QUATERLY PROGRESS REPORT

Project Title:	Real-time Predictive Optimal Control of Active and Passive Building Thermal Storage Systems
Covering Period:	June 14, 2004 to September 30, 2004
Date of Report:	October 15, 2004
Recipient Organization:	University of Colorado
Partners:	University of Nebraska at Lincoln and Johnson Controls Inc.
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1. Project Objectives: The main goal of this project is to develop, test, and implement a robust real-time building controller for commercial buildings that utilizes the combined capacity of building thermal mass and thermal energy storage systems to optimize cooling and ventilation equipment operation under dynamic electricity rates. This load management and optimization technology will be integrated with the building automation system to minimize energy consumption and demand as well as operating cost while ensuring human comfort.

2. Background: A simulation environment based on EnergyPlus (a state-of-the-art dynamic building simulation program currently under development and refinement by the U.S. Department of Energy) has been modified as part of a DOE-funded project (henze and Krarti, 2002) to include:

- Detailed and simplified models for active TES systems (Ihm et al, 2003).
- Several internal optimization routines have been integrated into EnergyPlus (Guo et al, 2003).

Figure 1 illustrates the interaction of the various components with EnergyPlus simulation environment. This simulation environment is used in this project to develop optimal controls for operating the TES systems to minimize operating costs while maintaining indoor thermal comfort.

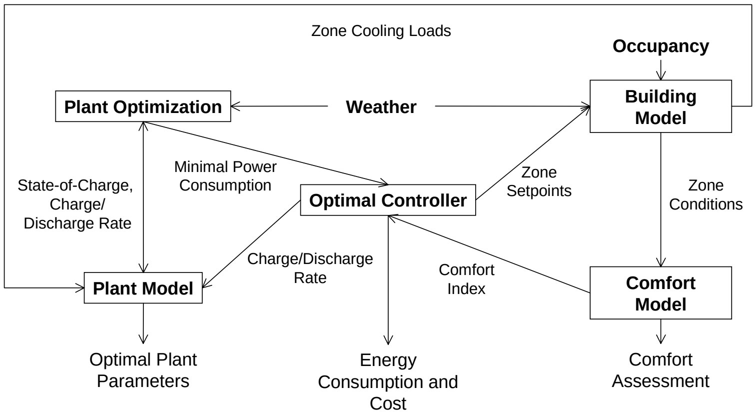

Figure 1: Flow of information within the simulation environment

3. Patents: None.

4. Publications/Presentations: Two papers are in preparation:

- "Analysis of Optimal Pre-cooling Strategies for Office Buildings" by Steve Morgan and Moncef Krarti to be submitted to the ASHRAE Transactions.
- "Benefits of Optimal Controls for both Passive and Active Thermal Storage Systems" by Dong-cheo Seo and Moncef Krarti to submitted to ASME Solar Conference in Orlando, FL. August 2005.

5. Progress in Past Quarter and Current Status:

The project has two main phases as outlined in the Statement of Work:

- Phase I: Laboratory testing to determine the performance of the proposed TES optimal controls under controlled environment using the HVAC laboratory at the University of Colorado.
- Phase II: Field testing to evaluate the TES optimal controls for two buildings: one in Colorado and the other in Nebraska.

Table 1 summarizes the various tasks and the status of each task. Specifically, we did focus on both tasks 1 and 2:

- to integrate the TES optimal control with the direct digital control (DDC) for the HVAC laboratory and,
- to prepare the HVAC laboratory for testing including calibration of all relevant sensors (temperature, airflow, and power).

Figure 2 provides a view of the HVAC laboratory at the University of Colorado. Summary of results of various activities are provided in the following sections.

Table 1: Status of various tasks described in the Statement of Work as of 9/30/2004

PHASE Task No.	Description	Status
PHASE I	**Design and Laboratory Testing**	
1	Design a Prototype Controller	Complete
2	Prepare HVAC Laboratory	In Progress
3	Design Lab Experiments	In Progress
4	Conduct Lab Experiments	To start on 11/1/04
5	Analyze and Interpret Lab Experiments	To start 11/15/04
6	Phase I Documentation	In progress
PHASE II	**Field Testing**	
7	Identify Potential Field Test Sites	One site in Colorado has been identified
8	Prepare Field Sites	To start after completion of phase I
9	Design Field Tests	To start after completion of phase I
10	Conduct Field Tests	To start after completion of phase I
11	Analyze Field Test Data	To start after completion of phase I
12	Phase II Documentation	To start after completion of phase I
	Final Report	To start after completion of phase I

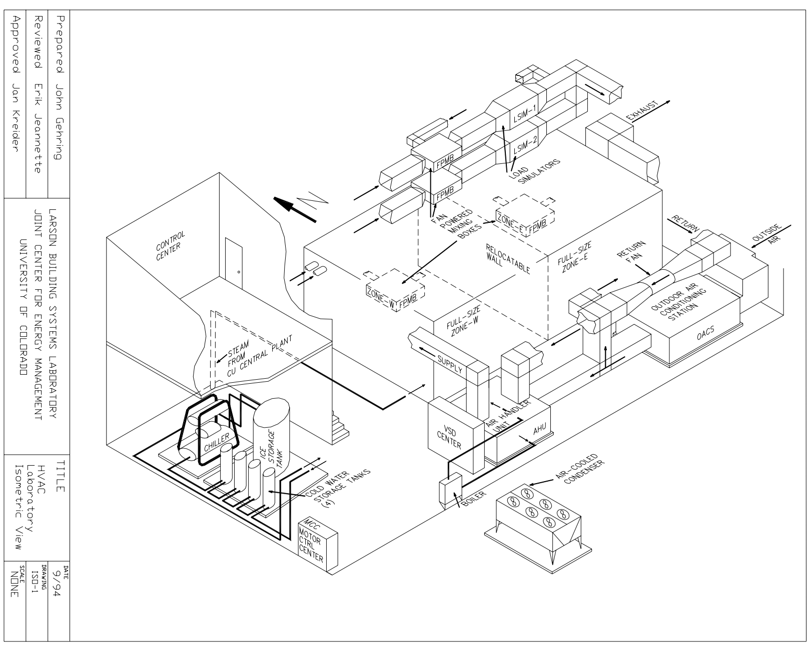

Figure 2: Isometric View of the Full-Scale HVAC Laboratory at the University of Colorado

Design of TES controller

Using the simulation environment, a series of parametric analyses have been carried to determine the important factors that affect the TES optimal controls. Various parameters are considered including:

- Climate (Boulder, CO; Madison, WI; Chicago, IL; San Francisco, CA; and Phoenix, AZ)
- Building shape (to vary the envelope surface exposed to outside, three shapes for a three-story office building are analyzed: 65.6ftx65.6ft or 20mx20m; 49.2ftx88.6ft or 15mx27m; 32.8ftx131.2 ft or 10mx40m)
- Utility rate (time-of-use rates with various ratios of on-peak to off-peak demand and energy charges)

The TES controller is designed to take advantage of both passive and active TES systems. However, when there is only passive TES system (i.e., there is some thermal mass within the building fabric), the controller can be utilized to determine the best controls for pre-cooling to reduce the peak demand and ultimately the total energy cost. Table 2 indicates the potential energy savings in July for a three-story office building in Boulder, CO when the utility rate has energy charge of 0.10/kWh during the on-peak time (9 AM to 6 PM), and of $0.025/kWh at other times. The demand charges are $8.0/kW during the on-peak hours (9 AM to 6 PM) and $0.0/kW during off-peak hours. Table 3 show the potential savings for the same building when both passive and active TES system exist and are optimally controlled.

Table 2: Potential cost savings due to optimal controls to utilize only passive TES system in Boulder, CO for various shapes of a three-story office building during July

Control	Shape (m)	Peak Demand (kW)	Energy (kWh/day)	Cost ($)	% Saved by Control
Optimal	20x20	43.2	750	1664	15.3%
Optimal	15x27	41.6	737	1607	15.7%
Optimal	10x40	43.4	682	1624	13.3%
Conventional	20x20	54.6	559	1964	
Conventional	15x27	53.0	565	1905	
Conventional	10x40	52.2	535	1872	

Table 3: Potential cost savings due to optimal controls to utilize both passive and active TES systems in Boulder, CO for various shapes of a three-story office building during July

Control	Shape (m)	Peak Demand (kW)	Energy (kWh/day)	Cost ($)	% Saved by Control
Optimal	20x20	16.8	1417	1344	31.5%
Optimal	15x27	16.7	1480	1402	26.4%
Optimal	10x40	16.5	1425	1345	28.1%
Conventional	20x20	54.6	559	1964	
Conventional	15x27	53.0	565	1905	
Conventional	10x40	52.2	535	1872	

A more detailed description and discussion of the parametric analyses and their results is being reported in two papers (Morgan and Krarti, 2004; and Seo and Krarti, 2005). In particular, the simulation results pinpoint the important factors affecting the performance of TES optimal controls.

The TES controller is being implemented in the laboratory as a DDC-based software that interacts with an external computer that carry out the simulation. In particular, the software performs the following tasks:

1. Read data from data acquisition system for current and future conditions (i.e. zone temperatures, ice level, energy use for various equipment)
2. Calculate through the simulation environment the operating set-points for air-handling unit supply and return fans, chiller and active thermal storage system that result in a minimum energy/demand costs, and
3. Write the set-points and operating modes for the active TES system to files accessible from the building automation system to ensure implementation of these set-points.

For the active TES system, the following operating modes are defined:

- Chiller cooling mode: the chiller is operated to meet directly the cooling load.
- Chiller cooling and charging mode: the chiller is utilized simultaneously to meet the cooling load and to charge the ice tank.
- Chiller cooling and discharging mode: the chiller and the ice tank are used to meet the cooling load.
- Charging mode: the chiller is utilized only to charge the ice tank.
- Discharge mode: the ice tank is discharges to meet the cooling load.

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Currently, the simulation environment based on EnergyPlus is used to adequately mirror the actual building dynamic response. The calibration of the building model will have to be performed with very little measured data. However, a RC-network model will be explored to determine the most suitable modeling approach that can be easily integrated within a building automation system.

Preparation of the HVAC Laboratory

The two full zones in the HVAC laboratory (see Figure 3) have been set to simulate a typical cooling load profile for office space using the electric baseboards.

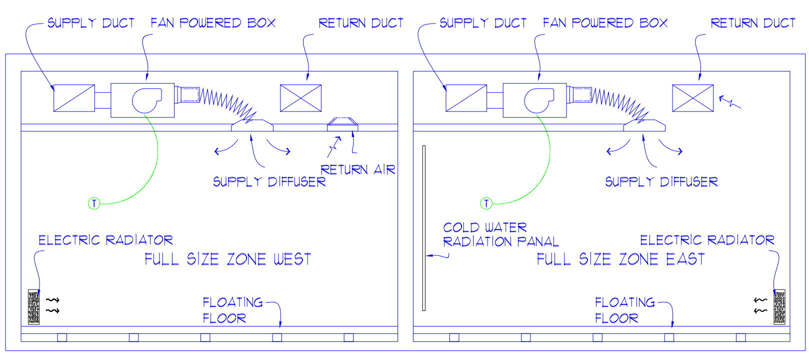

Figure 3: Set-up for the two full-sized zones in the HVAC laboratory

Most of the sensors within the HVAC laboratory have been re-calibrated to ensure accurate measurements for the testing. Figure 4 shows an example of this calibration effort for the airflow measurements (based on Ebtron sensors) using pitot-tube traverse. Figure 5 illustrates the calibration effort for the ice level measurement within the ice tank of the HVAC laboratory.

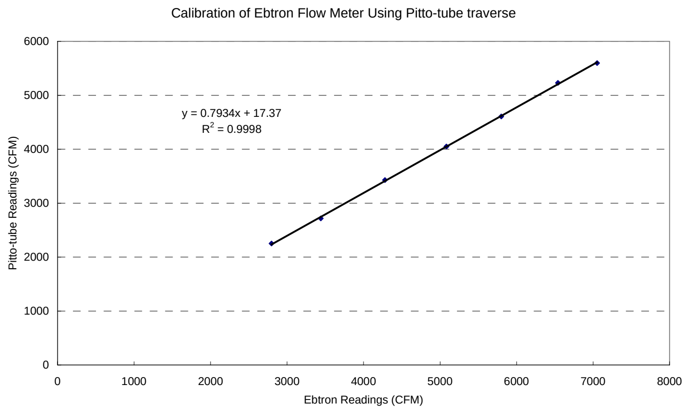

Figure 4: Pitot-tube traverse calibration of the Ebtron airflow sensor for the AHU in the HVAC laboratory

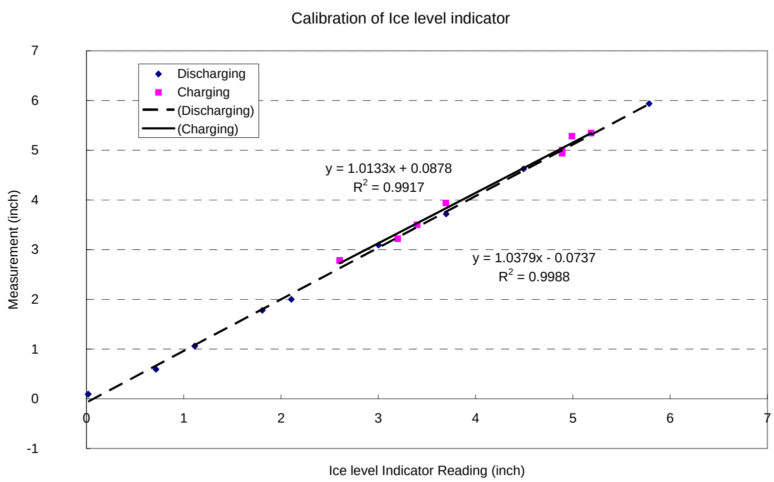

Figure 5: Calibration of the ice level indicator during charging and discharging for the ice tank in the HVAC laboratory

Identification of Potential Building Field Testing

One building has been identified in Colorado. The building is ideal and suitable for this project since it is equipped with an ice storage system and with a state-of-the art automation system. The building is the Zach Elementary school located in Fort Collins, CO. It consists of 65,000 sq. ft. total floor area of which-about 48,000 sq. ft. is on the ground level, with the remaining 17,500 sq. ft. on the second floor. The building has 25 classroom spaces, a gymnasium, cafeteria, library, computer lab, and some offices for staff. Zach Elementary school is occupied from 8 am to 3:30 pm by about 500 students and staff members. Some of the features of the Zach Elementary school are summarized below:

- HVAC System: The HVAC system at Zach Elementary School is a VAV system served by a chiller/ITS cooling system and a gas-fired boiler heating system. There are 5 air-handling units or AHUs on the roof, using hot and chilled water from the central plant.
- Chiller: The chiller is a Trane CGAFC50-50 ton 460 volt 3 phase unit. This is a scroll compressor condenserless chiller.
- Ice Storage System: The TES system is a Calmac 1500C 570 ton-hr unit. It has a latent capacity of 486 ton-hr and a sensible capacity of 84 ton-hr.
- AHUs: The AHUs combine for 70 hp and 51700 cfm delivered to the space.

Figure 6 shows the front of Zach Elementary school. The plan is to start implementing optimal TES controls starting May 2005 when the cooling season starts.

Figure 6: Front of Zach Elementary School, a potential building to implement the TES optimal Controls

7. Plans for Next Quarter:

For the following tasks will be performed during the next quarter (October 1, 2004 through December 31, 2004):

- Task 3: Design and develop the test suite (to account for various cooling load profiles, utility rates, and thermal mass levels). The expected challenge for this task will be to vary the mass level within the full-zones (the preliminary solution seems to add tubes filled of water to increase the interior thermal mass within the zones).
- Task 4: Perform the laboratory tests.
- Task 5: Start the analysis of the laboratory test results.

References:

Henze, G., and M. Krarti (2002), "Predictive Optimal Control of Active and Passive Building Thermal Storage Inventory: Analysis, Modeling, and Simulation", Report to DOE/NETL. Agreement DE-FC-26-01INT41255.

Ihm, P., M. Krarti, and G. Henze (2003) "Implementation of TES models within EnergyPlus" Proceedings for International Building Simulation Conference, Nederland.

Morgan S. and M. Krarti (2004) "Analysis of Optimal Pre-cooling Strategies for Office Buildings" to be submitted to ASHRAE Transactions.

Seo, D., and M. Krarti (2005), "Benefits of Optimal Controls for both Passive and Active Thermal Storage Systems" to be submitted to ASME Solar Conference in Orlando, FL. August 2005.

Zhou, G., P. Ihm, M. Krarti, and G. Henze (2003) "Integration of Optimization Routines within EnergyPlus" Proceedings for International Building Simulation Conference, Nederland.