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Using Thermal Mass and PCM to Shift Demand Off-Peak: A Paradigm Shift in Cold Storage Design

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ABSTRACT

Cold storage facilities are likely not the first buildings that come to mind when thinking about high performance buildings. However, the number and size of these facilities are growing every year, in part due to a worldwide focus on improving the "cold chain" for perishable food products. For most cold storage facilities in temperate regions peak electricity consumption occurs during product harvest, which occurs in the summer and autumn months during daylight hours when temperatures and electricity prices are the highest. Because it is not feasible to shift cooling loads by changing the harvest operation or schedule, and because of a heightened interest by utilities and regulators in demand side load management, it seems imperative to question the efficacy of the refrigeration industry status quo construction type – the low-mass, insulated metal panel (IMP) building.

With grant support from the Rural Energy for America Program (REAP), the authors designed and constructed a cold storage facility which uses a unique wall and refrigeration system that together reduce energy use and shift electrical demand to off-peak times of the day . The energy efficient wall employs structural concrete membranes wrapped around an R-100 insulated core. Enhanced thermally with phase change material (PCM), the thermal storage capacity of the wall is increased tenfold, theoretically enabling the facility to span a six hour peak-demand period without relying on conventional refrigeration. Load shifting is paramount to the increased reliability and efficiency of the energy grid. To this end, utility companies have implemented peak-pricing models and incentive programs to encourage energy users to shift off-peak. Calculations show that the completed building presented in this paper will reduce energy costs by 50% compared to industry standard, Title 24 construction, resulting in a simple payback for the added investment in less than four years.

INTRODUCTION

The industrial sector is the largest user of electricity in the United States. Refrigerated warehouses, the focus of this paper, are significant users of industrial energy with a growing energy demand worldwide due to increased focus on preserving the cold chain. These structures typically use refrigeration energy 24 hours per day, seven days a week, but the highest usage, often more than half of the annual total, occurs during the summer and fall daytime hours when outside temperatures and electrical demands are at their highest and when the refrigeration systems perform at their worst. Shifting energy usage to the cooler, off-peak hours addresses several important issues. First, the reliability and energy efficiency of the grid is increased; second, on-site clean energy technologies, which operate at peak during these periods, can be downsized to supply clean energy to run the facility; third, refrigeration system operation is shifted to the cooler night time temperatures, improving their operating efficiencies; and fourth, the additional upfront investment can be paid back within reasonable time frames by purchasing power at the lower off-peak rates and capitalizing on utility incentive programs.

In recognition of these advantages, a number of approaches for shifting energy usage have been experimented with over the last several decades. Altwies and Reindl performed finite element analyses on a novel technique for shifting loads in freezer storage facilities by using the thermal storage capacity of the product itself. With this technique warehouse temperatures were reduced off-peak and allowed to rise during peak demand times – though never above freezing – to preserve product quality. With this passive approach, they reported significant annual cost savings even though additional

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refrigeration capacity was required to overcool the facility off-peak. Castellon, et al., Kosny et al. and others have reported significant successes using phase change material (PCM) in the residential sector to store energy, by slowing the transmission of heat into and out of the building and shift energy demands off peak. In all of these experiments a passive approach to energy storage and retrieval was employed and a wide 'delta T' was utilized.

Refrigerated storage warehouses, particularly those used for the post-harvest cool down and temporary storage of fresh farm produce, present a more difficult problem. The ideal temperature is often 34 F (1.1 C) plus or minus 1 F (0.55 C). The absolute lower limit is 32 F (0 C). Cooling the air below this temperature runs the risk of frost damage to the product. At the upper end of the cooling spectrum, the industry standard is 38 F (3.3 Celsius). Additionally, peak pricing periods typically coincide with the peak receipt, post-harvest cooling, processing and shipping of product. Using prime growing areas, such as the Salinas Valley in California as an example, the peak demand pricing occurs weekdays during the six hours between 12:00 pm and 6:00 pm. Harvest typically starts during the early morning hours, when the crops are hand packed in the fields and loaded onto flatbed trucks. Once loaded, the trucks transport the produce to a local cold storage warehouse. The product begins arriving around 10:00 am and continues to arrive throughout the peak demand time. Upon arrival, the product is 'pre-cooled' using a variety of pre-cooling techniques that include hydro-shower coolers, vacuum coolers and specialized air cooling tunnels. The precooling method varies by product, but the intent of the pre-cool is to quickly lower the product temperature to 34 F (1.1 C) and therefore preserve product quality and extend shelf life. Upon reaching the target temperature the product is taken immediately into the refrigerated warehouse where it will stay until shipped. Under this scenario the refrigerated warehouse is subjected to multiple sources of heat intrusion simultaneously.

Skin loads are ever present and are highest during the summer peak-demand times when external air temperatures can reach over 100 F (38 C) and where surface temperatures exposed to direct solar radiation can reach upward to 140 F (60 C). The industry standard low mass wall system has been value engineered to address these skin loads with minimum upfront cost using closed cell foam insulated metal panels of 4", 5",and 6" thickness with insulation values between R28 and R40.

Infiltration loads in these post-harvest coolers are greatest during the delivery and loading of product into and out of the warehouse. Automatic high speed doors, refrigerated docks with truck seals, air locks and other techniques have been employed in an effort to reduce these loads. Warehouses also use flexible plastic curtains on forklift doors to reduce infiltration. While an improvement over open doorways these typically form a poor seal with the floor and sides of the opening allowing infiltration even when forklifts are not moving through the curtain.

Product load is another source of heat. Although pre-cooled, the product located at the exterior edges of the pallet are at desired temperature, while the interior product temperature is typically higher. In addition, the product continues to respire while it is in the warehouse, releasing more heat. Internal heat loads from lighting, equipment and unit cooler fans are also highest during this peak pricing period.

In summary, skin, infiltration, product and internal building loads are at their maximum during the electrical utility peak pricing periods, however, to preserve product the operations cannot be changed and the temperatures cannot be allowed to rise more than a few degrees Fahrenheit.

PREVIOUS STUDIES BY THE AUTHORS

In 2010, the authors designed a 20,000 square foot refrigerated storage building and developed a spreadsheet with visual basic algorithms implementing ASHRAE transfer functions to predict and compare the energy performance against the California Title 24 IMP building. Construction on the 'California Endive' cooler began in May 2011 and completed five months later to receive the first harvest in October.

Although this building represents a special case, it nevertheless offers some important lessons. The building stores chicory root at slightly below freezing temperatures for up to eight months. To produce endive, chicory root must be cooled to below 30 F (-1.1 C), forcing the roots into dormancy, and the temperature must be maintained within plus or minus ½ degree F (0.3 C) of the 29 F (-1.7 C) set point. The warehouse cannot be overcooled [Altwies & Reindl] to shift loads nor can the product temperature be allowed to rise much above the set-point, lest the roots leave dormancy. Upon removal from the freezer the roots are warmed and fertilized with a liquid solution to initiate a second growth resulting in endive. The roots are loaded into the freezer during the months of October and November and pre-cooled in the facility.

Unloading occurs over the course of the year but can be staged during the morning or evening hours so that infiltration loads from the unloading activities can be avoided during the 12:00 noon to 6:00 pm peak pricing period.

The building construction system provides an R-100 wall with concrete thermal mass on both the interior and exterior surfaces. The exterior concrete skin offers thermal inertia which captures the daytime solar energy, delaying its entry into the building and re-radiating the heat to the cooler nighttime environment during commissioning and prior to receiving product. Infrared thermal imaging taken during the hottest part of the day of an exterior wall exposed to direct solar insolation showed no thermal transmission.

As mentioned earlier, a complex spreadsheet simulation using site specific hourly temperature and solar data with Visual Basic algorithms based on ASHRAE heat transfer functions was developed. The calculation methodology accounted for the R-value, the thermal dynamics of the building's inner and outer mass elements, the amount and temperature of the product mass, and published research regarding the specific product cooling behaviors. The results suggested that a 40% - 60% reduction in the annual energy *costs* could be realized when compared to a standard Title 24 insulated metal building (IMP) which requires R-28 insulation in the walls but does not have thermal mass storage capability, with appropriate operating strategies. Achieving these savings assumed the building's refrigeration being turned off during the peak pricing period, relying on the stored thermal energy in the walls and product to maintain the storage temperature for the 6 hour peak pricing period. Because the owner of the facility can shift their operations (loading and unloading) to off-peak hours, infiltration and internal lighting and forklift loads can be nearly eliminated during peak hours.

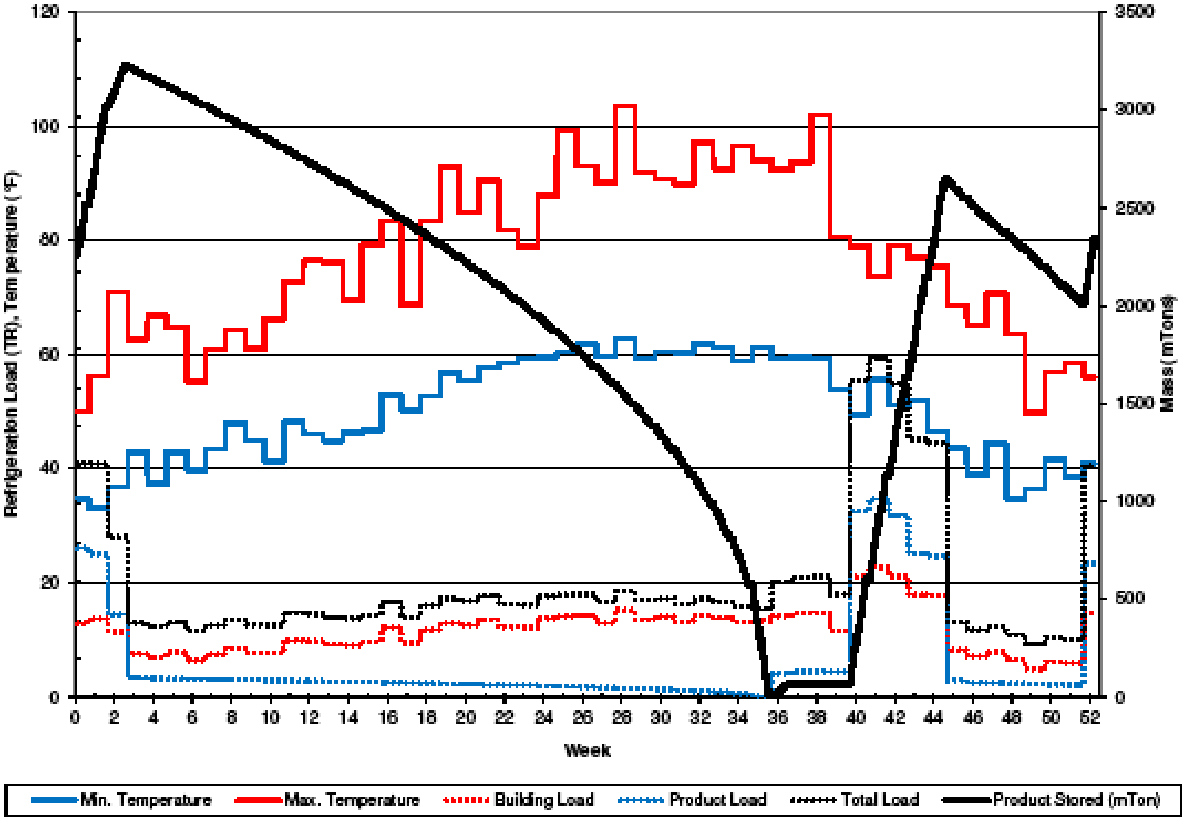

Figure 1 Annual load profile for CA Endive facility showing temperature, electricity demand and electricity use.

Figure 3 illustrates the calculated annual product load profile for the endive facility, the high and low daily ambient temperatures, and calculated total refrigeration load for the building throughout the year. The chart shows that the refrigeration load is greatest when the chicory roots are going into storage (weeks 0-4 and weeks 41-47). The refrigeration load is shown to be relatively insensitive to the ambient temperatures and total product stored for this facility due to the thermal characteristics of the product itself and the mass-insulation-mass construction of the building's wall.

Two years of utility energy bills show the owner paying approximately $113,000 annually compared to a third party engineer's estimate of $135,000 annually for a Title 24 IMP, and the local utility company's estimate of $200,000 annually. Unlike the planned operating scenario, the Owner and his refrigeration contractor have not implemented any demand control strategies for the refrigeration system during the utility peak period. We have been told the Owner is suspending loading and unloading operations during peak utility periods and closing the doors.

The utility bills show however the unabated operation of the refrigeration system during the peak period, therefore the Owner is not seeing the full benefit of the high mass building. A simple strategy using the thermal mass in the building effectively to offset the product storage demands to off peak periods could reduce peak demand 120 kW, reduce peak kWh as well, and save approximately another $12,600.00 annually bringing the total annual savings to $35,000. Assuming half of the load is for pre-cooling this results in an annual *storage* cost savings of ($35,000/$67,500) resulting in an operating electrical cost savings for the high mass storage compared to that estimated for the standard low mass building of approximately 52%. These savings fall in the middle of the 40% to 60% projected by the spreadsheet model.

THE CASE FOR PCM: ACTIVE STORAGE AND ACTIVE RETRIEVAL

In the above case, a passive approach using the thermal storage of the walls, slab and product is capable of shifting time of use for the storage component, as previously explained. In typical cold storage applications shifting all operations to eliminate infiltration and internal heat gains from equipment, lighting, and the refrigeration system is not an option. Often product respiration generates significant heat. For facilities with a more standard operating profile, shedding the refrigeration electrical demand and energy use while maintaining acceptable storage temperatures during the six hour utility peak requires that the building's thermal storage replace the cooling energy required for ongoing operations and the stored energy be effectively retrieved within the six hour period.

The particular building currently under construction is a 7,000 square foot (650 square meters), 34 F (1.1 C) produce cooler with 20 foot (6.1 m) high walls for Coke Farm. The cooler is an addition to an existing facility and shares a partition wall with an existing building. Based on standard steady state methodology for refrigeration load calculations, the refrigeration requirements were estimated at 26 refrigeration tons (RT) (91 kW) peak load. The skin loads are lower than a standard IMP building for reasons discussed above and the shared partition walls with the existing building. On the other hand, our dynamic spreadsheet model calculated the peak load at 14 RT (49kW) for the hottest two consecutive days of calendar year 2012, as shown in Figure 4. The difference in the two calculation methods was in the estimated infiltration load (5.5 RT vs. 13.7 RT for the steady state method). Peak product respiration load was similar in both methods, while peak lighting loads, skin loads, and equipment loads were all reduced in the dynamic model. These results agree with common experience that thermal mass delays and levels refrigeration load over the day. The dynamic model estimates the cooling load during the 12 PM to 6 PM peak periods as 75.5 refrigeration ton hours (906,000 BTU), (269kWh).

The total square footage of exterior wall is 4,700 square feet (437 square meters). With an average thickness of 3.25 inches (8.6 cm) the concrete can store approximately 9.75 BTU/sqft/degree F. If we were to allow a 10 F (5.5 C) change in *wall* temperature the concrete would provide 460,000 BTU, or approximately half of the required storage. To enhance the wall's thermal storage capacity we asked a vendor to design a PCM that would provide 94 BTU per square foot of wall and have a freeze/melt temperature at 26/28 F [-3.3/-2.2 C]. Early Differential Scanning Calorimetry (DSC) data is provided below in Figure 5(a).Under this scenario, the PCM provides about 440,000 BTU.

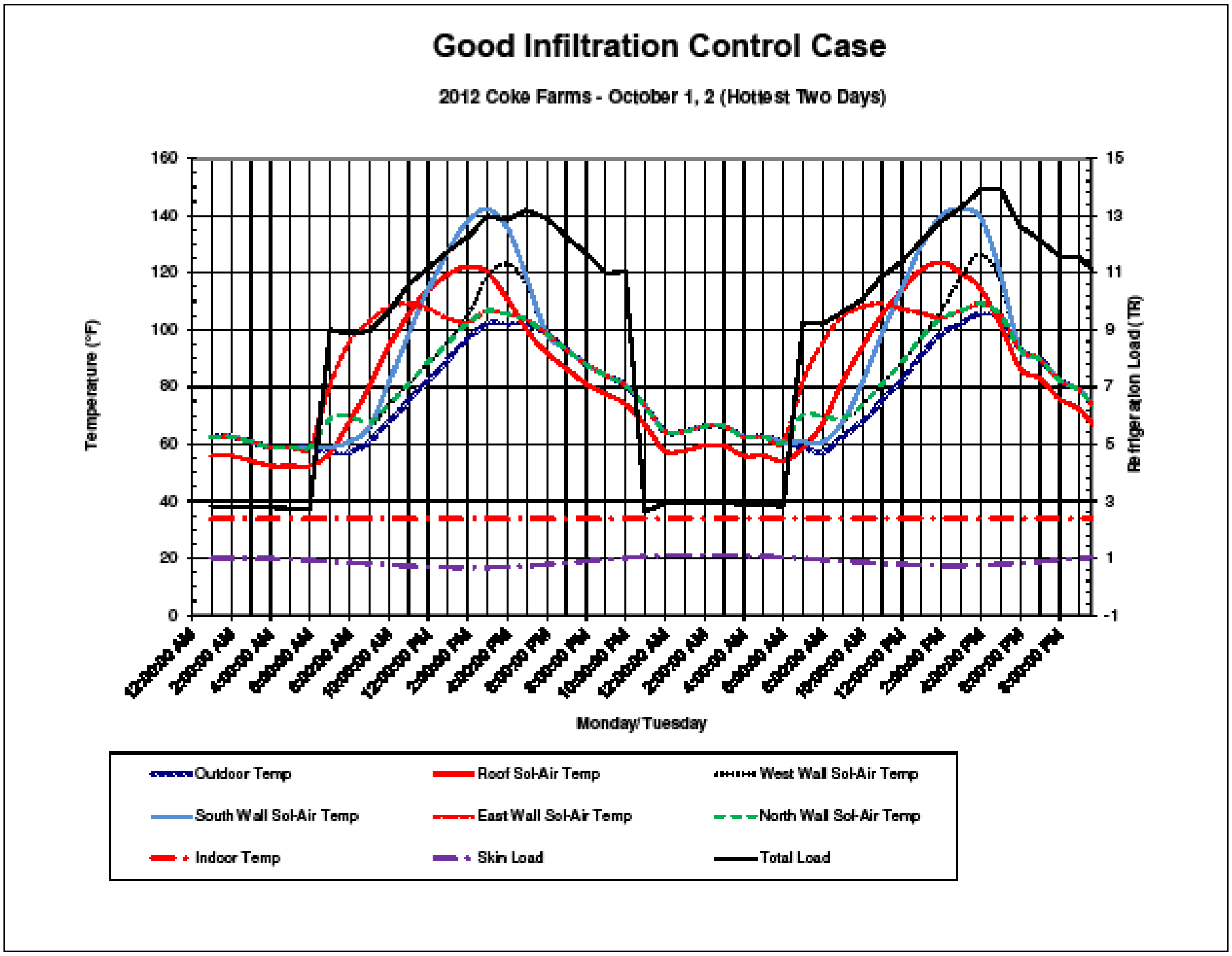

Figure 2 Demand loads by the dynamic model

Design Approach

The initial idea was simple in concept. Increase the effective thermal capacity of the inner concrete surfaces and link this thermal storage to the refrigeration system to *actively* remove heat from the thermal mass during non-peak utility hours and return heat to the mass during peak utility hours (store and retrieve cooling energy). Because of the storage temperature (34 F, 1.1 C) standard water ice thermal storage which can only provide 32 F single phase coolant isn't practical or efficient. Due to the close temperature approach extremely large room cooling units would be required increasing cost. High circulation air volumes and water flow rates would increase parasitic losses dramatically. Conventionally, a liquid ammonia recirculation system is the system of choice. However, the owner of the facility desired an efficient solution that avoided ammonia within the cold room for both personnel and product safety. For that reason CO2 was chosen as the secondary refrigerant. To achieve the enhanced thermal storage capacity of the 3" thick inner concrete layer several PCM technologies were evaluated. Micro-encapsulation was initially favored but cost and deleterious impacts on the strength of the concrete ruled this option out. The selected approach used a double layer plastic film mat with pockets filled with the PCM material installed between the inner concrete layer and the foam core of the wall as shown in Figure 5(b).

The design called for high pressure 3/8 inch refrigerant line to loop through the phase change mats at 7"centers. 1 1/2" inch supply and return headers at the top of the wall are connected to the refrigeration tubes. Conventionally, water in PEX tubing has been the coolant of choice for radiant comfort cooling applications; however at below freezing temperatures around food products propylene glycol/water mixtures must be used. At lower temperatures and higher concentrations greater viscosity and reduced heat transfer significantly increases pumping power. To minimize pump energy, maximize heat transfer efficiencies, safety and environmental concerns CO_2 was selected as the secondary refrigerant of choice. Pearson discussed the heat transfer and pumping efficiencies of re-circulated CO_2. CO_2 can be used as a secondary refrigerant either as a single phase or two phase fluid.

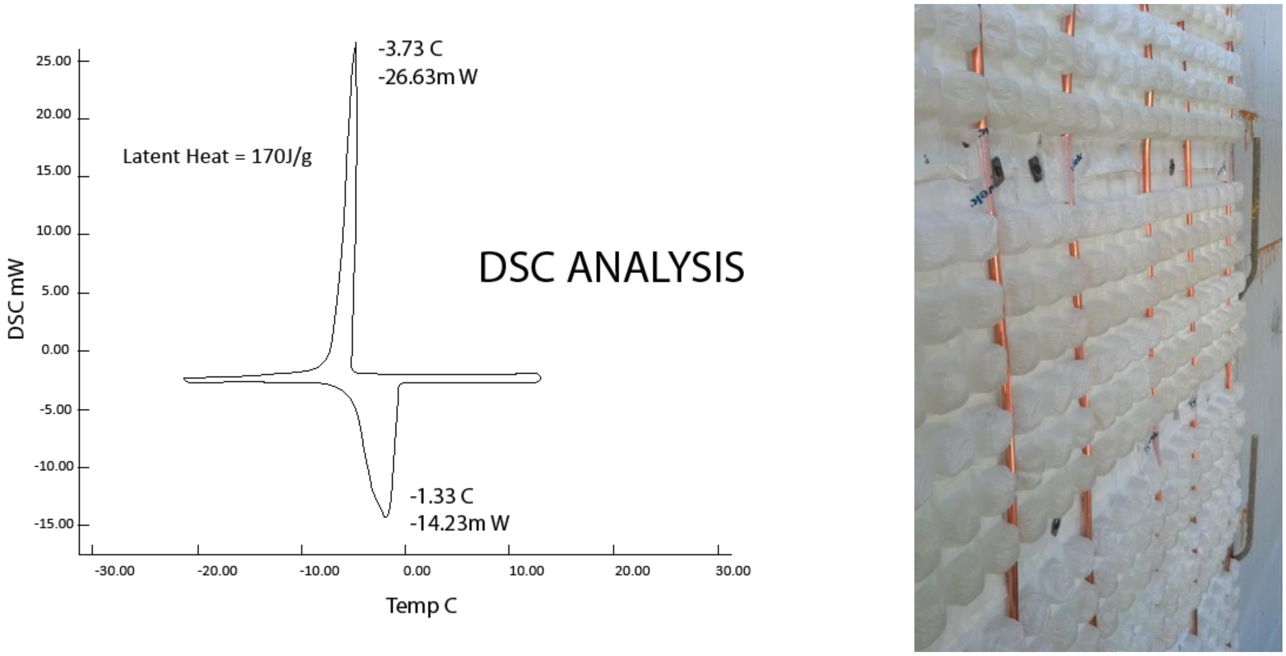

Figure 3 (a) Early DSC data for PCM and (b) the PCM mats installed with copper tubing laid over top.

In this case the two phase approach was chosen because a constant temperature is maintained throughout the heat transfer elements. This is favorable for maintaining a uniform temperature throughout the wall and uniform freezing of the PCM and also a constant fluid temperature during the PCM melt cycle. A standard vapor compression NH_3 system condenses the vaporized portion of the CO_2 in a flooded plate heat exchanger.

While preparing the wall with the PCM mats, some of them began to leak. Although assured by the manufacturer the PCM was harmless and inert to a variety of materials the PCM mats were removed at the request of the facility Owner. Given the construction schedule it was not possible to re-package the PCM material and place it in position in advance of placing the shotcrete. However, a test wall has been constructed with (i) PCM mats that were not leaking, (ii) PCM installed in thin plastic sticks directly attached to the tubing to solve future potential leaking problems, (iii) micro-encapsulated PCM placed in the shotcrete mix and (iv) a control with only concrete and refrigeration tubing as finally provided in the cooler. Since the phase change material was anticipated to provide 50% of the on peak cooling an energy alternative thermal storage was required if the project was to meet 100% shifting of refrigeration energy use to off peak. A system configuration has been developed placing the PCM at the central plant in insulated plastic storage tanks with coils of high pressure rated thermoplastic tubing. For experimental purposes insulated plastic tanks filled with water are being added as well in series with the PCM tanks. During the off peak period the returning two phase CO_2 from the room evaporators will discharge into a CO_2 receiver pressure vessel. In this vessel the vapor will separate from the liquid, and the vapor will rise to the cold NH_3/CO_2 heat exchanger where the vapor will condense at 25 F (-3.8 C). The ammonia side of heat exchanger will operate as a flooded thermo-syphon at 20 F. Once condensed, the CO_2 flows back to the receiver.

A VFD controlled magnetic coupled sealed pump circulates the CO_2 to the room evaporators. A portion of the CO_2

liquid is diverted to the storage tanks holding the PCM and water. A pressure drop caused by a manual flow balance valve causes boiling to occur and heat will be absorbed causing the water and PCM tanks to freeze.

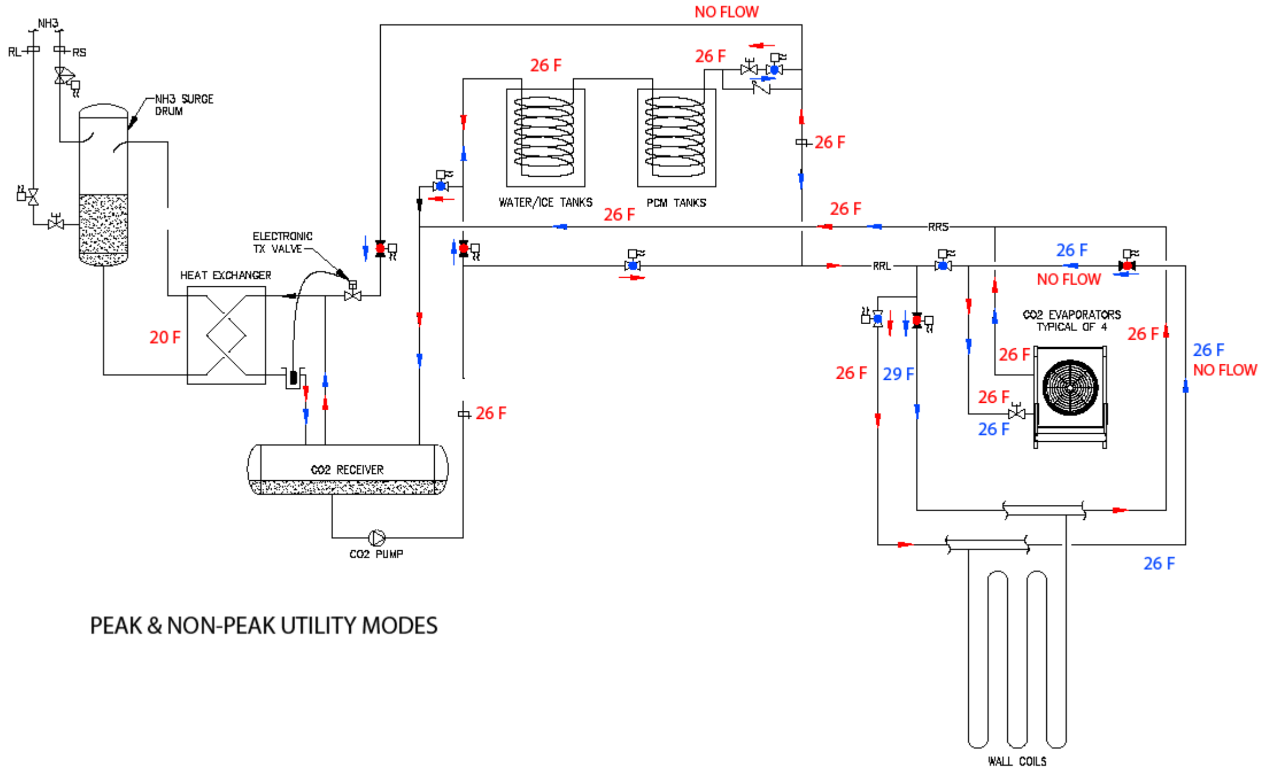

Figure 4 Mechanical system design for (a) Non-peak pricing utility mode and (b) peak pricing utility mode.

During the peak utility price period the system refrigerant flow changes. The CO_2 liquid pump continues to run and circulate the coolant. However, the liquid flow path changes and the CO_2 will first travel to the thermal storage tanks passing through the water ice tanks and then the PCM storage tank in reverse series flow compared to the freezing cycle.

The exiting flow bypasses the thermal storage tank coils expansion and solenoid valves by way of check valves which permit the reverse direction flow. The cooled CO_2 liquid then divides into two flow paths. One pipe returns 95% of the flow to the ammonia/CO_2 heat exchanger. The other pipe returns 5% of the cooled liquid CO_2 to the supply pipe feeding the cold room. At the cold room the liquid CO_2 is first sent to the wall headers, through the wall coils and then to the evaporators where it follows the standard path through the flow balance/expansion valves where a portion changes phase absorbing heat from the room. The two phase CO_2 leaves the evaporators and travels back to the CO_2 receiver as during normal operation. The CO_2 gas separates from the liquid and rises as before to the top of the ammonia/CO_2 heat exchanger which is now also being fed 29 F (-1.7 C) liquid CO_2 liquid through an expansion valve and distribution pipe from the thermal storage tanks. A portion of the sub-cooled liquid changes phase absorbing heat while the mass of the liquid also warms to 33 F absorbing the heat transferred from the cold room. During utility peak periods the ammonia system operational pressure settings are raised to allow the stored energy recovery cycle.

During this on peak operational phase the saturation pressure and temperature of the CO_2 in the receiver and heat exchanger must rise in order for any meaningful heat transfer to occur without the ammonia refrigeration system being engaged. The 40 RT (141 kW) of evaporator capacity at an 8 F (4.8 C) temperature difference (TD) as compared to an anticipated room load of 14 RT (49kW) allows the cooling demand to be met at a 3 F (1.66 C) TD. The room temperature is allowed to float to 37.5 F (3.1 C) therefor an evaporator temperature of 34 F (1.1 C) will meet the cooling needs without accounting for the passive cooling effects from the walls and floor.

Upon termination of the on peak utility period the CO_2 flow configuration cycles back to recharge the storage tanks and walls. The ammonia system operating pressure is reset equivalent to 20 F (-6.7 C) saturation temperature in the heat exchanger. The liquid CO_2 feed to the top of the ammonia/CO_2 heat exchanger is terminated by closing a solenoid valve. For facilities with conventional liquid recirculation ammonia systems a potential exists to exploit this strategy using water/ice and PCM storage. For higher storage temperatures (40 F, 4.5 C or greater) water/ice storage alone could be used.

CONCLUSION

The authors have presented the specific challenges of cold storage facilities which include; high skin loads, high infiltration loads and high product loads all coinciding within the hours of peak demand charges. A structural system, designed to reduce skin loads and supply large amounts of thermal storage is presented along with an integrated refrigeration system designed to charge the thermal storage off-peak and access it on demand. Additionally, the construction system is robust and long lived, employing concrete skins wrapped around an R-100 core that require little maintenance. The system meets the earthquake requirements for immediate occupancy buildings such as fire stations and hospitals, thus reducing the risk of damage and demolition even in a maximum credible event. These features lessen the frequency of replacement and reduce the demand on resources.

On the basis of previous constructions, calculations and finite element analysis, the author's estimate that the presented design will shift 75 ton-hours of refrigeration each day for a $14,000 annual savings, resulting in a simple payback of 4 years ($56,000 additional building costs/$14,000). Extrapolating the general design approach to a variety of thermally demanding situations including classrooms, auditoriums and churches could have a profound impact on comfort and the annual cost of energy.

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