVAC system cost reductions. Daylighting is achieved at virtually no cost through building redesign (going to a long narrow building which can be easily daylit from north and south with only modestly increased glass area).
- . Concept #2 is modestly more costly because the added cost of significantly more glazing (used in the daylighting strategy) and the evaporative cooling system, could not be completely offset by savings throughout the rest of the design (especially in the light structural system and reduced roof costs).
- . It is significant that an evaporative cooling system was designed with approaches cost effectiveness in such a small building.
- . A careful reading of the building code allowed Concept #2 to be drafted without an elevator. If this were a public building in which an elevator is required for handicapped areas, the estimated cost would increase \$3.00/sq.ft. or more.

FIGURE 53

COST COMPARISON: INTEGRATED PASSIVE COOLING SYSTEMS

CONCEPTS #1 & #2

(OPEN SHOP NOT INCLUDING SITE WORK)

SYSTEM DESCRIPTION	BASE CASE	CONCEPT #1		CONCEPT #2	
	SYSTEM COSTS \$/SF	COST DIFF. \$/SF	REASON	COST DIFF. \$/SF	REASON
		(11,000sf)		(10,000sf)	
GENERAL REQUIREMENTS @ 10%	4.16	+0.26		+0.37	
FOUNDATIONS	0.72	+0.32	•added linear footings	+0.04	•smaller pads
SLAB ON GRADE	1.31	-0.65	•size of slab reduced	-0.65	•size of slab reduced
SUPERSTRUCTURE	5.03	+3.91	•precast beams, columns, double-T's	-0.29	•lighter elements, very narrow perimeter bay size
ROOFING	4.41	-2.19	•size of roof reduced	-2.05	•size of roof reduced
EXTERIOR WALLS	2.78	+2.87	•size, curtain wall framing, reflector shades	+0.44	•added light shelf, deleted facing trim, added mansard
EXTERIOR GLAZED OPENING	3.66	--		+4.41	•storefront assemblies, large glass increase, clerestory
INTERIOR PARTITIONS	2.32	-0.70	•reduced interior partitions, no glass block	-0.39	•reduced amount, eliminated glass block
DOORS	1.37	--	•added 4 metal doors	-0.11	•due to building size difference
CEILING FINISHES	1.13	-0.08	•due to building size difference	+0.29	•drywall around mechanical bulkheads
FLOOR FINISHES	1.63	-0.15	•due to building size difference	+0.02	•ceramic tile in added bath
SPECIALTIES	0.13	+0.07	•added bath	+0.07	•added bath
EQUIPMENT	0.15	--			
CONVEYING	--	+3.18	•elevator		
PLUMBING	1.68	+0.50	•2nd floor bathrooms	+0.54	•2nd floor bathrooms
HEAT, VENTILATION & AIR CONDITIONING	8.23	-3.85	•eliminated chiller, ductwork, no VAV	+1.89	•JHP return air fan, reduced ductwork
ELECTRICAL	7.10	-0.65	•used roundducts, less temp. control	-0.53	•added airhandling & evap. cooling equipment, cooling tower
			•due to building size difference		•due to building size difference
TOTAL COST	45.81	+2.84		+4.05	
GENERAL CONTRACTOR'S OVERHEAD & PROFIT @ 10%	4.58	+ .28		+ .41	
SUBTOTAL	50.39	+3.12		+4.46	
BOND @ 1%	0.50	+ .03		+ .04	
TOTAL ESTIMATED CONSTRUCTION COST - OPEN SHOP	50.89	+3.15 54.04		+4.50 55.39	

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CHAPTER VII

IMPLICATIONS FOR ECONOMICS OF PASSIVE COOLING SYSTEMS

System economics are important to both building designers and government energy research managers. System first cost must be weighed against potential savings by every designer who proposes an energy efficient solution to a client. The lower the first cost and/or the greater the annual energy savings, the easier it will be to gain acceptance of each new passive cooling technology. The summation of all of these applications will define the eventual impact of passive cooling technologies and the net reduction in the nation's energy bill.

The design solutions presented in Chapters III through VI give an indication of potential first-cost of each passive solar cooling technology considered. First cost increases (and percentages) are summarized in Figure 54.

Climate, building use, configuration, and utility rate are the primary determinants of potential energy cost savings of each passive cooling technology. In the Cooling Assessment, potential energy cost savings for each technology were computed assuming a single utility rate schedule applied to potential energy savings in each of 11 different climates. A summary of the minimum and maximum possible savings are summarized in Figure 55.

Research, since, has shown that within a given climate, a wide variety of energy bills may result, depending on the local utility rate structure that applies. For example, a survey of typical bills revealed that for annual energy consumption in the base case, utility costs could range anywhere from \$.50/sq.ft.-yr to nearly \$2.00/sq.ft.-yr across the U.S. If these findings were to be applied to the findings in the Cooling Assessment, the range of potential minimum and maximum savings would increase.

When increases in first cost are divided by annual savings, the result is simple payback. Although a crude financial measure, simple payback is commonly used and is adequate for our simple comparison across technologies. The minimum and maximum payback for each technology studied is summarized in Figure 56.

Based on a review of Figure 56, it appears that the priorities assigned to the passive cooling technologies in the Cooling Assessment should not be changed for small buildings. For natural lighting, the potential for little or no first cost increase combined with the highest annual savings confirm its first priority. Modest first cost increases for mass with night ventilation strategies (with somewhat less projected annual cost savings) confirm a second priority. Low first cost increases and modest savings give evaporative cooling strategies an equal second priority.

FIGURE 54

SUMMARY OF
PASSIVE SOLAR COOLING SYSTEMS CONCEPT
INCREMENTAL FIRST-COSTS

(OPEN SHOP NOT INCLUDING SITE WORK)

BASE CASE BUILDING:
(1-story; 10,000 sq.ft.)

\$50.89/Sq.Ft.

Single Story - Single Technology Applications

Exam Daylighting

- Roof Solution Only
- By Building Redesign

Mass With Night Ventilation

Evaporative Cooling System

CONCEPT #1			CONCEPT #2		
\$/SF	Δ \$	Δ %	\$/SF	Δ \$	Δ %
\$53.82	+\$2.93	+6%	\$54.21	+\$3.32	+7%
\$48.39	-\$2.50	-5%	\$49.89	-\$1.00	-2%
\$51.33	+\$.44	+1%	\$51.47	+\$.58	+1%
\$51.79	+\$.90	+2%			

Two Story - Integrated Technology Applications

Integrated Passive Cooling Systems
(2-story¹; 10,000 sq.ft.)

\$54.04	+\$3.15	+6%	\$55.39	+\$4.50	+8%
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- 1) The two-story solutions are not truly comparable to the one-story base case. Estimates of a two-story base case run from 15% over the one-story base case (\$55 - \$60), for comparable quality construction.

FIGURE 55
SUMMARY OF
PASSIVE SOLAR COOLING SYSTEM CONCEPT

ENERGY COST SAVINGS

(BASED ON BLAST/DOE-2 SIMULATIONS AND
TYPICAL UTILITY COSTS IN 11 U.S. CLIMATES)

	LOWEST REPORTED SAVINGS (\$/SF/YR)	HIGHEST REPORTED SAVINGS (\$/SF/YR)
NATURAL LIGHTING	\$.10	\$.53
MASS WITH NIGHT VENTILATION	\$.02	\$.23
EVAPORATIVE COOLING	\$.01	\$.09

FIGURE 56

SUMMARY OF
PASSIVE SOLAR COOLING SYSTEM CONCEPTS

COST EFFECTIVENESS AS MEASURED BY SIMPLE PAYBACK IN SMALL BUILDINGS

	CONCEPT NUMBER	FIRST COST INCREASE \$ ¹ /SF	UTILITY COST SAVINGS ²		YEARS TO SIMPLE PAYBACK	
			MIN	MAX	MIN	MAX
• NATURAL LIGHTING: - Roof Only - Building Redesign	1	+2.93	.10	.53	6	30
	2	+3.32	.10	.53	6	33
	1	-2.50	.10	.53	0	0
	2	-1.00	.10	.53	0	0
	1	+ .44	.01	.12	4	40
	2	+ .58	.02	.23	3	30
• EVAPORATIVE COOLING	1	+ .90	.01	.09	10	90

1) From Figure 54

2) From Figure 55

In considering the cost effectiveness of any conservation option, it is important for the building designer to be aware of both utility structure at the site and of the likely impact of a passive solar cooling strategy on that pricing structure. For example, energy saving strategies in general reduce energy use (and energy costs) at the margin. If marginal utility costs are high, a strategy will be significantly more cost effective than if marginal costs are low. (The marginal cost of electricity rates is indicated by how much the cost per kWh of electricity falls as consumption increases.)

Passive cooling strategies also affect components of a utility bill differently. For example, mass with night ventilation tends to reduce peak demand more significantly, while traditional evaporative cooling solutions tend to reduce energy consumption. Daylighting strategies have a significant effect on both consumption and demand. The attractiveness of a particular passive strategy, and its underlying economic viability, will depend in large measure on selecting the right strategy for the job -- that is, the one most effective in reducing the most costly components of the anticipated building energy bill. As integrated solutions are studied further, it will be important to track the net impact on both consumption and demand so that designers can advise clients with confidence about the likely impact of combined passive solar cooling strategies on their annual utility bills.

CHAPTER VIII

RECOMMENDATIONS FOR FUTURE RESEARCH OF PASSIVE COOLING TECHNOLOGIES

Throughout the project, discussions were held both formally and informally about research work done to date and useful work that could be done in the future. In spite of expected, and sometimes heated, differences of opinion about the details of such work, building professionals at the design workshops unanimously commended the laboratories and the federal government for opening up the government research process to practicing professionals for their input. It was hoped that in the future, infrequent opportunities like the one provided by the workshops could be increased.

In addition to encouraging closer interaction between the research community and practicing design professionals, several observations and specific research questions emerged as a result of this collaborative effort to develop passive cooling system concepts. The topics recommended for future research relate to both specific passive technologies and a more general line of inquiry concerning building energy mechanics. The designers were very excited about the potential of the technologies, but very reluctant to attempt to sell the untested and unverified ideas to clients. The risk is far too high for the design team to experiment with, -- concepts that may result in discomfort or, in the worst circumstances, adversely affect the health, safety, and welfare of occupants.

The following sections summarize the observations and recommendations for future research for each passive cooling technology.

I. Daylighting Systems

Of all passive technologies addressed in this work, daylighting is closest to adoption by the professionals:

- . Practicing designers were very receptive to the technology, though clients are probably less so.
- . Techniques using diffuse skylight are receiving considerable current attention within the design community.
- . Systems using both diffuse skylight and beam sunlight are a relatively new area of inquiry and are not as well understood by the professionals. Most questions posed during this work relate to application of techniques rather than basic research.

Issues which merit further research include:

- . Lightwell geometry and its effect on distribution and quality of lighting
- . Control of beam sunlight within the building
- . Interaction with the artificial light system (interactive/dynamic system controls)
- . Greater understanding of user requirements, habits and comfort limits
- . Design tool development:
 - Sensitivity studies to test the preliminary "rule-of-thumb" of 2.5% roof glazing to floor area.
 - Physical as well as mathematical modeling procedures and measurement techniques
- . Concepts for using beam sunlight in large office buildings (multi-story) and other building types.

2. Mass with Night Ventilation Systems

In general, the acceptance of cooling strategies which take advantage of building mass is not as widespread as the acceptance of daylighting. Although this technology takes advantage of common building elements and is potentially capable of reducing cooling costs (for both electric consumption and demand), important issues remain unresolved:

- . Fundamental energy mechanics have not been resolved.
- . Reliable simulations algorithms for convective transfer to mass do not exist
- . Potential added complexity and cost of adding this strategy to current building practice has not been quantified.

It was the general consensus of the workshop participants that important basic research still needs to be done. Issues to be addressed include:

- . Mass charging and discharging - What is really required in terms of mass density, heat capacity, surface area? What are the tradeoffs between each?
- . Low temperature heat transfer coefficients -- Charging and discharging of building mass is not well understood for passive heating techniques - it is significantly less well understood for cooling applications. Researchers are currently investigating the validity of accepted heat transfer coefficients. This research, together with the analyses used to develop the assessment of cooling potential for night ventilation suggest, but do not prove, that low

temperature transfer is possible. Until the underlying assumptions regarding this have been proven, the professionals cannot risk acceptance of the results.

- . Configuration options and coupling to the space - Comfort control is a vital issue in the design of commercial buildings, with much more rigid limits than residential design. A major obstacle to acceptance of purely passive technologies has been their tendency to defy sensitive control. As a result, practitioners indicated a preference for indirect approaches -- i.e., separating the cooling resource (mass) from the occupied space. Specific issues of concern are how best to connect indirect strategies to occupied spaces or, alternatively, how to apply strategies directly -- with confidence.
- . Interaction with mechanical systems -- Are there opportunities for "piggyback" systems? Must operation sequences be separated? What are the effects of passive system or mechanical system efficiency?

3. Evaporative Cooling Systems

Evaporative Cooling concepts have been well known for decades. There is new and increasing interest in this technology because it not only offers a low cost alternative for reducing electric energy consumption, but also offers the potential for significantly reducing electric demand charges. There continues to be serious doubt, however, about marketplace economics and acceptance. Research areas suggested include:

- . Ways to extend performance to humid climates
- . Quantitative assessment (validation) of demand shedding potential - Does it occur at the times and in the amounts needed to garner big cost savings?
- . Lower cost control and storage strategies to increase likely applications in small buildings.
- . Potential economics of scale in manufactured systems to reduce costs (especially for smaller applications)
- . Application to large buildings.
- . Effects of equipment performance characteristics.

4. Integrated Passive Cooling Technologies

There was general disappointment among all workshop participants at the lack of research to date into integrated systems. It was generally agreed that:

- . Integrated solutions are expected to provide greater energy savings than any single passive cooling technology application.
- . Energy savings from integrated solutions are unique to the integration and are not strictly additive. (The impact will generally be less than the sum of the affects of the strategies applied.)

- . Integrated solutions are much more in keeping with the design process than are single technology applications.
- . Passive strategies -- at least in early applications -- will have to be integrated with common HVAC systems.

Although relatively little workshop time was allocated to investigating potential integrated passive cooling technologies, the concepts developed suggest some useful lines of inquiry:

- . Natural lighting solutions are so attractive and potential energy savings so great that integration with all other technologies should be investigated.
- . Integration of evaporative cooling systems with currently available HVAC systems appears possible with only modest problems. The potential for early acceptance into existing technology suggests a high priority on the work.
- . Integration of mass and HVAC systems in the plenum is likely to significantly enhance acceptance of mass/ventilation strategies. Investigation of the thermodynamics of heat exchange to and from mass should receive high priority because of potentially wide applicability.
- . Integration of evaporative cooling and mass with night ventilation systems has yet to be attempted. Theoretical work should be done as soon as possible to see if this integration is reasonable.