(5) Real-Time Predictive Optimal Control of Active and Passive Thermal Storage Systems

This project will develop a real-time optimal controller for thermal storage systems from design through prototype development and testing in laboratory conditions, followed by field implementation in two commercial buildings.

Total project cost: $335,426
Funding request: $150,489
Project Lead: University of Colorado - Boulder
Project Participants: University of Nebraska – Lincoln; Johnson Controls

Publications/Presentations

Two papers have been written and will be submitted for review:

- “Analysis of Optimal Pre-cooling Strategies for Office Buildings” by Steve Morgan and Moncef Krarti submitted to the ASHRAE Transactions.
- “Benefits of Optimal Controls for both Passive and Active Thermal Storage Systems” by Dongcheo Seo and Moncef Krarti, presented and published in the ASME Solar Conference in Denver, CO, July 2006
- “Laboratory Testing of on-line Predictive Optimal Control for TES systems” B. Ma and M. Krarti, submitted to the ASHRAE Transactions.

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 (now in Iowa, see Appendix-A).

Table 1 summarizes the various tasks and the status of each task. Specifically, we did focus on all the tasks for Phase I.

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	Complete
3	Design Lab Experiments	Complete
4	Conduct Lab Experiments	Complete
5	Analyze and Interpret Lab Experiments	Complete
6	Phase I Documentation	On-going
PHASE II	**Field Testing**	
7	Identify Potential Field Test Sites	One site in Co and one site in Iowa
8	Prepare Field Sites	Complete
9	Design Field Tests	Complete

10	Conduct Field Tests	On-going
11	Analyze Field Test Data	To start May 1, 2005
12	Phase II Documentation	To start in May 1, 2005
	Final Report	To start after completion of phase II

Phase 1 (Completed): Lab Testing

The TES controller has been implemented and tested in the Larson laboratory as a DDC-based software that interacts with an external computer to carry out the simulation analysis. 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.

The laboratory testing results -summarized in the Progress Report No. 3 and is being written in a final report draft- indicated the simulation provide an adequate model for the real dynamic behavior of the HVAC laboratory.

Phase 2 (On-Going): FieldTesting

Building Description

As outlined in the proposal, two buildings have been prepared to test the TES controller. The site in Colorado consists in of the Zach Elementary School as depicted in Figure 2 (a 65,000 sqft building located in Fort Collins, CO) equipped with a Calmac 1500C 570 ton-hr ice storage system having a latent capacity of 486 ton-hr and a sensible capacity of 84 ton-hr.

Figure 2: Front of Zach Elementary School, in Colorado where the TES optimal Controller is being implemented and tested

Some implementation problems were encountered in the proposed second site in Nebraska. An alternative building in Iowa was selected instead as detailed below by the subcontractor Prof. Henze.

Model Calibration

A thermal building model for the Zach elementary school was developed in EnergyPLUS and then calibrated as outlined in Figure 3. The lighting and equipment loads were measured by a building audit, and the schedules were slightly adjusted to meet annual utility data obtained from the building manager. The results show that the calibration was done successfully. All months are within 5% of actual data. The low summer loads are due to the absence of occupants outside of normal school scheduling. Lighting power density is 1.05 W/ft^2, and equipment power density is 0.5 W/ft^2.

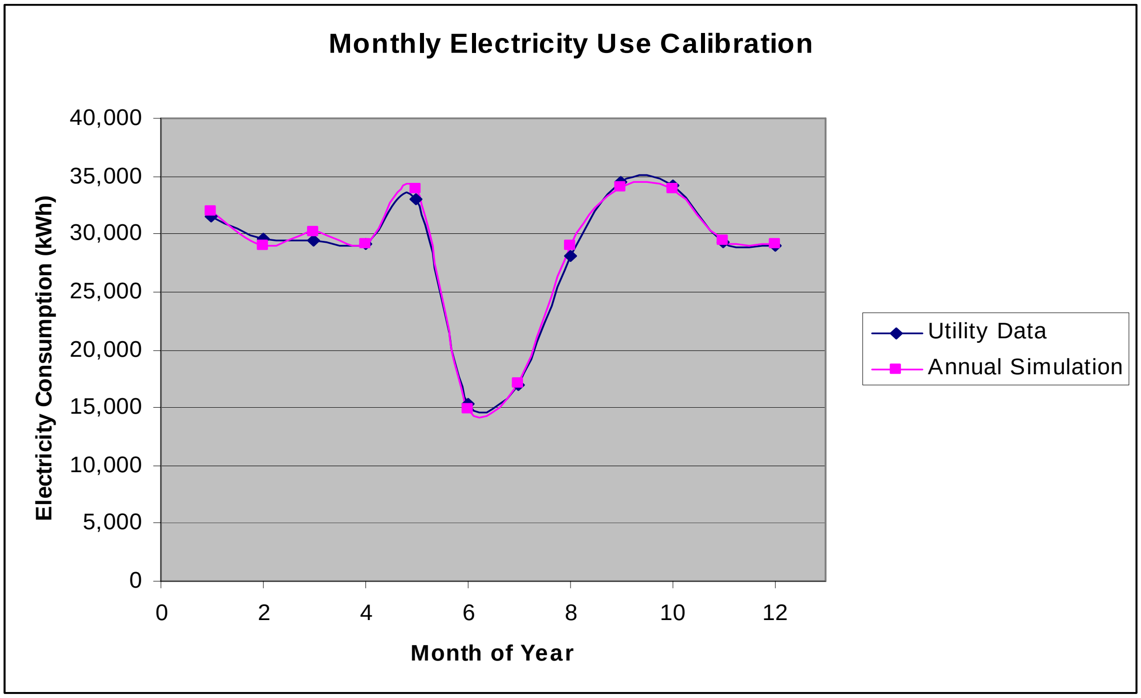

Figure 3 - Electricity Consumption Calibration

HVAC and plant specifications were obtained in the aforementioned building audit, but some details, such as design flow-rates and schedules, were modified to better mimic the performance of the actual building.

Thermal Mass Performance

Two preliminary tests were carried out to evaluate the performance of the thermal mass of the building. These tests were performed on Saturday and Sunday when the building was unoccupied to test the discharge of the thermal mass at two different pre-cooling temperatures. For day 1 of the tests, the precooling was set to 65 F from 12 am to 8 am. For day 2 it was set to 70 F for the same period. The results are shown in Figure 4.

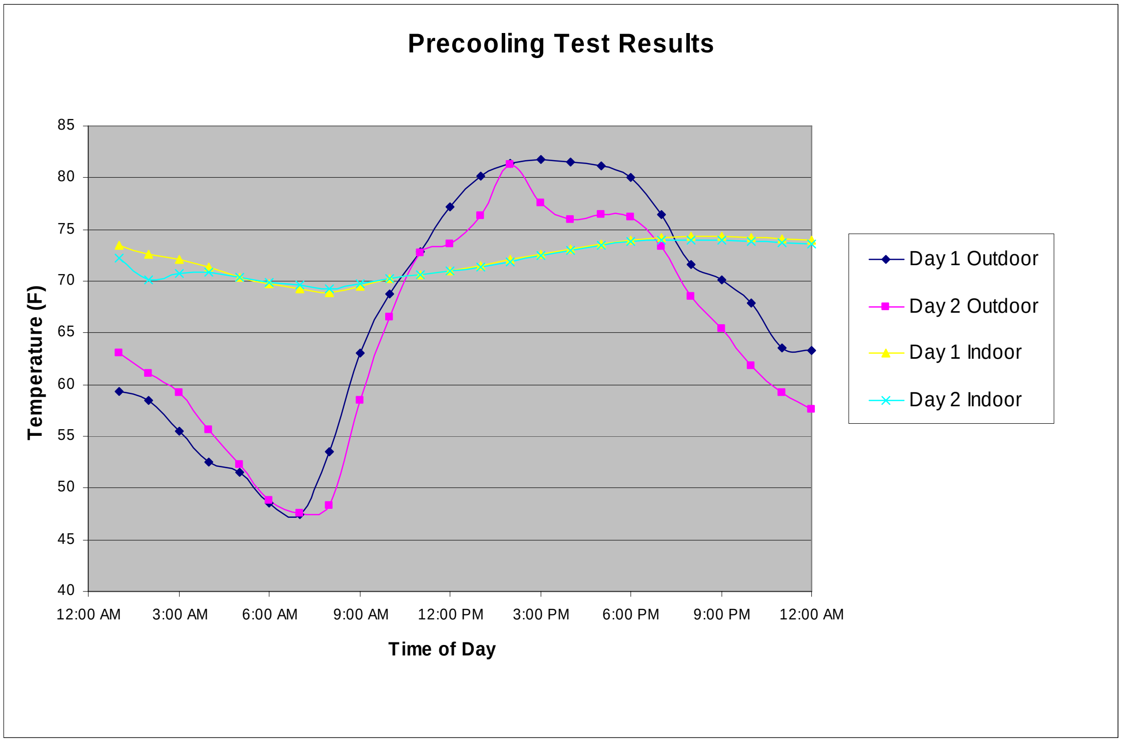

Figure 4 – Indoor-Outdoor Temperature Variation for Two Preliminary Building Thermal Mass Tests

The precooling/float tests were inconclusive because the space temperature did not reach 65 F (precooling setpoint) for that test. The 65 F test (Day 1) did reach a slightly lower temperature during precooling than the 70 F test. This may account for the resulting zone temperatures remaining almost identical despite cooler weather for the 70 F precooling test.

Pre-cooling Effectiveness

Due to cooperative weather it was possible to run tests on days with nearly identical weather. The temperatures were all within 1.2 F on an hourly basis, while the solar radiation differed by less than 10% hourly. The results below are actual values from the school's building automation system, and the results show that precooling is effective for this building. The results are best compared in the reduced discharge rate during the first hours of occupancy for the precooling case as well as the reduced total discharge from the ice system. Precooling reduced total ice discharge by 17.3% of total charge, or 347 kWh. This energy storage is the equivalent of 18.2 lbm/ft^2 of concrete thermal mass being charged and discharged at these setpoints (precooling at 5 F below occupied setpoints). The actual mass level of the building is closer to 75 lbm/ft^2, but the performance is affected by carpeting in the classrooms and thermal leakage.

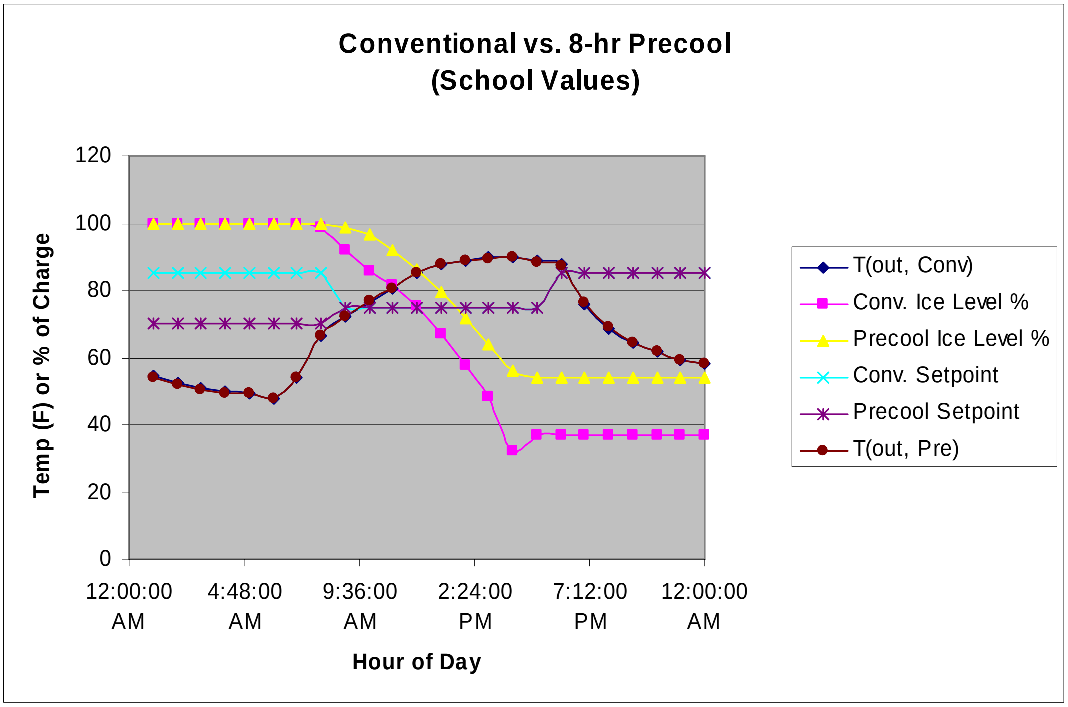

Figure 5 – Comparative Building Passive-Active TES Performance Between Conventional and Pre-cooling Controls

Optimized Control Tests

Tests were run for optimized control with 24, 12, 6, and 4 hour updates. Due to the low incentive of the actual utility rate in effect for this building, a high-incentive utility rate was used for some tests to encourage precooling use for testing. Some tests were run without precooling with the actual utility rate to observe predictor behavior. Tests were started at 12 am in all cases.

Standard Rate Tests

Two tests were run using the actual utility rate of the school. The demand incentive is high, but the energy rate is flat, so the optimization controller does not call for precooling in this swing-season weather.

The two days had very similar weather and ice discharge profiles, so one set of data and simulation results is shown. These results show how well the model represents the building. Temperature and ice level values are within 6% for all hours.

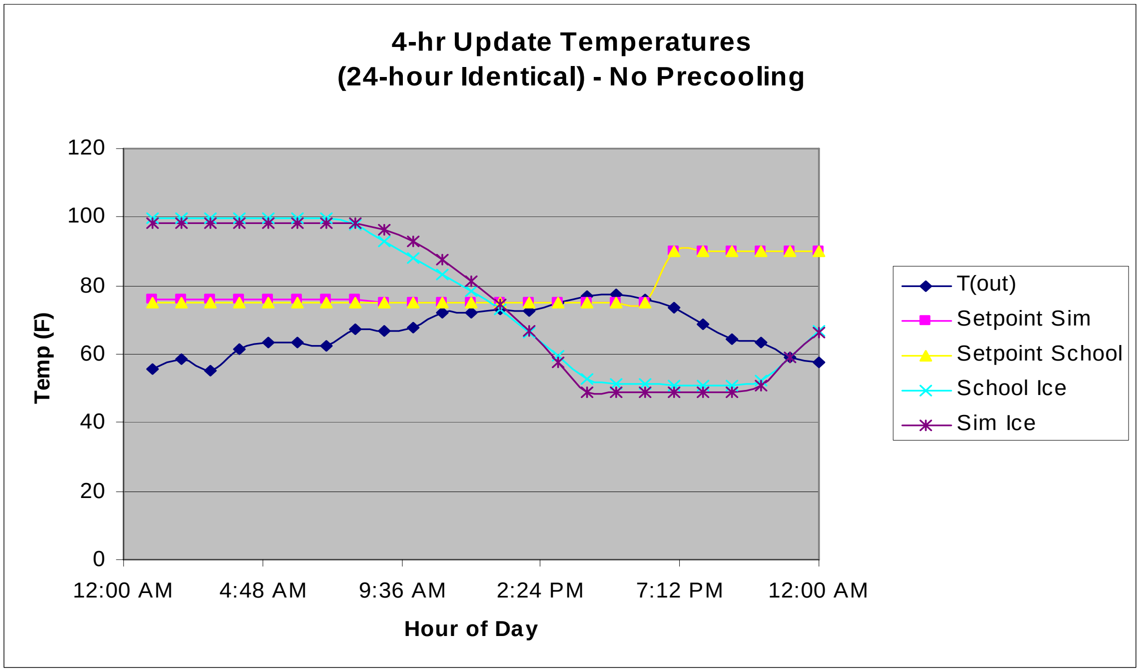

Figure 6– Building Passive-Active TES Performance Using Optimal Controls under Standard Rates

High-Incentive Rate Tests

Several more tests were run with an improvised utility rate that better reflects the actual load-shifting incentive. Due to the inability of a daily optimization algorithm to model the effects of a 12-month demand ratchet clause, the actual utility rate was altered. Table 2 shows the difference between the standard and high-incentive rate.

Table 2: Basic Features of the High Incentive Rate vs. Standard Rate

Actual	*Peak*	*Off-Peak*		*High-Incentive*	*Peak*	*Off-Peak*
Energy $/kWh	0.0164	0.0164		Energy $/kWh	0.164	0.0164
Demand $/kW	0	11.62		Demand $/kW	0	11.62

The high incentive tests were run for 24, 12, 6, and 4 hour update windows all called for basically the same performance of the building. There was an 8-hour precool at 70 F (±0.2 F) followed by a rapid discharge of the passive thermal mass. Setpoints rose to 75 F during the entire occupied period, and were left to float when occupants left at 6 pm. Setpoints changed insignificantly, if at all, between update windows (±0.2 F), and ice was discharged to meet the entire cooling load throughout the day. The chart below shows a typical test with setpoints charted for all updates.

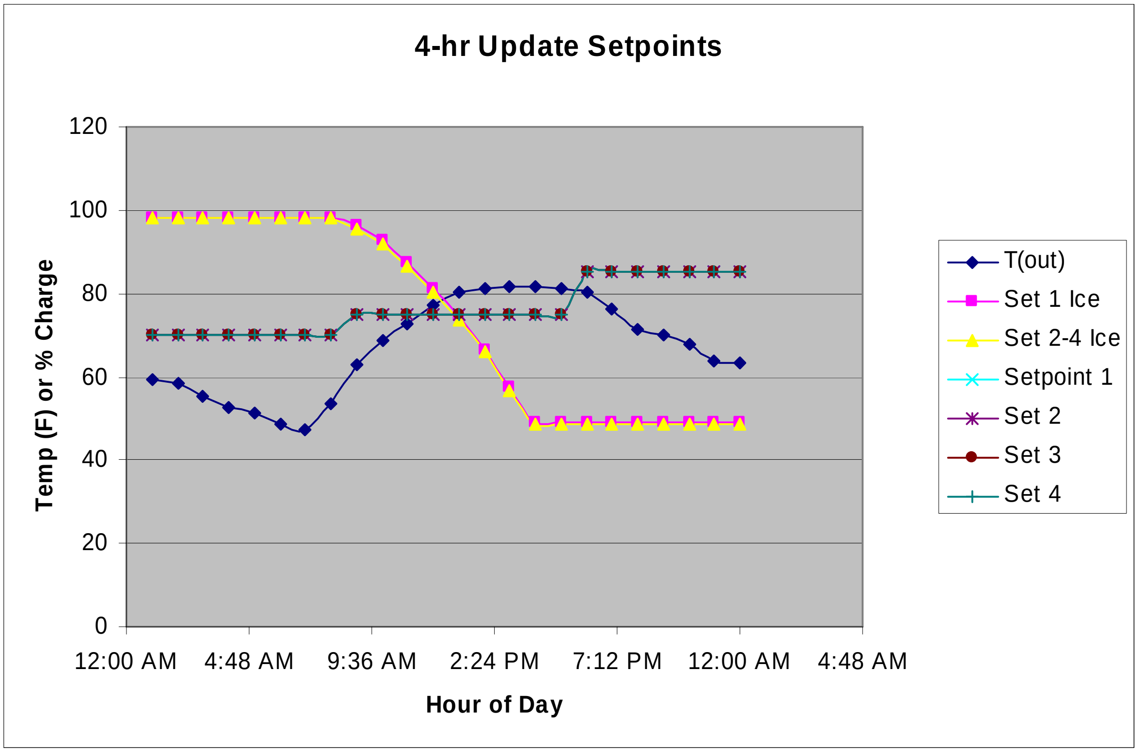

Figure 7– Building Passive-Active TES Performance Using Optimal Controls under High Incentive Rates

Of utmost interest for these tests is the cost data. Peak demand for all cases is identical because there is no change in peak electricity use. Pumps and fans still run for the optimized cases, and the chiller is not active during peak hours. Total electricity use is therefore an accurate cost indicator since the actual energy rate is flat ($0.0164/kWh). The results in the table below show that the increased fan energy use from precooling typically results in higher cost than conventional control, and this explains the lack of precooling for those tests using the actual rate.

Table 3: Summary of Testing Results for Optimal Controls

Update	*Precool Setpoint*	*High OAT*	*ITS Cooling Energy (kWh)*	*Fan Electricity (kWh)*	*Chiller Electricity (kWh)*
Conventional	N/A	80.2	1263	351	252.6
4-hour	70	81.7	1029	609	205.8
6-hour	69.9	83.2	1089	598	217.8
12-hour	70	80.8	1002	612	200.4
24-hour	70.1	81.5	1026	605	205.2

Preliminary Conclusions

These tests show several significant outcomes for this research. First and foremost, the results verify that this modeling and simulation process can effectively be applied to a real building in the field. The model for this building yields very similar results to the actual energy performance of the building, including space temperatures, mass response, HVAC energy use, and chilled water plant behavior. Furthermore these tests show that the optimization algorithm performs well under different rate structures. In the case with little load-shifting incentive (the actual rate) the optimization controller called for no preconditioning of the space, whereas with a high-incentive rate the precooling was utilized.

The update window made little difference for these tests since all called for the same setpoints for precooling. The demonstration of the effectiveness of precooling to shift load was good for validating the model, but it is unlikely to change the control strategy of this building. The increase in fan energy use is significant while offering no necessary thermal storage to the building's inventory. The ITS system is sized to meet the design day cooling load for its location, so additional thermal storage capacity is not needed.

Appendix A: Background on the Energy Plaza Experiments in Omaha, Nebraska

OPPD (Omaha Public Power District) who is the owner of the Energy Plaza building does not permit our optimization machines on their network for security reasons. Thus, we were required to use a virtual private network (VPN) connection. Our optimization system successfully carries out 1) weather prediction, 2) optimization, and 3) post-processing of the hourly optimal control commands. Plausibility of these results has been confirmed, even though precooling at night may not be conventional practice in the Energy Plaza. The relatively few commands are sent to an Excel file on the OPPD server via DDE (dynamic data exchange). The Niagara web-enabled building automation system reads these new setpoints from the open Excel sheet via its own DDE channel.

The experiment finally started on July 25th after three weeks of waiting for the permission from the building owner. However, it only ran for three days continuously due to a crash of the BAS server at the investigated building. The second (July 29th) and third (August 1st) attempt to restart of experiment also led to the same problems. Since the server is not only in charge of the BAS of the tested building, but also stores huge amounts of data of other buildings and facilities, including one power generation facility, the owner of the investigated Energy Plaza building required us to stop the experiment, and investigate the reasons causing the problem.

The investigation carried out by the IT department of the building owner and the controls contractor for this buildings revealed that two major reasons led to the unstable behavior of the building. The first one is the server itself is a relative old machine (Pentium III), and there are too many applications that had been running already. This has also been confirmed by the previous continuous commissioning team that had met the same problem when they tried to test new control sequences. The second reason is that the DDE link requires high sample rate during the data exchange (reading and writing), which heavily loads the server and consequently increases the chances to crash.

Several weeks ago, we proposed two possible solutions to solve the problem:

1. A new server is can be installed. The old server will do the same as previously, and our test program will be installed on another machine there, which has the same programs as the old server but dedicated for our purposes. By doing so, the old server will not be affected by our testing, and our program can also avoid interruption from the crashes of server.

2. Instead of letting the post-processing program implement the control command into BAS, those optimal results will be executed manually. The commands will be sent in each building mode, which is every 3 hours. Of course, this manual operation is not considered a permanent solution.

Today, on August 29, 2005, we learned from our contact at the Energy Plaza that they are unwilling to resume testing in spite of the two possible solutions we provided. They feel that the experiments may jeopardize the operation not only of the Energy Plaza building itself, but also several other buildings that are served by the same system.

For that reason, we need to find an alternative building in a very short time frame. We propose to use the Energy Resource Station (ERS) at the Iowa Energy Center in Ankeny, Iowa instead.

General Background on ERS

The ERS is both a light commercial building as well as a unique demonstration and test facility wherein laboratory-testing capabilities are combined with real building characteristics. It is capable of simultaneously testing two full-scale commercial building systems side-by-side with identical thermal loading. The ERS building, a single story structure with a concrete slab-on-grade, has a height of 4.6 m and a total floor area of 855 m^2, divided into a general area (office space, service rooms, media center, two class-rooms, etc.), and two sets of identical test rooms, labeled 'A' and 'B'; adjacent to the general area. Eight test rooms are organized in pairs with three sets of zones having one exterior wall (east, south, and west) and one set that is internal. Figure 3 presents a layout of the ERS including the four sets of identical test rooms used for the experiment.

Opaque exterior surfaces of the ERS are composed of several layers of construction materials with a thermal mass outside of the insulation. The percentage of the window area to exterior wall area is 15% on the east side, 16% on the west side, 32% on the south, and no windows on the north.

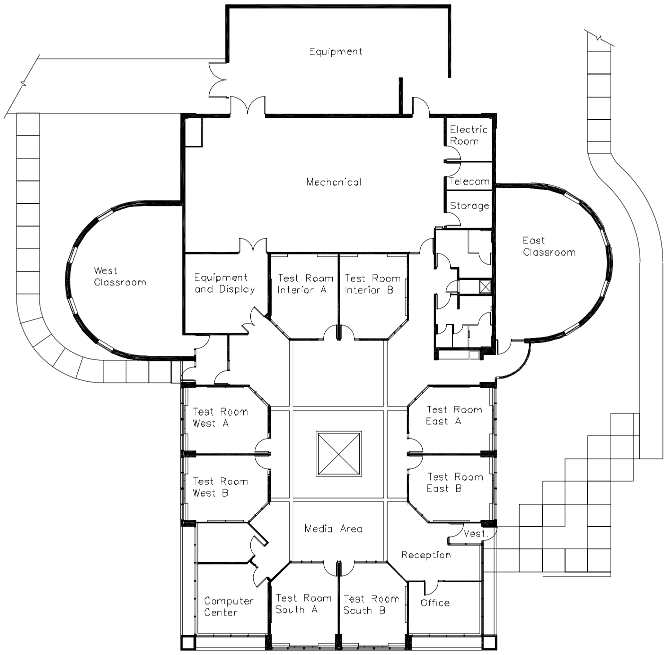

Figure 3: Layout of the proposed alternative test facility, the Energy Resource Station (ERS), Ankeny Iowa.

Primary and Secondary HVAC Systems

A central heating plant consisting of a natural gas-fired boiler and a cooling plant with three nominal 35 kW air-cooled chillers that operate in both chilled-water and ice-making modes are the primary pieces of mechanical equipment. The chilled-water loop is filled with 22% propylene glycol water solution. In addition, the building includes a 440 kWh internal melt ice-on-tube thermal energy storage (TES) tank as well as pumps and auxiliary equipment needed to provide cooling. District cooling can be provided by the DMACC campus chilled water plant but will not be used in this experiment. Hence, several modes of operation between these sources of cooling are possible in order to supply chilled water to the air handling units (AHU). A primary-secondary flow arrangement with dedicated constant-volume chiller pumps and secondary variable-flow distribution pumps in the AHU loop using variable-frequency drive (VFD) control is installed in the ERS.

Secondary HVAC systems include three air-handling units (AHU) that condition the building: Test rooms A and B are served by two similar single-duct variable air volume (VAV) with reheat AHU systems A and B, and the general area is served by a similar but larger AHU-1. An overhead air distribution system utiliz-ing pressure-independent VAV boxes supplies air to each test room using hydronic or 3-stage electrical resistance reheat.

Finally, there is an on-site weather station with measurements of outdoor air dry-bulb temperature, relative humidity, wind speed and direction, atmospheric pressure, total normal incidence solar flux, and global horizontal solar flux.

Investigated Test Rooms

Test rooms A and B, each with a net floor area of 24.8 m^2 and carpeted floor, will be used for the experiment. The ceiling height is 2.6 m and there is a plenum above the suspended ceiling with a height of 1.7 m. Having the same geometry and construction specifications, but being thermally isolated from each other; the identical pairs A and B experience the same heating and cooling load. Glazing area of the exterior zones consists of double-pane 6.4 mm clear insulating glass and measures 6.9 m^2.

Test rooms will be unoccupied; however, false internal heat gains can be introduced using baseboard heaters and lights to simulate the occupancy schedule of a typical building. Test rooms A are equipped with 2-stage lighting whereas test rooms B are fitted with dimming electronic ballasts, both with a maximum wattage of 585 W. The baseboard heater at each zone can operate at two stages with a maximum output of 1.8 kW (900 W per stage).

A comfort sensor measuring the air temperature, humidity, and wind speed will be placed in the middle of the rooms. Conditioned air at a temperature of 13°C will be supplied to the test rooms by two ceiling mounted diffusers in order to maintain the room temperature within a range of 20°C and 24°C during time of occupancy. The interior flow rate throughout the occupied period is characterized by a minimum flow of 94 L/s and a maximum flow of 189 L/s. Finally, all test rooms will be kept locked throughout the period of the experiment in order to avoid disturbance and interruptions. These conditions will be applied to all eight test rooms.

Experience with the ERS

During tests conducted during the last 2 years for two separate projects, we collected significant experience with the ERS facility and we believe that we understand its operation quite well. Not only that, we also have taken extensive measurements which will be used calibrate the building model used in the context of predictive optimal control.

The following articles were published based upon research conducted at the ERS:

Henze, G.P., D. Kalz, C. Felsmann, and G. Knabe (2004) “Impact of Forecasting Accuracy on Predictive Optimal Control of Active and Passive Building Thermal Storage Inventory." *International Journal of HVAC&R Research*, Vol. 10, No. 2, pp. 153-178, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, Georgia.

Henze, G.P., D. Kalz, S. Liu, and C. Felsmann (2005) “Experimental Analysis of Model-Based Predictive Optimal Control for Active and Passive Building Thermal Storage Inventory." *International Journal of HVAC&R Research*, Vol. 11, No. 2, pp. 189-214, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, Georgia.

Liu, S. and G.P. Henze “Experimental Analysis of Simulated Reinforcement Learning Control for Active and Passive Building Thermal Storage Inventory – Part 1: Theoretical Foundation.” *Energy and Buildings*; in press.

Liu, S. and G.P. Henze “Experimental Analysis of Simulated Reinforcement Learning Control for Active and Passive Building Thermal Storage Inventory – Part 2: Results and Analysis.” *Energy and Buildings;* in press.