THERMAL STORAGE WITH CONVENTIONAL COOLING SYSTEMS

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ABSTRACT
The newly opened Pennsylvania Convention Center in Philadelphia, PA; Exxon's Computer Facility at Florham Park, NJ; The Center Square Building in Philadelphia, are success stories for demand shifting through thermal storage. These buildings employ a simple thermal energy storage system that already exists in almost every structure - concrete.

Thermal storage calculations simulate sub-cooling of a building's structure during unoccupied times. During occupied times, the sub-cooled concrete reduces peak cooling demand, thereby lowering demand and saving money. In addition, significant savings are possible in the first cost of chilled water equipment, and the smaller chillers run at peak capacity and efficiency during a greater portion of their run time. The building, controlled by an Energy Management and Control System (EMCS), "learns" from past experience how to run the building efficiently. The result is an optimized balance between energy cost and comfort.

INTRODUCTION
The Pennsylvania Convention Center in Philadelphia, PA; Exxon's Computer Facility at Florham Park, NJ; The Center Square Building in Philadelphia -- all of these buildings have two things in common:

- Installed cooling capacity is dramatically less than the peak cooling load.
- All three buildings are able to satisfy peak cooling requirements.

These buildings illustrate different facets of a unique method of building design and operation - use of building structural mass to reduce peak cooling loads.

The use of structural mass for thermal storage has been applied successfully for many years in Scandinavia. In an effort to reduce demand on electric power plants in the dead of winter, an integrated building system engineering design manual was developed to simplify the integration of HVAC and structure while maximizing the heat storage (peak reduction). This system is referred to as Termadek (a Swedish development) and essentially consists of a concrete slab with hollow cores that serve as branch distribution ducts (see *Figure 1*). These core "ducts" not only provide instantaneous heating at peak periods, and draft reduction at windows - they also store or retrieve heat from the structure by virtue of the direct contact between the concrete and the supply air.

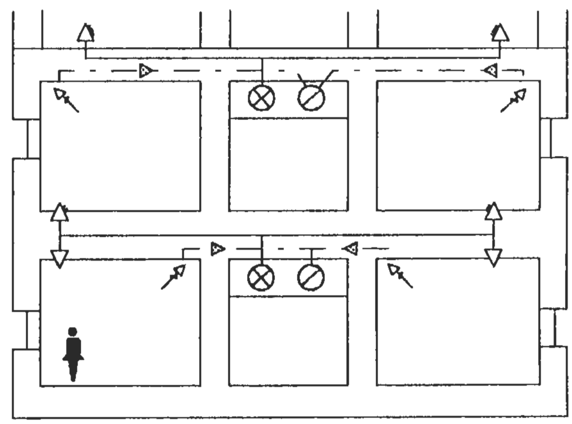

Figure 1: Termadek System

The thermal mass storage concept has been marketed widely in the United States for cooling in active systems (ice storage, and water storage). Although some of these systems offer a larger "cooling effect storage" capacity than building structural systems (since ice changes phase) these systems have a significant drawback in that they require the purchase of additional equipment.

Every structure, existing or planned has a built in thermal mass storage system - the structural components, furnishings, and stored items such as paper. *Figure 2* illustrates the relative thermal capacitance of two typical buildings: case one is a single zone building (2), case two is one floor of a typical office building (3).

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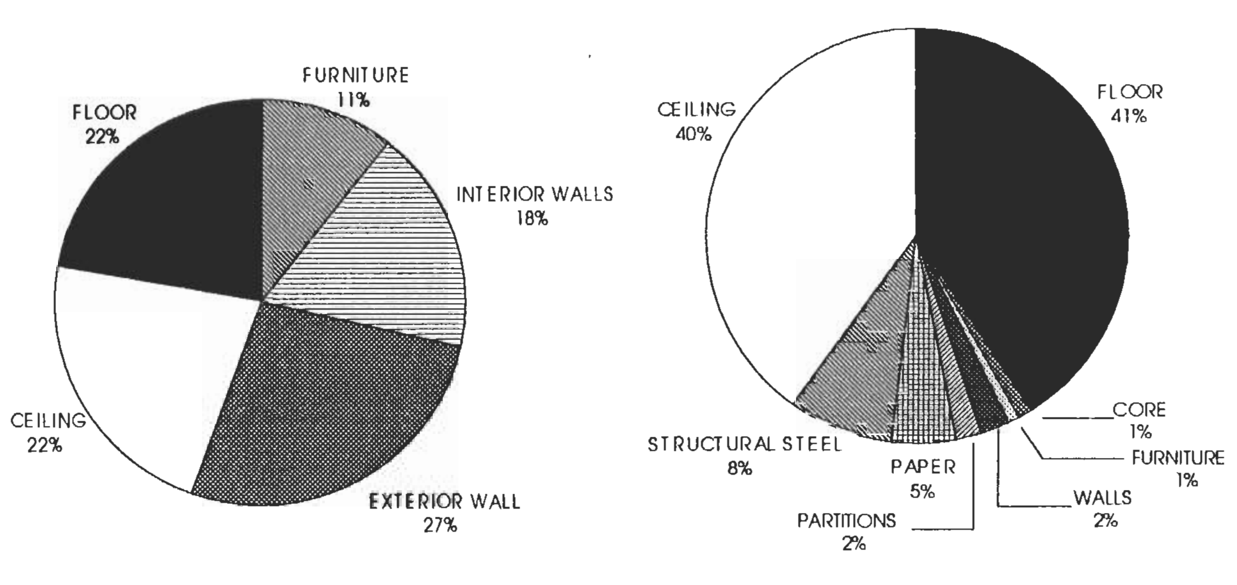


Case 1: Single Zone Building

Case 2: Single Floor of Typical Office Building

Figure 2: Thermal Capacitance of 2 Buildings

The purpose of this paper is twofold: encourage the application of this technology where appropriate, and call for research to standardize "design procedures" - not to present new research. In the next section it will become apparent that existing research has exhausted major portions of this design approach, and that there is sufficient impetus to begin the application of this design approach immediately.

LITERATURE REVIEW

Research and empirical studies have proven that properly managed passive, structural mass storage systems do not require the purchase of additional system components (other than a good Energy Management and Control System (EMCS) - which would be required for any ice or water storage system) yet they have similar benefits to an active system. In fact a system with a smaller capacity than would normally required by a conventional load calculation, can adequately meet the needs of many types of buildings.

Recently several studies have been performed to develop a database of information to apply this "flywheel" concept to peak cooling load reduction. Although each research project sheds new light on different areas of this design/control method, each project reaches some similar conclusions:

Braun states the first conclusion succinctly in the abstract of his work (1) - " . . . energy costs and peak electrical use can be significantly reduced through optimal control of the intrinsic thermal storage within building structures." Naturally, as the cooling peak is reduced, plant capacities and first costs are also reduced.

The investigations described below explore many of the factors that influence the magnitude of potential savings.

Elements of Thermal Storage

The ability of an engineer and the degree of success in utilizing thermal storage is limited or enhanced by one or all of the following factors:

- Comfort Limits
- Ambient Conditions
- Utility Rate Structures
- Occupancy Schedules
- Building Construction
- Cooling Plant Operating Characteristics

The challenge presented to the engineer is to utilize all of these as building blocks of an optimized comfort control system.

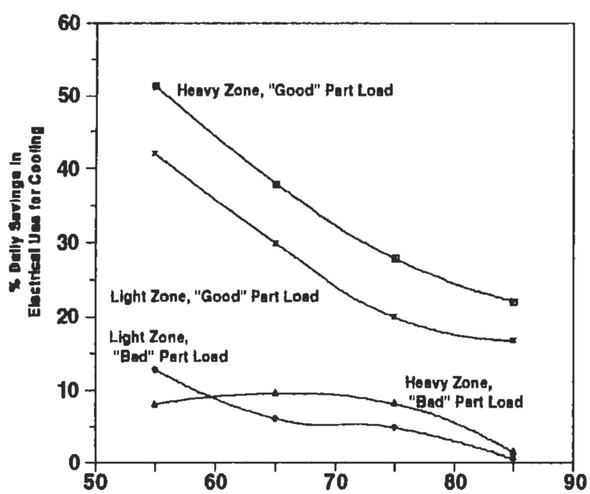
Comfort Limits

Although the goal of this discussion is to promote the reduction of energy and first costs, the primary concern remains comfort (of people or equipment). With this in mind, Andresen and Brandemuehl (2) cite increasing the throttling range as a very effective tool for peak reduction. By increasing the throttling range from 1.8° F to 7.2° F, peak cooling load reduces 10%.

In addition to the temperature the designer must be cognizant of humidity levels. The designer must be careful not to drive interior space surface temperatures below the dew point of outdoor air or indoor ambient air at comfort conditions. Condensation on surfaces could prove disastrous for any facility.

Ambient Conditions

The intelligent use of "free cooling" in conjunction with precooling of a building's structure can result in operating costs of approximately 35% of that of standard "night set back" control. If a chiller is utilized to precool the structure, significantly higher savings- up to 50% per day - are possible (see *Figure 3*). Energy consumption savings increase as the ambient temperature drops. This assumes that there are no time of day rates. If the building is served by a power company that charges for time of day or demand usage, savings will increase (1).

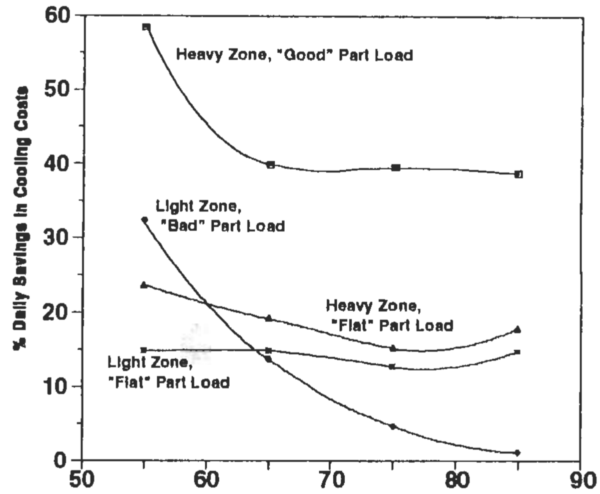


Daily energy cost savings for optimal vs. night setback control (no time-of-day rates, clearness index 0.6)

Figure 3: Savings Without Time of Day Rates

Utility Rate Structures

Pre-cooling a building that is served by a power company that charges for demand or time of day usage can reduce cooling costs by almost 60% (1) (see *Figure 4*).



Daily Energy Cost Savings for optimal vs. night setback control (on-peak period: 8 a.m. - 8 p.m., 2-to-1 on-to off-peak rates, clearness index 0.6)

Figure 4: Savings With Time of Day Rates

Occupancy Schedules

Buildings that operate on a cyclical schedule (8 to 10 hours occupied, 16 to 14 hours unoccupied per day) provide an adequate "recharge" period required to precool the structure for the following day. As a building's schedule approaches 24 hour occupancy, storage capacity is reduced, and thus savings diminish.

Building Construction

The physical characteristics of a building's construction is one area where the designer can have a significant impact on the amount of energy a building can store as well as the "reaction time" of the building to a load change.

As shown above in *Figure 2* the thermal capacity of the building is predictable based on the knowledge of the type of building components. In general the heavier the building, the heavier the construction, the higher the potential for cost savings (see *Figures 3 and 4*). Ruud et. al. have carried this concept to a second level by developing a prediction of a building's effective storage capacity which is primarily a function of the coupling of the storage medium with the supply air streams. This revised distribution of heat capacity is depicted in *Figure 5* (3). Comparison of *Figure 2 Case 2* with *Figure 5* indicates that materials and surfaces that come in direct contact with conditioned air utilize more of their intrinsic energy storage capacity than materials such as structural items that are traditionally hidden from conditioned air.

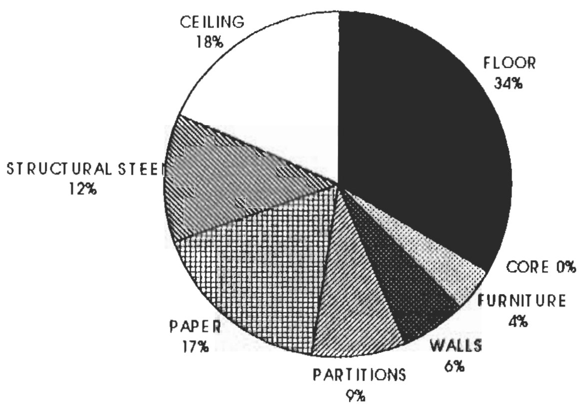


Figure 5 Effective Storage Capacity of Building Components

The concept of coupling an air stream with storage material is further explored in the comparison of plenum vs. ducted return models (2). By providing better coupling between the return air stream, ceiling lights, and the ceiling slab the engineer can further reduce cooling costs. Carpeting is a detriment to good coupling between supply air and the floor slab. Removing carpeting increases the potential energy storage of the floor by 13% (3).

Cooling Plant Operating Characteristics

Figure 3 and *Figure 4* above also illustrate the potential savings associated with choosing the right chiller for a particular building; although even a chiller with poor part-load performance characteristics can save energy, a chiller with good part load characteristics presents the potential for significantly higher energy cost savings.

All of the elements of thermal storage mentioned above impact the control algorithm utilized to reduce cooling costs. The control algorithm essentially must be able to predict and optimize the following control characteristics:

- minimum precool temperature
- system recharge time period

Today's EMCS's are capable of developing a database of past system performance and "learning" to optimize control of the building's cooling system. Once the system has established a database of system performance, the only essential input from the plant operator is the next day's expected dry bulb temperature, and occupancy schedule.

The elements of thermal storage information presented above is purposely left unrefined for various reasons. First, the facts presented are not easily generalized to all buildings. In fact, given the diversity of structures, the savings outlined above could be significantly different than those presented here. In addition none of the elements are difficult to quantify and relate to a specific building. This information is presented merely as a summary of existing research and as proof that the actual field studies that follow are founded on sound engineering judgment. The magnitudes of savings possible and the simplicity of the concept make good common sense without a great deal of mathematical support.

FIELD STUDIES

EXXON - FLORHAM PARK

Exxon's early 60's vintage office building in Florham Park, NJ was designed for minimal office systems power usage. The proliferation of personal computers in the workplace overwhelmed their existing HVAC system (see *Figure 6*). Indoor space temperatures reached well into the 90's. Since the facility operates on an 8 to 10 hour per day schedule, the design engineer recommended the building set point be lowered to 65° F during unoccupied hours to reduce the temperature of the building's structure and pre-cool it for the following day. The set point, chosen to avoid condensation in their computer equipment, provides enough cooling to shift about

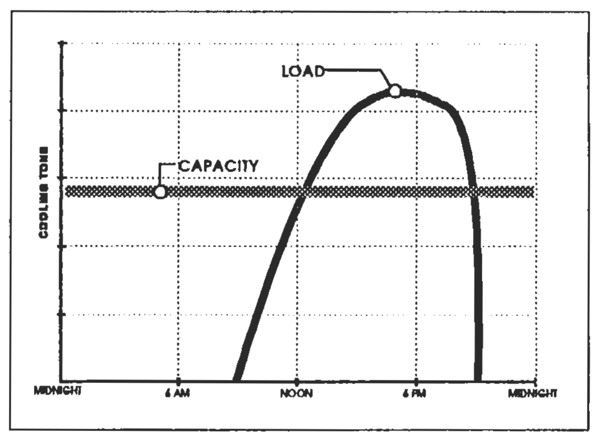


Figure 6 Load Profile and Capacity - EXXON

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half the building's load to the evening hours. By shifting the load to the unoccupied period, space temperatures reduced to between 72° F and 78° F. At first resetting space temperature was performed manually. Satisfied with the solution, Exxon installed an EMCS to automate the procedure.

CENTER SQUARE BUILDING

The Center Square building operators currently use concrete slab thermal storage to provide additional capacity while their chiller plant is being upgraded. This control method allows them to satisfy a 4,500-5,000 ton peak load with only 3,500 tons of mechanical refrigeration.

These studies illustrate the fact that thermal mass storage can be used to provide immediate relief for systems that lack capacity (provided the building has a cyclical occupancy schedule).

THE PENNSYLVANIA CONVENTION CENTER

Design began in 1988 on the Pennsylvania Convention Center. This project was intended to represent the beginning of a new era in Philadelphia. A high profile project that through the architecture intended to connect the region's past successes (the railroads) with the 21st century. The entire convention complex includes a large exhibit hall (the size of seven football fields) connected to the Reading Terminal Building (a 19th century, arched train shed that covers 2 city blocks) - a total of 1.2 million square feet. The majority of the Shed had fallen into disrepair after a extended period of sitting idle. The Reading Terminal Market on the ground floor of the Shed has remained active to date. Construction and renovation of the Shed had to allow shop keepers to remain open while the entire Shed was brought up to current codes and standards of comfort. To carry the complex into the 21st century, the engineering needed to reflect the leading edge of technology and product innovation.

Load Calculations

Initial load calculations for the complex by conventional ASHRAE calculation methods indicated 7,300 tons of cooling would be required. Comparison to other convention centers (on a gross square foot per ton basis) indicated that this convention center would require from 10% to 100% more capacity than other convention centers (see *Table 1*):

Table 1: Comparison with other convention centers.

Location	Installed Sq.Ft. / Ton
Houston, TX	195
Orlando, FL	237
New Orleans, LA	218
Washington, D.C.	209
Atlanta, GA	395
1st Pass - Philadelphia	179

The apparent discrepancy between the initial load calculation and existing convention centers was explained by 2 primary factors:

- Increased Ventilation Rates
- No Allowance for Occupancy Diversity

By accounting for diversity the load was reduced to approximately 4,500 tons, or 290 gsf/ton (see *Figure 7*).

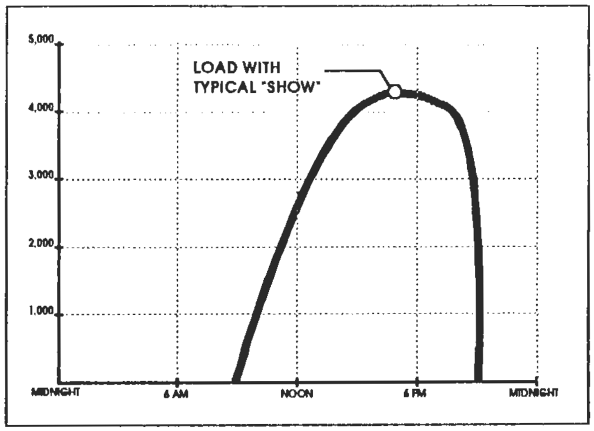

Figure 7 Load Profile - Diversified Pennsylvania Convention Center

Late in 1989 the convention authority asked the engineer to develop cost saving measures to reduce the project budget. The resulting "value engineering" effort lead to the application of structural mass thermal storage.

Structural Mass Thermal Storage

The HVAC system as originally designed incorporated 4 gas fired chiller/heaters capable of producing a total of 4,500 tons of refrigeration. The structural system of the Exhibit Hall utilized reinforced concrete slabs, beams and columns. The evaluation that followed attempted to determine how

Table 2: Heat Storage Capacity Calculation

Philadelphia Convention Center - Heat Storage Characteristics		
Total Concrete Volume	= (310,000 sf) x (1.65 ft)	= 512,820 cu ft
Concrete Weight	= (512,820 cu ft) x (140 lb/cu ft)	= 71,794,800 lb
Heat Content of Concrete	= (71,794,800 lb) x (0.156 BTU/lb/F	= 11,199,989 BTU/F

many of the chillers could be eliminated by utilizing the massive concrete structure as a heat sink.

The following elements were used by the engineer to determine the storage capacity (tons) of the slab:

- Specific Heat of Concrete - 0.156 BTU/lb/F
- Area of Slab - 310,000 sq. ft.
- Average Thickness of Slab - 1.65 ft.
- Density of Concrete - 140 lb/ft.

Given the heat storage capacity calculated in *Table 2*, and assuming: 78° F space temp, varying slab temperatures, and a 10 hour cool-down (slab re-charge) period, the following tons can be stored in the concrete as shown in *Table 3*:

Table 3: Tonnage Stored in Slab

Space Temp	Slab Temp	delta T	Tons *
78	65	13	1213
78	67.5	10.5	980
78	70	8	747
78	72.5	5.5	513
78	75	3	280

*** tons = (heat content) / (10 hours x 12,000) x delta T**

With the information in *Table 3* a new cooling load profile was generated (see *Figure 8*). 1000 tons were eliminated from the installed capacity of the chiller plant. To make up for this tonnage, the complex is operated in the following fashion: in anticipation of a peak load day, the space is cooled below 65° F for 12 to 15 hours prior to occupancy. Approximately 30 minutes prior to occupancy, the space air temperature increases to 68° F-70° F and thermostats attempt to maintain this temperature. By days end, 10 hours later, with a full compliment of people and equipment for a big show, temperatures may rise to 78° F. On days when peak loads are not expected, the building is sub-cooled for a shorter time. The optimization software will determine required re-charge time based on a database of past system performance, expected next day temperature, and expected show time.

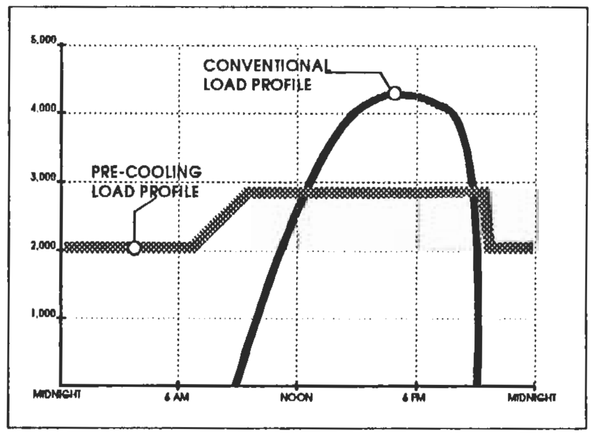

Figure 8: Revised Load Profile
Pennsylvania Convention Center

This design change saved the convention authority approximately $1,000,000. This savings was offset by approximately $200,000 in optimization software and sensors for a net savings of $800,000. Detailed energy cost savings calculations were not completed since the chiller/heaters are gas fired and are not subject to demand charges.

This building represents an actual working model of structural mass thermal storage with which the engineer intends to develop a greater understanding of control algorithms and other aspects of thermal mass storage optimization.

Through simulation of the Convention Center's summer loads with a series of calculation 1000 tons was shaved from a conventional peak load simulation. This resulted in a chiller selection 1000 tons smaller than would have been selected from the conventional load. The calculations simulated sub-cooling of the building's concrete slab during unoccupied times. During occupied times, the sub-cooled concrete reduces peak cooling demand, thereby lowering demand and saving energy costs. In addition there were significant savings in the first cost of chilled water equipment, and the smaller chillers run at peak capacity and efficiency during a greater portion of their run time. The building, Controlled by an EMCS, "learns" from past experience how to run the building efficiently. The EMCS continuously updates a database of its own performance, constantly comparing prior performance and weather to current conditions to anticipate load requirements. The result is an optimized balance between system cost and comfort.

CONCLUSIONS

Buildings with concrete and other "storage capable" materials as part of their structure, operating on a cyclical schedule, can be designed with smaller cooling systems and operated with demand savings. Thermal mass storage offers the following benefits:

- Energy Cost Savings
- System Component First Cost Savings
- Immediate Relief for Existing Undersized Systems

By employing a unique control strategy and carefully picking a sub-cool temperature set point, engineers and building owners can achieve excellent results without straying too far from a conventional cooling system design.

EXPLORATORY GOALS

As with any new technology, further work is required to draw this concept into mainstream design practice. Several of these areas are:

- Confirm Heat Storage Algorithms
- Develop Correlation Factors for Construction Realities
- Identify Additional Independent Variables Affecting Storage
- Develop Design Procedures for Pre-cooling Optimization

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