OPTIMAL CONTROL OF HARVESTING ICE THERMAL STORAGE SYSTEMS

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ABSTRACT

Thermal storage is becoming a standard consideration in HVAC and process cooling systems. As the technology is refined, more attention is being given to minimize the energy consumption and power demand requirements. This paper addresses a method for optimal control of a harvesting ice storage system. A simplified procedure is used to develop 24 hour load data. Example installations will be shown.

INTRODUCTION

The desire to implement an optimal control for an ice storage system is based on the fact that a higher kw/ton is used to generate ice rather than generate chilled water in the 42° F temperature range. The objective of an optimal control is to minimize the cost of power and energy consistent with a given utility rate structure. Two types of ice storage systems will be discussed in general terms of optimal control with emphasis and detail on the optimal control of ice harvesting thermal storage systems.

OPTIMAL CONTROL AND UTILITY RATE STRUCTURES

To understand the need for optimal control, one has to look at the predominant utility rate structures. Utility rates are divided into two main segments:

DEMAND COMPONENT: The demand component is a charge for the capital costs of the power plant.

ENERGY COMPONENT: The energy component pays for the commodity used, including fuel, operating and maintenance costs.

The electric utility will vary these charges based on its load characteristics and with some 2,900 electric utilities there are quite a few rates. For purposes of this paper, only one general form of the rate structure will be used to explain how it effects the concept of optimal control.

BASIC RATE STRUCTURE

	ENERGY CHARGE	DEMAND CHARGE
ON PEAK	HIGH	HIGH
OFF PEAK	LOW	LOW

In the basic rate structure, the low off peak demand charge and low off peak energy charge will generally show significant cost savings in producing as much of the cooling as possible during off peak. In the non peak cooling months, typically October through May, all or most of the cooling effect should be made during the off peak hours. The loads which cannot be met from the off peak hours must be met through minimum chiller operation during the on peak period. When the daily loads are less than the ice generating capacity of the system, then only the amount of ice needed the next day should be produced to replace the depleted ice. This mode of operation is referred to as ice priority control.

GENERAL CHARACTERISTICS OF ICE STORAGE EQUIPMENT

STATIC ICE BUILDERS

A compressor aided configuration is illustrated in Figure 1. During the cooling period the ice charge inside the ice builder tank acts as an evaporator coil surface, cooling the return chilled water.

Operation of the refrigeration system during this period slows the meltdown and thereby provides more cooling capacity. This concept eliminates the need for a separate chiller evaporator and duplicate refrigeration components. However, it dramatically increases system operating costs, because the compressor must operate
at its most inefficient point with pipes completely covered with ice. Figure 2 shows the effect of operating such a system with various amounts of ice on the pipes.

The evaporator temperature of 10° F and compressor suction temperature of 8° F represent a chiller operation of nearly 2 kw/ton.

Figure 3 shows a static ice builder with parallel chiller evaporator. The operation is similar to Figure 1, except that direct cooling loads can be met with chiller evaporator loads, thereby improving the efficiency at considerably increased equipment costs.

In both Figures 1 and 2, the ice is

built up on the pipe following the general rules shown in Figure 2. As the ice begins to insulate the pipe a lower and lower evaporator temperature is produced showing a higher and higher kw/ton. In systems where the ice is not melted daily, the recharge of the system is done very inefficiently since ice is an excellent insulator. The marginal topping of a system can show seasonal operation of 1.5 to 2.0 kw/ton.

THE ICE HARVESTING SYSTEM

Ice harvesting systems separate the function of making ice and storing ice. The ice is formed on the outside of flat heat exchangers arranged in vertical banks to a thickness of less than .25 inches. The ice is harvested by introducing warm gas into the inside of the plates. The warm gas breaks the bond between the ice and the plates causing the ice to drop into the storage tank. By decoupling the manufacture of ice from the storage of ice, the same evaporator surface that makes the ice can also operate as a high efficiency chiller meeting the building loads directly. Figure 4 shows an ice harvesting system. A fully packaged ice harvesting system is placed over a storage tank. The water recirculation pump operates whenever the compressor is operating. If there is no load, the system makes ice. Each pound of ice is made in .25 inch increments at less than 1 kw/ton. The last pound of ice is made with the same efficiency as the first pound of ice, whether it is hour one, or year twenty. When the water flowing over the plates is above 32° F, the system operates as a high efficiency chiller. This occurs whenever the building load is directly applied to the ice harvesting system.

Optimal Control Strategies

Optimal control strategies for static ice builders and harvesting ice generators are the same. However, the execution is much simpler with the harvesting ice generator, and the consequences of control error are much less severe. The basic control strategy is as follows:

Mode 1. Daily load less than the maximum ice capacity of the system.

Operation 1. Make only enough ice in the off peak period to meet the load.

Mode 2. Daily load greater than the maximum ice capacity of the system.

Operation 2. Make a full charge of ice in the off peak period and minimize the chiller operation to limit demand.

The STATIC ICE BUILDER will require a predictive strategy to operate efficiently in mode 1. Since it is necessary to completely melt the ice charge prior to rebuilding the next day, the predictive strategy must be accurate and reliable, far beyond the normal weatherman's predictions, or the depletion of storage will necessitate the restoration of chiller mode and the setting of new peaks.

The HARVESTING ICE GENERATOR/CHILLER does not require a predictive strategy to operate efficiently in mode 1. Inherently, each pound of ice is made at the same efficiency. Therefore, simply fill the tank each off peak period as required. For example, if the daily load is 25% of capacity only 25% of the ice is melted. Topping the tank is accomplished efficiently. The real advantage is that there is always a full tank to begin the next melting period, and if the loads are higher than expected, the ice stored in reserve is there to meet the loads without bringing a chiller on line and setting a new peak.

Operation in mode 2 requires a predictive strategy for both the static ice builder and the ice harvester. The remaining portion of this paper will address the principles of predictive controls as applied to ice harvesting chillers.

UNDERSTANDING THE LOAD TO BE PREDICTED

The cooling load on a building consists of the following components.

EXTERNAL LOADS:

SOLAR
CONDUCTION
OUTSIDE AIR (ventilation)
OUTSIDE AIR (infiltration)

INTERNAL LOADS:

LIGHTS
PEOPLE
EQUIPMENT
APPLIANCES

These loads become loads on the air-conditioning system through a complex interchange of energy to the air mass. Convective loads and latent loads become instantaneous loads on the air-conditioning system. Radiant loads are absorbed by the building materials and furnishings and become a delayed load, out of phase with the instantaneous loads. Calculation of the actual load in any given hour is quite complex. However, calculation of the 24 hour load is absolutely trivial, if weather can be predicted.

Sizing the airside of an air-conditioning system requires a zone by zone calculation to determine individual peaks. These zones are aggregated on to an air handling unit. The aggregate instantaneous load becomes the coil load and is used for sizing chilled water piping. In a conventional system, the chiller is sized to meet the instantaneous simultaneous peak of the air handling units.

In a thermal storage system, the 24 hour load is the critical information necessary to size the refrigeration plant and storage. This load can be obtained from hour by hour calculations, or from the simplified procedure proposed.

The 24 hour load = The 24 hour gains regardless of when they occur - the heat loss to the surroundings

The 24 hour loads may be computed as follows:

where equipt = equipment
appli = appliances
oash = outside air sensible heat
oalh = outside air latent heat

people = activity level * number * total hours
lights = wattage * number * total hours
equipt = power * conversion * total hours
appli = power * conversion * total hours
oash = 1.1 * cfm * (toa - tr) * applicable hours
oalh = 4840 * cfm (Wo - Wr) * applicable hours

The 24 hour solar and conduction loads are computed as follows:

Solar

The solar contribution is computed with Equation 1.

$$QSOL = \sum_{i=1}^{N\,EXP} (MSHGF_i \times AG_i \times SC_i \times CLFTOT_i) \qquad (1)$$

where N EXP = number of different glass exposures

QSOL = averaged solar contribution

MSHGF = maximum solar heat gain factor for orientation i for July at the specified latitude (Btu/hr-sf)

AG_i = glass area for exposure..i (sf)

SC_i = shading coefficient of glass for exposure i

$CLFTOT_i$ = 24 hour sum of CLF for orientation i, Table 1

Transmission Load

The transmission load consists of conduction through walls, roof, and glass.

(1) Glass: The contribution due to glass is computed from Equation 2.

$$QT = \sum_{i=1}^{N\,surf} (AG_i \times UG_i)\ (\bar{T}_o - T_I \times .24 \qquad (2)$$

where N surf = number of conduction surfaces in the zone

AG_i = glass area
UG_i = U value of the glass
$\underline{A}_F$ = building area
T_o = outside (diversified) temperature
T_i = inside temperature to be maintained

(2) Opaque surfaces (walls and roof) The contribution from the opaque walls consists of a contribution due to the air-to-air temperature difference, and a time averaged solar component due to absorption of solar radiation on the outer surface.

Equation 3 is used to compute the contribution due to air-to-air temperature difference.

$$QT = \sum_{i=1}^{N\,surf} (UA)_i \times \bar{T}_o - T_i) \times 24 \qquad (3)$$

where UA_i = UA product for surface i

The solar contribution from the opaque surfaces is computed in the summer, using Equation 4.

$$QTS = \sum_{i=1}^{N\,EXP} (A_i U_i \times CLTDS_{Jul} K) \times 24 \qquad (4)$$

Table 1
CLF for Glass

	CLF SUM	12 HR AVG	24 HR AVG
N	11.57	.96	.48
NE	5.15	.43	.22
E	5.46	.46	.23
SE	6.2	.52	.26
S	6.43	.54	.27
SW	6.23	.52	.26
W	5.46	.46	.23
NW	5.15	.43	.22
HOR	8.22	.69	.34

Table 2
CLTD Solar Component
24 Hour Average
(CLTDS)

July

Dir	Latitude 16	24	32	40	48	56
N	9	6	6	5	5	5
NE	14	13	11	11	11	11
E	14	15	15	15	16	17
SE	9	11	13	14	17	19
S	3	4	7	10	14	17
SW	9	11	13	14	17	19
W	14	15	15	15	16	17
NW	14	13	12	11	11	11
Roof	22	23	23	22	22	20

January

Dir	Latitude 16	24	32	40	48	56
N	1	1	0	0	-1	-1
NE	4	3	2	1	0	0
E	11	9	7	6	4	1
SE	18	17	16	15	14	8
S	22	23	26	21	18	12
SW	18	17	16	15	9	8
W	11	9	7	6	4	1
NW	4	3	2	1	0	0
Roof	15	11	7	3	-2	-5

Color Correction Multipliers K

	D	M	L
Wall	1	.83	.65
Roof	1	.75	.50

The net effect is that a complex hourly load shown in Figure 5 may be computed easily and represented accurately by Figure 6. This works very well for design purposes, but what about off design days?

PREDICTIVE CONTROL TECHNIQUES

The 24 hour future load may be predicted by knowing the following:

1. Lighting schedules
2. People occupancy schedules
3. Equipment schedules
4. Appliance schedules
5. Outside air schedules
6. Fraction of cloud cover
7. Daily average temperature

The techniques defined above are used for load calculations.

Figures 7a and 7b show the typical effects of the loads. As the ambient conditions change, the operational modes change. Figure 7a shows the summer design day loads with mode 2 operation. Figure 7b shows winter day loads with mode 1 operation.

Once the 24 hour load is known for any given system, the ice storage capacity is known and the available run time of the equipment is known. If the ice capacity is greater than, or equal to the load, mode 1 prevails. If the load is greater than the ice capacity, the chiller operation is computed as follows:

Chiller average tons =
(24 hour load-ice capacity)/chiller runtime

Operation of the chiller at this tonnage will minimize total system demand. Figure 8 shows a typical operating scenario for meeting the load in mode 2.

This level of predictive control may be implemented using a microprocessor control system.

CONCLUSION

Harvesting ice generators do not require optimal control systems to optimize ice production. That is inherent in the system design.

Optimum chiller operation can be obtained with predictive control using simplified algorithms.

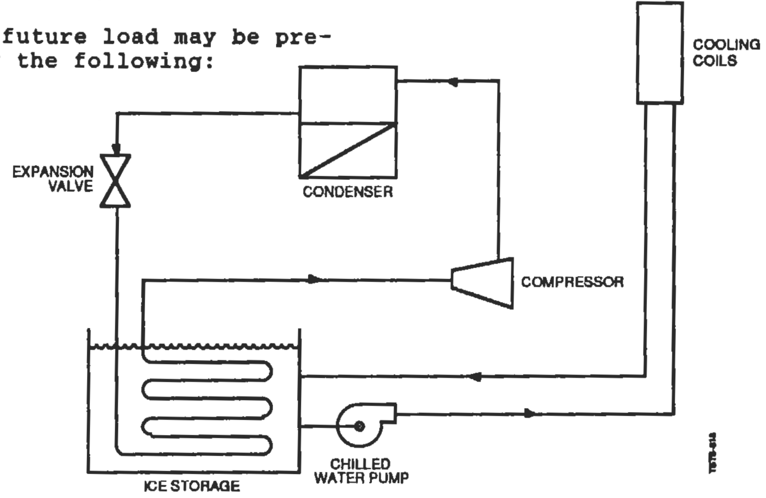

Figure 1 Compressor-Aided Storage System

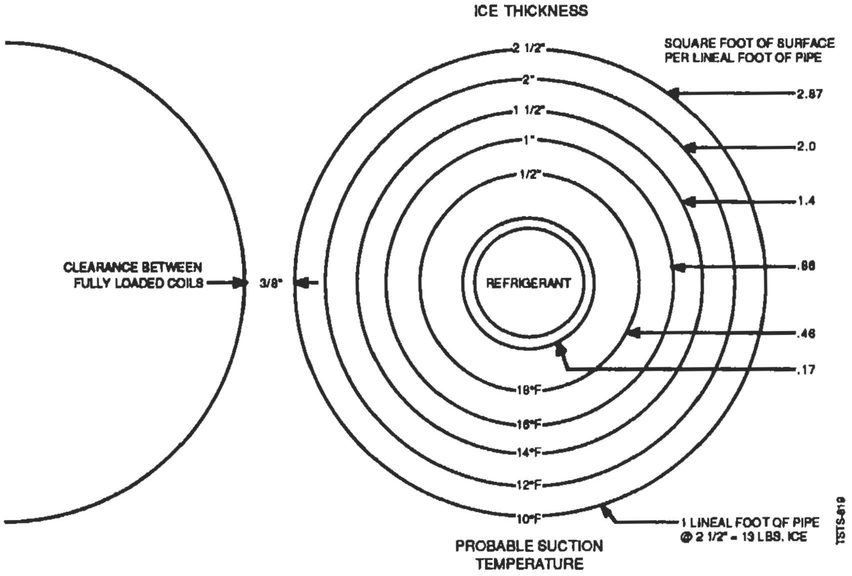

Figure 2 Pipe Coil Data

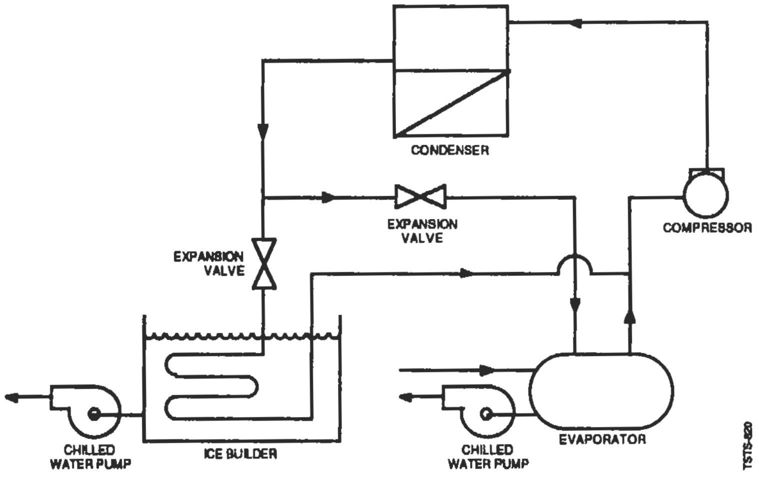

Figure 3 Ice Storage/Parallel Evaporator Arrangement

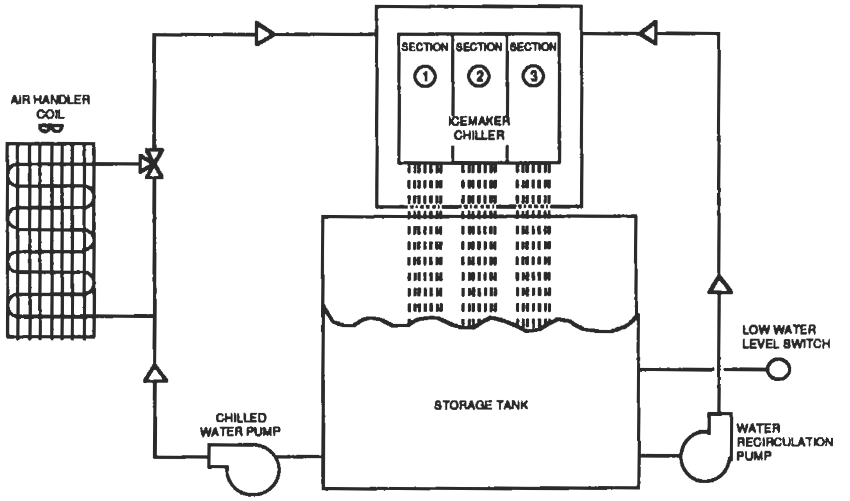

Figure 4 Icemaker Plate Module

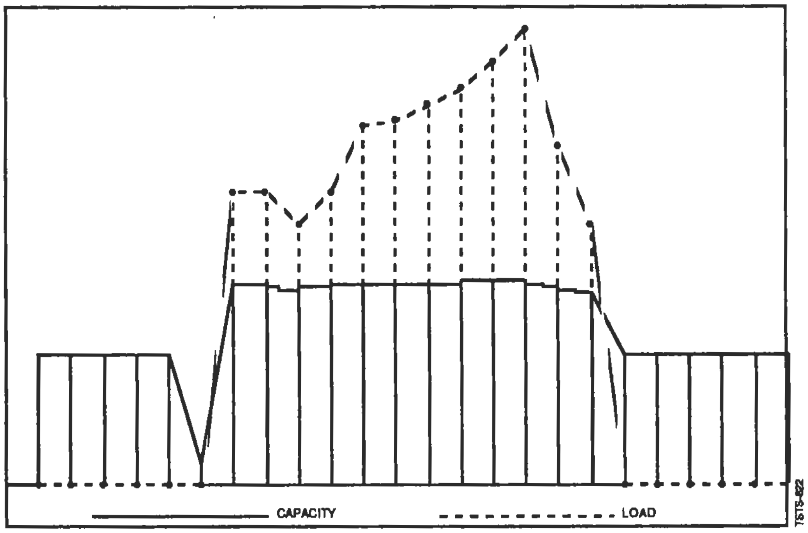

Figure 5 Capacity and Load—Daily Load Leveling for Tuesday

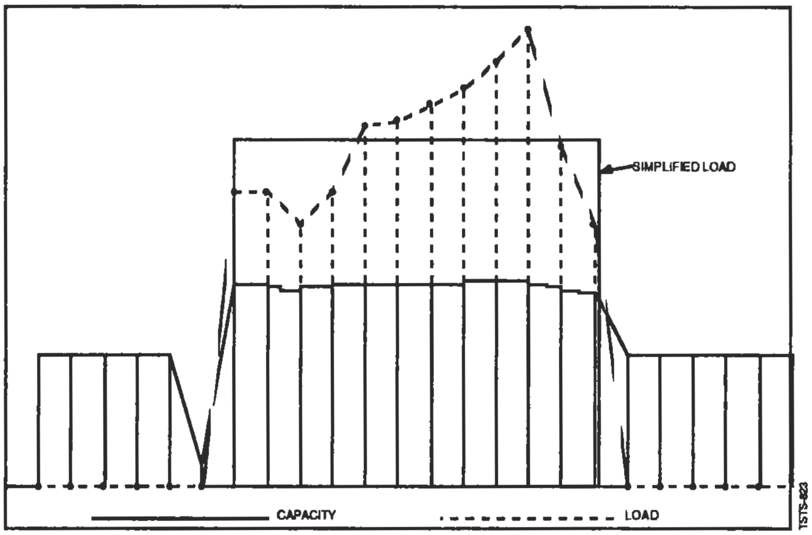

Figure 6 Capacity and Load—Daily Load Leveling for Tuesday with Simplified Load Superimposed

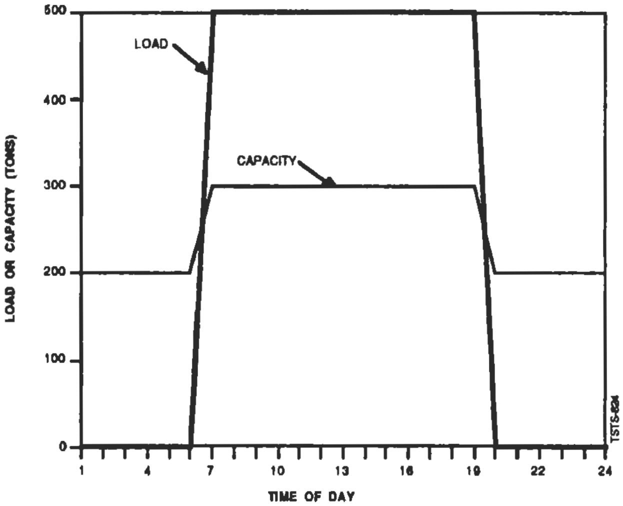

Figure 7a Summer Design Day—Mode 2

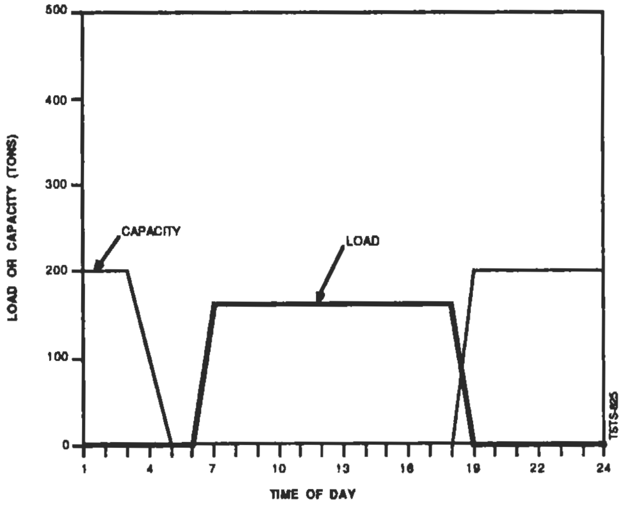

Figure 7b Winter Day—Mode 1

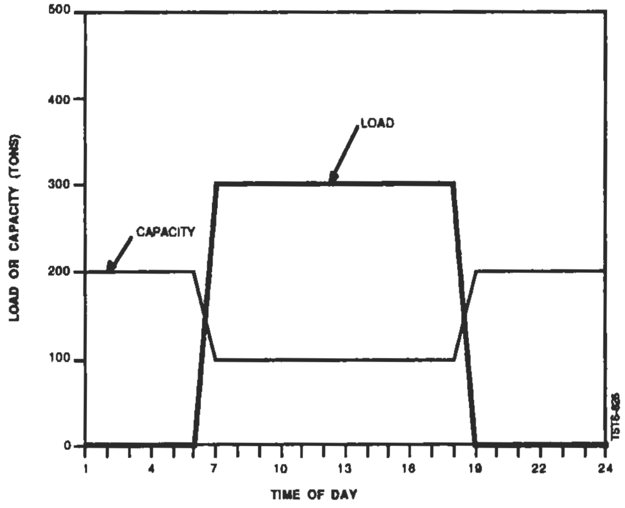

Figure 8 Intermediate Day—Mode 2