BRINE CIRCULATED
ICE THERMAL STORAGE SYSTEM DESIGN
- CASE ILLUSTRATION -

Partial Ice Storage for Air Conditioning Application

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The technology of ice thermal storage application for air conditioning system is not new and it is not difficult. Actually, the system design requires only the very basic technical know-how and engineering practices.

Many basic principles required for ice thermal storage system design are already outlined in the articles of "The System Configuration" and the "Brine circulated Ice Thermal Storage Systems". The important points are summarized here for ready reference as the following:

1.0 The design must be "system" approach.

2.0 The system configuration must be correct. (See the article of "The System Configuration".

3.0 The ice builders must be arranged to avoid hydraulic short circuit and to avoid thermal short circuit. The brine flow must be designed to avoid ice melting problem.

4.0 The system operating mode either based on ice priority or chiller priority must be determined and the operation principal must be followed; otherwise, the system has no characters.

5.0 The brine chiller and ice builder must be selected in accordance with the system operation mode as designed.

6.0 The ice builder must be selected and checked to have the charge and discharge efficiencies as the following:

6.01 Charge efficiency - The ice builder must have the capacity to store the total latent

TR-HR with the following conditions specified:

(A) Full ice built within the time period specified.

(B) At the design refrigeration TR of the chiller.

(C) Under the design entering brine temperature, i.e. the ice builder shall not require brine lower than the design entering temperature. Brine flow rate and the final pull down brine temperature are to be as specified.

6.02 Discharge efficiency - The ice builder must be able to deliver the cooling TR at each hour as allocated and especially the final hours at the design leaving brine temperature and the brine flow as specified.

7.0 The system control must be arranged in accordance with the operating mode to provide the TR-HR for the air conditioning at each hour at a constant system leaving chilled water temperature and constant chilled water flow.

8.0 The system must be installed and operated in accordance with the operating mode as designed.

Most ice thermal storage systems have failed because the designer without even knowing the characteristics of the ice builders. The ice thermal system shall not fail if system is properly designed and follows the above outlined principles.

BASE DESIGN REQUIREMENTS
FOR THE JOB:

This example is based on brine circulated system. The general descriptions of the job used in this example are as the following:

A. The building is an office complex. Air conditioning is required from 8:00 AM to 6:00 PM. No air conditioning is required in the evening.

B. A central chilled water plant with partial ice thermal storage is to be considered.

C. The system is to be designed for brine circulation. A plate type heat exchanger is to be used to produce the chilled water for the air side equipment.

D. The system is to use water cooled condenser and R-22 refrigerant standard chillers.

E. The space for ice builders is to be allocated based on the optimum system operating efficiency of the chillers at the design day.

F. The chillers are to be with screw compressor with hot gas bypass for operation from 10% to 0% load. The unit is to be modified for ice thermal storage application.

G. The chilled water primary circuit temperature is 40°F leaving and 55°F return for the following reasons:

(1) Better air quality.
(2) Smaller chilled water piping system.
(3) Smaller chilled water pumping horsepower.
(4) Smaller air handling equipment.
(5) Lower fan horsepower.

H. The brine temperature entering to the ice builder during the ice making operation is to be 22°F, leaving at 27°F.

OUTLINE DESIGN CONDITIONS:

System Chilled Water:	Return	55°F
	Leaving	40°F

Cooling Water from cooling tower:

Day time:	Return	100°F
	Leaving	90°F
Night time:	Return	97°F
	Leaving	87°F

Constant cooling water flow is to be used for design for both air conditioning and ice making duties.

In order to obtain 40°F primary leaving chilled water for air condition duty, the brine leaving temperature from the ice builder during discharge day time operation is to be 38°F.

Peak building cooling load:	1,000 TR
Air conditioning period, day time:	10 Hours, 8:00 AM to 6:00 PM
Operation change over :	1 Hour
Ice making duty, night time :	13 Hours

LOAD PROFILE:

Cooling load profile at the design day is shown as below:

Table-1 Cooling Load Profile

Cooling Time Period	Cooling Load
8:00 - 9:00 AM	560 TR
9:00 - 10:00 AM	735 TR
10:00 - 11:00 AM	830 TR
11:00 - 12:00 AM	940 TR
12:00 - 1:00 PM	960 TR
1:00 - 2:00 PM	980 TR
2:00 - 3:00 PM	1,000 TR
3:00 - 4:00 PM	935 TR
4:00 - 5:00 PM	780 TR
5:00 - 6:00 PM	540 TR
Total 10 hours	8,260 TR-HR Design day

SYSTEM DESIGN:

An ice thermal storage system which is having lowest annual power consumption and possibly having easiest system control is the system that is having the following arrangements:

I) The chiller and the ice builder is in series operation.

II) The chiller is to be located in the up stream of ice builder. The return brine from the plate type heat exchanger flows through the chiller first and then to the ice builder. This position shall allow the chiller to be operated at a higher return and higher leaving brine temperatures anytime during air conditioning application. Higher leaving brine temperature means higher evaporative temperature and lower power consumption, better efficiency and larger cooling capacity.

After the system configuration is decided, it is very important to determine if the system is to be operated on ice priority mode or on chiller priority mode. From the article of "System Configuration", ice priority mode is always better than chiller priority mode, therefore, this example shall base on ice priority mode. A separate section is provided for the illustration of chiller priority mode in this article.

CASE ILLUSTRATION
ICE PRIORITY MODE
ICE THERMAL STORAGE SYSTEM

DAY TIME AND NIGHT TIME
LOAD CALCULATION FOR THE CHILLER
AND ICE STORAGE CAPACITY
DETERMINATION:

The basic design criteria of the project is as the following:

(1)	Peak design building cooling load:	1,000 TR
(2)	Air conditioning period, day time:	10 Hours
(3)	Operation change over :	1 Hour
(4)	Ice making duty, night time :	13 Hours

The cooling load profile is shown in Table-1. The total design cooling required for the design day is 8,260 TR-HR. The peak cooling load is 1,000 TR between 2:00 to 3:00 PM.

The formulas to calculate the compressor refrigeration capacity and ice storage capacity for Ice Priority mode operation from the article of "System Configuration" are as the following:

$$TR2 = \frac{\text{PEAK TR} \times D}{D + CCR \times N}$$

TR1 = CCR x TR2

Ice storage capacity (TR-HR)
for the ice reserve unit
= TR1 x N

Ice melting (TR) from ice reserve unit
per hour during peak design day:

$$\text{Ice melting TR} = \frac{TR1 \times N}{D}$$

$$CCR = \frac{TR1}{TR2}$$

PEAK TR =	Peak building design load.
N =	Night time ice duty compressor running hours.
D =	Day time A/C duty compressor running hours.
TR1 =	Ice duty TR at ice duty operating conditions.
TR2 =	A/C duty TR at A/C duty operating conditions.
CCR =	Compressor capacity ratio, rated ice duty TR and rated air conditioning TR of the compressor.

The above formulas should give the optimum TR1 and TR2 allocations for the compressor for both air conditioning duty during day time operation and ice making duty during night operation based on the performance of the screw compressor at the design points.

The CCR factor is the compressor capacity ratio which is from the manufacturer's compressor data and the actual compressor performance at the operating conditions of this job, the CCR factor is 0.64 for this example. This CCR factor is to be checked and is to be re-justified for each case.

Therefore, the data for the formulas are:

PEAK TR = Peak building design load.
= 1000

N = Night time ice duty compressor running hours.
= 13

D = Day time A/C duty compressor running hours.
= 10

CCR = Compressor capacity ratio, rated ice duty TR and rated air conditioning TR of the compressor.
= 0.64

$$TR2 = \frac{1{,}000 \times 10}{10 + 0.64 \times 13}$$

= 546 TR

TR1 = 0.64 x TR2

= 0.64 x 546

= 349 TR

Therefore:

Compressor or chiller day time duty is 546 TR
(Air conditioning supplement duty)

Compressor or chiller night time duty is 349 TR
(Ice making duty)

Ice storage capacity = 349 x 13

= 4,537 TR-HR

Daytime ice melting = 4,537/10

= 454 TR (Per Hour)

The ice reserve unit is to deliver a fixed cooling of 454 TR every hour as calculated for the design day and for normal operation based on ice priority mode.

The cooling TR-HR available for air conditioning operation during day time operation from both the chiller supplement and from the ice builder are listed in the Table-2. The cooling sources indicated in the Table-2 shall be the cooling available on hourly basis for the office building at the design day.

Table-2 Cooling Source Allocation

Cooling Time Period	Cooling Load Profile	Cooling From Ice Reserve Units	Cooling Supplement By Chiller Units
8:00 - 9:00 AM	560 TR	454 TR	106 TR
9:00 - 10:00 AM	735 TR	454 TR	281 TR

10:00 - 11:00 AM	830 TR	454 TR	376 TR
11:00 - 12:00 AM	940 TR	454 TR	486 TR
12:00 - 1:00 PM	960 TR	454 TR	506 TR
1:00 - 2:00 PM	980 TR	454 TR	526 TR
2:00 - 3:00 PM	1,000 TR	454 TR	546 TR
3:00 - 4:00 PM	935 TR	454 TR	481 TR
4:00 - 5:00 PM	789 TR	454 TR	335 TR
5:00 - 6:00 PM	540 TR	454 TR	86 TR
Total 10 Hours	8,260 TR-HR	4,540 TR-HR	3,729 TR-HR

Total 8,269 TR-HR

The total cooling requirement for the design day for the building is 8,260 TR-TR; The cooling capacity produced by the ice thermal storage system is 8,269 TR-TR. If no safety margin is included in the cooling load or load profile, a 15% operational margin is recommended for the chiller and the ice builder.

This example assumes that the peak load and the load profile already included the safety factor of 15%, therefore, no additional operational margin is added.

The chiller used is suggested to be screw type compressor instead of centrifugal. The partial load performance of a centrifugal machine is very poor and it is not stable at the low partial load or small temperature difference operation, because the compression head of a centrifugal is limited and have surge problem. Screw compressor can be operated down to 10% without surge and the performance is fairly stable when it is operated at small temperature difference.

For an ice priority mode system, the chiller (compressor) only operates at the hour when the building is at 100% peak load which is 1,000 TR in this example. The chiller will be operated at partial load as the supplemental cooling for all other hours even during the design day. The energy consumption is therefore, greatly reduced.

BRINE CIRCULATION CALCULATION:

The brine temperature and flow for ice making is very important. Therefore, the brine circulation rate is usually based on night operation for the ice thermal storage system.

The temperature range (the entering brine temperature - leaving brine temperature) for the ice builder should be reasonably small as possible, the practical range is 5°F to 7°F. For example, if the entering brine temperature required for the ice builder is 22°F, with 5°F temperature range, the design leaving brine temperature from the ice builder is 27°F.

The brine circulation flow rate is also to be balanced with the operating conditions during the discharge cycle. The brine circulation rate will be too large if the brine temperature range is too small and the LMTD is too high if the brine temperature range is too big which is no good for the ice builder.

The brine used for ice thermal storage system is the common brine of Ethylene Glycol and the concentration of the brine shall be 35% by weight so that the brine will not freeze up during pull down operation at the final hour of ice making. The brine flow is calculated as the following:

Refrigeration capacity for ice making:	349 TR
Entering brine temperature to ice builder:	22°F
Ice builder brine leaving temperature:	27°F
The average brine temperature:	24.5°F.

From the brine curves of Figure-18 to Figure-22 in the article of "Brine Circulated Ice Thermal Storage System", the transportation properties of the brine are:

Freezing temperature:	-5°F
Specific Gravity:	1.0546
Specific Heat:	0.86

The brine flow for the 349 TR is calculated by using the formula (1) as shown in the article of "Brine Circulated Ice Thermal Storage System":

Btu/hr = 499.8 x GPM x S.G. x Cp x (T2 - T1)

Btu/hr = 349 TR x 12,000
= 4,188,000 Btu/Hr.

S.G. = 1.0546
Cp = 0.86
T2 = 27
T1 = 22

Therefore:

4,188,000 = 499.8 x GPM x 1.0546 x 0.86 x (27 -22)

Brine flow = GPM = 1,848 Gallons per minute.

Therefore, the design conditions for night time ice making duty for the ice builder is 349 TR, supply with 1,848 GPM 35% by weight of Ethylene Glycol brine at the entering temperature of 22°F to the ice builder, leaving at 27°F.

THE SYSTEM LAYOUT:

The ice thermal storage system layouts are as the following:

1.0 If two brine chillers are to be used and connected in parallel, the ice making duty of each of the two brine chillers is 175 TR to cool 924 GPM 35% by weight of Ethylene Glycol brine from 27°F to 22°F. The brine circuit for the brine chillers for the ice duty is shown in the Figure-1.

2.0 Same brine flow of 1,848 GPM is to be kept for air conditioning duty operation. The peak cooling load required is at 2:00 p.m. which is 1,000 TR. The building is to be cooled by the combination of (i) the TR-HR from ice melting and (ii) the supplement from the chillers. 454 TR is from ice melting and 546 is from the chiller supplement at this hour. See the cooling sources listed in the Table-2.

3.0 Figure-2 shows the system design operating conditions for the daytime operation. The operating temperatures are determined as the following:

(A) The lowest reasonable leaving chilled water temperature can be obtained from brine circulated ice thermal storage system is about 40°F through the plate type heat exchanger with leaving brine of 38°F from the ice builder. The return chilled water is 55°F, the chilled water range is 15°F.

(B) Ice melting from the ice builder is 454 TR, therefore, with brine flow of 1,848 gpm and leaving brine temperature of 38°F, the entering brine temperature to the ice builder is calculated at 44.45°F.

(C) The brine temperature leaving the brine chillers is same temperature as the brine entering to the ice builder, i.e. 44.45°F. The capacity of the two brine chillers is 546 TR. Therefore, the brine entering temperature to the chillers is 52.23°F.

(D) The chillers are to be controlled with a leaving chilled brine temperature of 44.45° for air conditioning operation during day time. The brine chillers are unloaded when the return brine temperature is lower than 52.23°F or the leaving brine temperature is lower than 44.45°F.

(E) The chillers are not operating whenever the building load is lower than 45.4% or when the return brine temperature to the chillers is below 44.45°F.

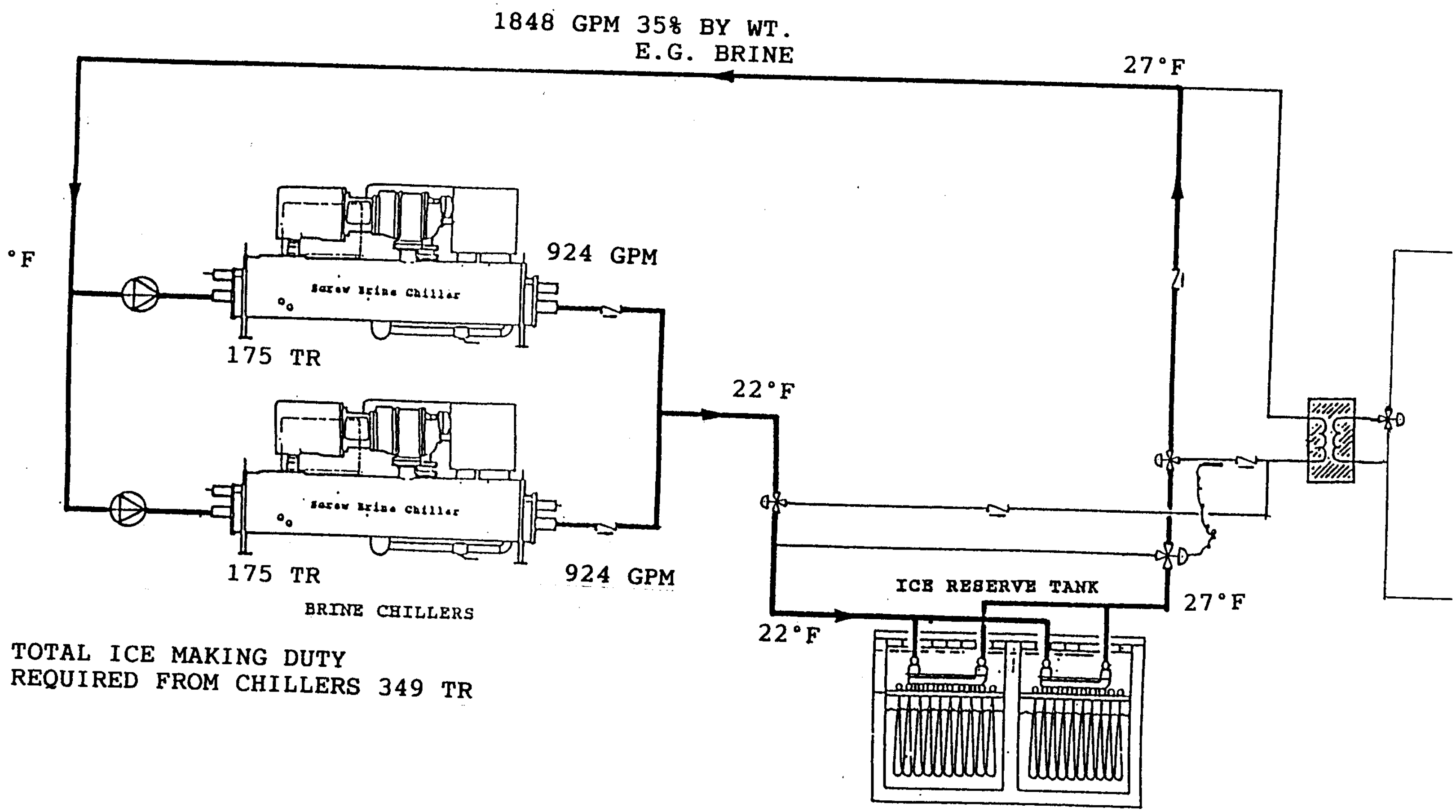

FIGURE-1 SYSTEM LAYOUT
NIGHT TIME ICE MAKING OPERATION
ICE PRIORITY

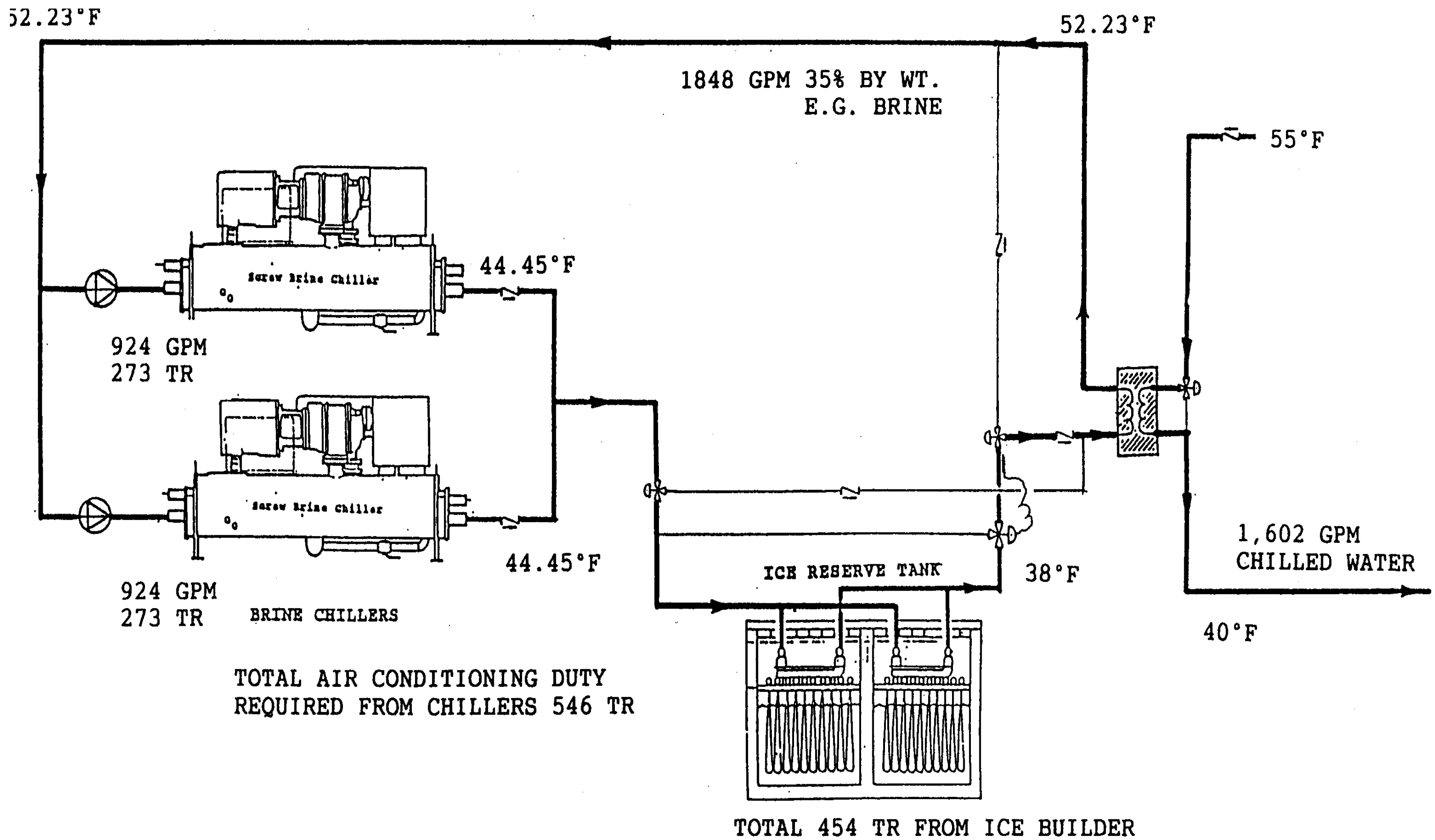

FIGURE-2 SYSTEM LAYOUT
DAY TIME A/C OPERATION
ICE PRIORITY

(F) With 55°F return to 40°F leaving, 15°F temperature range for the chilled water at peak design load of 1,000 TR, the chilled water flow is 1,602 gpm.

THE MODES OF OPERATION:

The Table-2 shows the mode of ice priority operation. The ice builder delivers a fix amount of 454 TR cooling every hour, if the cooling is not enough for the building, the cooling is supplemented by the chiller. This is the mode of the system being designed for the design day and for the entire cooling of the season.

The Figure-3 shows the Temperature and Capacity chart. The scale on the top is the 100% load line. The return chilled water temperature is 55°F and the leaving chilled water temperature is 40°F. The vertical line on the right is the system load from 0% to 100%. This system chart provides the capacity, the operating conditions, the supplement cooling from the brine chiller and the ice melting from the ice builder. This chart provides the information for load conditions from any partial load to the 100% design load.

At 100% load, 546 TR is provided by the chillers, it is equivalent to cool the 1,602 gpm chilled water from 55°F to an intermediate temperature (Ti) of 46.81°F. The ice builder provides 454 TR, it is equivalently to cool the 1,602 gpm chilled water from 46.81°F to 40°F by the ice melting.

At 80% partial load, a horizontal line is drawn at 80%. The chilled water return temperature is 52°F instead of 55°F. The chilled water is equivalently to be cooled down by chillers from 52°F to 46.81°F and is equivalently further cooled down to 40°F by ice melting. Actually, from the brine circuit, the brine temperature leaving the ice builder is kept at 38°F, the brine temperature leaving the plate type heat exchanger is 49.38°F at 80% load instead of 52.23°F and the brine leaving the chillers is 44.45°F.

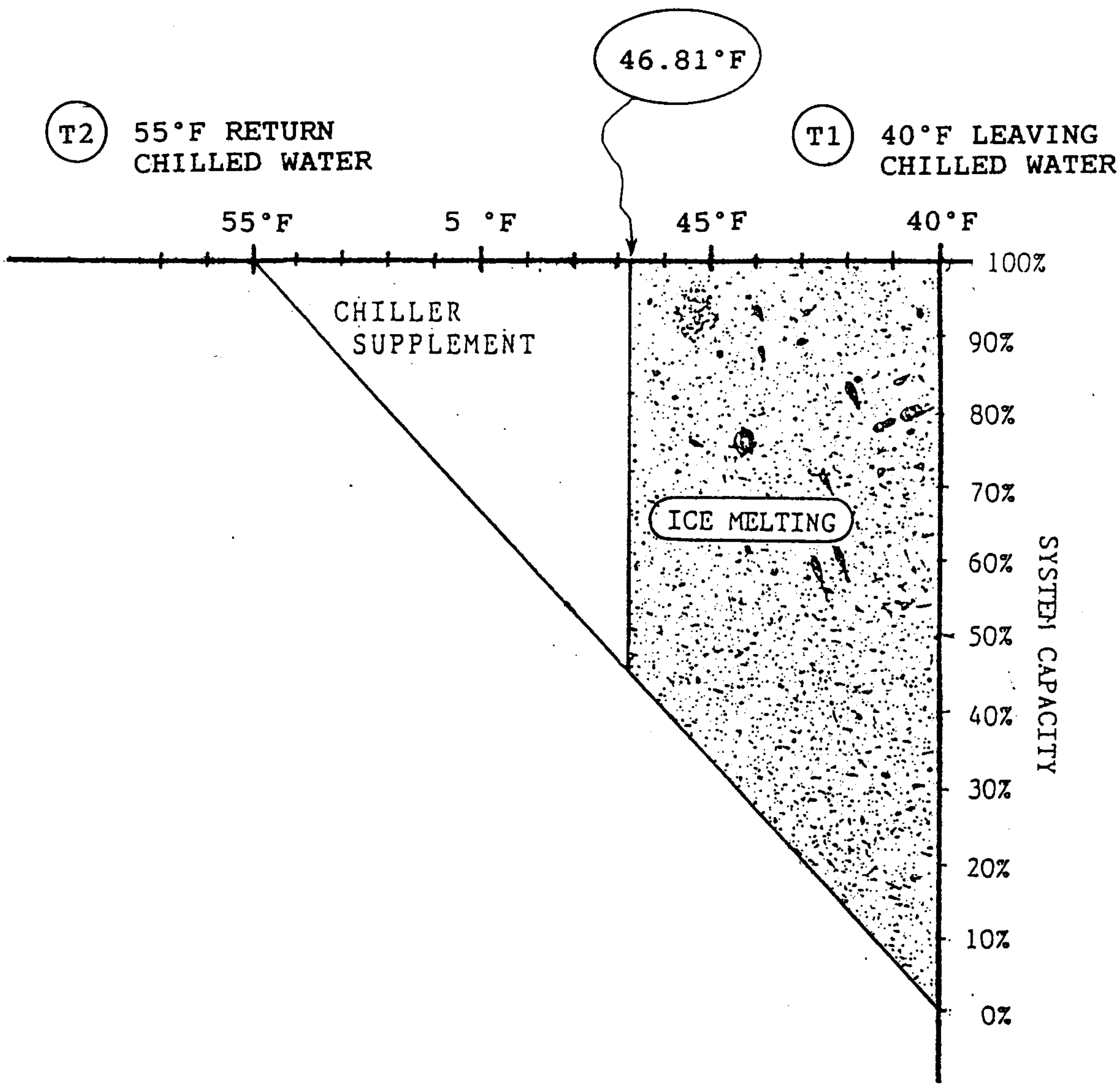

FIGURE-3 TEMPERATURE & CAPACITY CHART
ICE PRIORITY

The chiller load and the ice load of the system at various building cooling load are tabulated as the following:

Table-3 Cooling Load Sharing

Cooling Load	Cooling Supplement By Chiller Units	Cooling From Ice Reserve Units
1,000 TR (100%)	546 TR	454 TR
830 TR (83%)	376 TR	454 TR
735 TR (74%)	281 TR	454 TR
540 TR (54%)	86 TR	454 TR
350 TR (35%)	0 TR	350 TR
250 TR (25%)	0 TR	250 TR

This system (see Figure-2) is designed in such way it provides the maximum flexibility in operation. The air conditioning for the building can be obtained by selecting any one of the cooling modes as listed below to suit the actual cooling requirement of the building:

(1) By just the brine chillers only.

(2) By just the ice melting only.

(3) Or by the combination of the brine chillers and the ice melting from the ice builder.

THE SPECIFICATION AND REQUIREMENTS
FOR ICE BUILDER
ICE PRIORITY SYSTEM

The specification for the ice builder is very important to tie down the performance of the ice builder. The criteria of the specifications are as the following:

A. ICE STORAGE CAPACITY:

4,537 TR-HR OF NET LATENT HEAT OF THE ICE. THE TR-HR OF CHILLED WATER SHOULD BE EXCLUDED.

B. CHARGE EFFICIENCY:

THE CHARGING TIME IS 10 HOURS. THE DESIGN CONDITIONS FOR THE ICE RESERVE UNIT DURING THE ICE MAKING CYCLE ARE:

BRINE:	35% BY WEIGHT OF ETHYLENE GLYCOL.
BRINE INLET:	22°F.
BRINE OUTLET:	27°F.
REFRIGERATION CAPACITY:	349 TR.
BRINE FLOW:	1,848 USGPM.
CHARGE TIME:	LESS THAN 13 HOURS.

C. DISCHARGE EFFICIENCY:

THE DISCHARGE TIME IS 15 HOURS. THE DESIGN CONDITIONS FOR THE ICE RESERVE UNIT DURING ICE MELTING CYCLE ARE:

BRINE:	35% BY WT. ETHYLENE GLYCOL
DISCHARGE TIME:	10 HOURS.
DISCHARGE BRINE TEMP.:	38°F CONSTANT
BRINE FLOW:	1,848 USGPM

THE DISCHARGE TR SHALL BE 454 TR AND THE LEAVING BRINE TEMPERATURES SHALL BE 38°F. THE TR AND LEAVING BRINE TEMPERATURE REQUIRED FROM THE ICE RESERVE UNIT FOR THE LAST SIX HOURS OF DISCHARGE OPERATION:

5TH HOUR:	454 TR38°F
6TH HOUR:	454 TR38°F
7TH HOUR:	454 TR38°F
8TH HOUR:	454 TR38°F
9TH HOUR:	454 TR38°F
10TH HOUR:	454 TR38°F

THE SPECIFICATIONS AND
THE REQUIREMENT FOR
THE BRINE CHILLERS
ICE PRIORITY SYSTEM

THE TWO BRINE CHILLERS ARE TO BE DESIGNED FOR DUAL DUTIES OF MAKING ICE IN THE NIGHT TIME AND TO PROVIDE SUPPLEMENT COOLING FOR AIR CONDITIONS DUTY DURING THE DAYTIME OPERATION. THE DESIGN OPERATING CONDITIONS OF THE TWO BRINE CHILLERS ARE:

BRINE CHILLER UNITS:

TWO CHILLED BRINE CHILLER UNITS TO COOL 35% BY WEIGHT OF ETHYLENE GLYCOL BRINE FOR THE FOLLOWING DUTIES:
EACH UNIT:

I) NIGHT TIME ICE MAKING OPERATING CONDITIONS:

CAPACITY, EACH:	175 TR
BRINE FLOW:	941 GPM
INLET BRINE TEMP:	27°F
LEAVING BRINE TEMP:	22°F
COOLING WATER FLOW:	786 GPM
INLET COOLING WATER TEMP:	87°F
OUTLET COOLING WATER TEMP.:	97°F

II) DAY TIME OPERATING CONDITIONS:

CAPACITY, EACH:	273 TR
BRINE FLOW:	941 GPM
INLET BRINE TEMP:	52.23°F
LEAVING BRINE TEMP:	44.45°F
COOLING WATER FLOW:	786 GPM
INLET COOLING WATER TEMP:	90°F
OUTLET COOLING WATER TEMP.:	100°F

SYSTEM OPERATING MODE AND CONTROLS

After the system is designed, the designer should specify the operating mode for the system. the control which either by manual or by microprocessor automatic control system is to be designed and installed in accordance with the functions as specified in the operating mode. Most important of all, the ice must be burn in accordance with the design and the schedule; the system shall be installed properly in accordance with the designed. If changes are made during the actual operation, it shall not be in any conflict with the operating mode and system configuration as specified.

The specification for the operating mode shall be as details as possible, it shall include the entire system functions, the design operating conditions and the control set points. The minimum information of the operating mode specification shall include the following items:

1) The system configuration.

2) Relative position of chiller, up stream or down stream of the ice builder.

3) Ice priority or chiller priority.

4) Series or parallel operation.

5) Design system operating conditions.

6) System set points.

7) The operating methods for full load and for partial loads.

8) How the ice thermal storage system should be controlled, the set points and time schedule.

CASE ILLUSTRATION
CHILLER PRIORITY MODE
BRINE CIRCULATING ICE
THERMAL STORAGE SYSTEM

This example is to show the difference in concept for chiller priority mode of the ice thermal storage system:

Example: Chiller Priority

Air conditioning required:	10 Hours
Peak building design load:	1,000 TR

Air conditioning operation:	10 Hours
Operation change over:	1 Hour
Ice making duty operation:	13 Hours

The building cooling load profile is the same as the Table-1:

Cooling Time Period	Cooling Load
8:00 - 9:00 AM	560 TR
9:00 - 10:00 AM	735 TR
10:00 - 11:00 AM	830 TR
11:00 - 12:00 AM	940 TR
12:00 - 1:00 PM	960 TR
1:00 - 2:00 PM	980 TR
2:00 - 3:00 PM	1,000 TR
3:00 - 4:00 PM	935 TR
4:00 - 5:00 PM	780 TR
5:00 - 6:00 PM	540 TR
Total 10 Hours	8,260 TR-HR

The compressor CCR is 0.64.

The formulas for the calculation of optimum compressor TR and optimum ice storage capacity for PASC with chiller priority mode operation are as the following:

$$TR2 = \frac{\text{DESIGN TR-HR}}{\text{CCR} \times N + D}$$

Ice thermal storage capacity, TR-HR
for ice reserve unit
= TR1 x N

Ice melting (TR) from ice reserve unit
during peak design hour

= (PEAK TR) - TR2

TR-HR =	Design day TR-HR required for the building.
TR2 =	Compressor TR at air conditioning duty at the design operating conditions during day time.
TR1 =	Compressor TR at ice duty under the design operating conditions during evening hours.
D =	Day time hours space to be air conditioned.
N =	Night time hours to build ice.

$$TR2 = \frac{\text{DESIGN TR-HR}}{064 \times N + D}$$

$$= \frac{8{,}260}{0.64 \times 13 + 10}$$

$$= 451 \text{ TR}$$

TR1 = 0.64 x TR2

= 0.64 x 451

= 289 TR

Therefore:

Compressor or chiller day time duty 451 TR
(Air conditioning base load)

Compressor or chiller night time duty 289 TR
(Ice making duty)

Ice storage capacity = 289 x 13

= 3,757 TR-HR

Ice melting (TR) from ice reserve unit
at the peak design hour

= (Peak TR) - TR2
= 1,000 - 451
= 549 TR

The definition of chiller priority is to utilized the chiller capacity or to operate the chiller first and supplement the cooling with the ice to satisfy the building load. From this example, the peak load of the office building is 1,000 TR. Under the chiller priority mode, the calculated optimum ice storage capacity is 3,757 TR-HR and the chiller capacity is 451 TR for the design day in accordance with the formulas. The cooling source and load allocations for each hour at the design day based on chiller priority mode are shown in Table 4.

Table 4, Cooling Source Allocation, Chiller Priority

Cooling Time Period	Cooling Load Profile	Cooling By Chiller (or Comp.)	Supplement By The Ice Cooling
8:00 - 9:00 AM	560 TR	451 TR	109 TR
9:00 - 10:00 AM	735 TR	451 TR	284 TR
10:00 - 11:00 AM	830 TR	451 TR	379 TR

11:00 - 12:00 AM	940 TR	451 TR	489 TR
12:00 - 1:00 PM	960 TR	451 TR	509 TR
1:00 - 2:00 PM	980 TR	451 TR	529 TR
2:00 - 3:00 PM	1,000 TR	451 TR	549 TR
3:00 - 4:00 PM	935 TR	451 TR	484 TR
4:00 - 5:00 PM	789 TR	451 TR	338 TR
5:00 - 6:00 PM	540 TR	451 TR	89 TR
TOTAL 10 HOURS	8,260 TR-HR	4,510 TR-HR	3,759 TR-HR

Total 8,269 TR-HR

Again, the chiller priority mode is to use the chiller as the main cooling source, if the cooling is not enough, it is supplemented with ice melting. In the chiller priority mode, the chiller is basically operating all the time. From the Table 4, the chiller is to produce 451 TR as the base; the system is supplemented by the ice to satisfy the cooling requirement of the building in the event that the building load is greater than the chiller load of 451 TR.

If the cooling is arranged by ice melting instead of chiller, this is no longer a chiller priority mode. It makes no sense to design a system with chiller priority mode and yet the chiller is not used in accordance with the priority designated.

BRINE CIRCULATION CALCULATION:

If the entering brine temperature for the ice builder is to be designed for 22°F, with 4°F temperature range, the design leaving brine temperature from the ice builder is 26°F.

The brine shall be Ethylene Glycol and the concentration of the brine shall be 35% by weight. The brine flow is calculated as the following:

The average brine temperature is 24°F.

From the brine curves of Figure-18 to 22 of the article "Brine Circulated Ice Thermal Storage System", the transportation properties of the brine are:

Freezing temperature:	-5°F
Specific Gravity:	1.0546
Specific Heat:	0.86

The brine flow for the 290 TR is calculated by using the formula (1) as shown in the article of "Brine

Circulated Ice Thermal Storage System":

Btu/hr = 499.8 x GPM x S.G. x Cp x (T2 - T1)

Btu/hr = 290 TR x 12,000
= 3,480,000

S.G. = 1.0546
Cp = 0.86
T2 = 26
T1 = 22

Therefore:

3,480,000 = 499.8 x GPM x 1.0546 x 0.86 x (26 -22)

Brine flow = GPM = 1,920 Gallons per minute.

If two chillers are to be used, the night duty of the two brine chillers shall be to cool 1,920 gpm. The two units are arranged in parallel, the duty of each chiller is 145 TR to cool 960 GPM 35% by weight of Ethylene Glycol brine from 26°F to 22°F. The brine circuit for the brine chillers for the ice duty is shown in the Figure-4.

The day time water chilling duty of the two chillers is determined as the following:

The peak cooling load is at 2:00 p.m. which is 1,000 TR. The building is to be cooled by the combination of (i) the chillers (451 TR) and (ii) the TR-HR from ice melting (549 TR).

Figure-5 shows the system design operating conditions for the daytime operation. The operating temperatures are determined as the following:

The lowest reasonable leaving chilled water temperature can be obtained from brine circulated ice thermal storage system is 40°F by using brine at 38°F available from the ice builder. If the chilled water range is to be designed at 15°F, the return chilled water shall be 55°F.

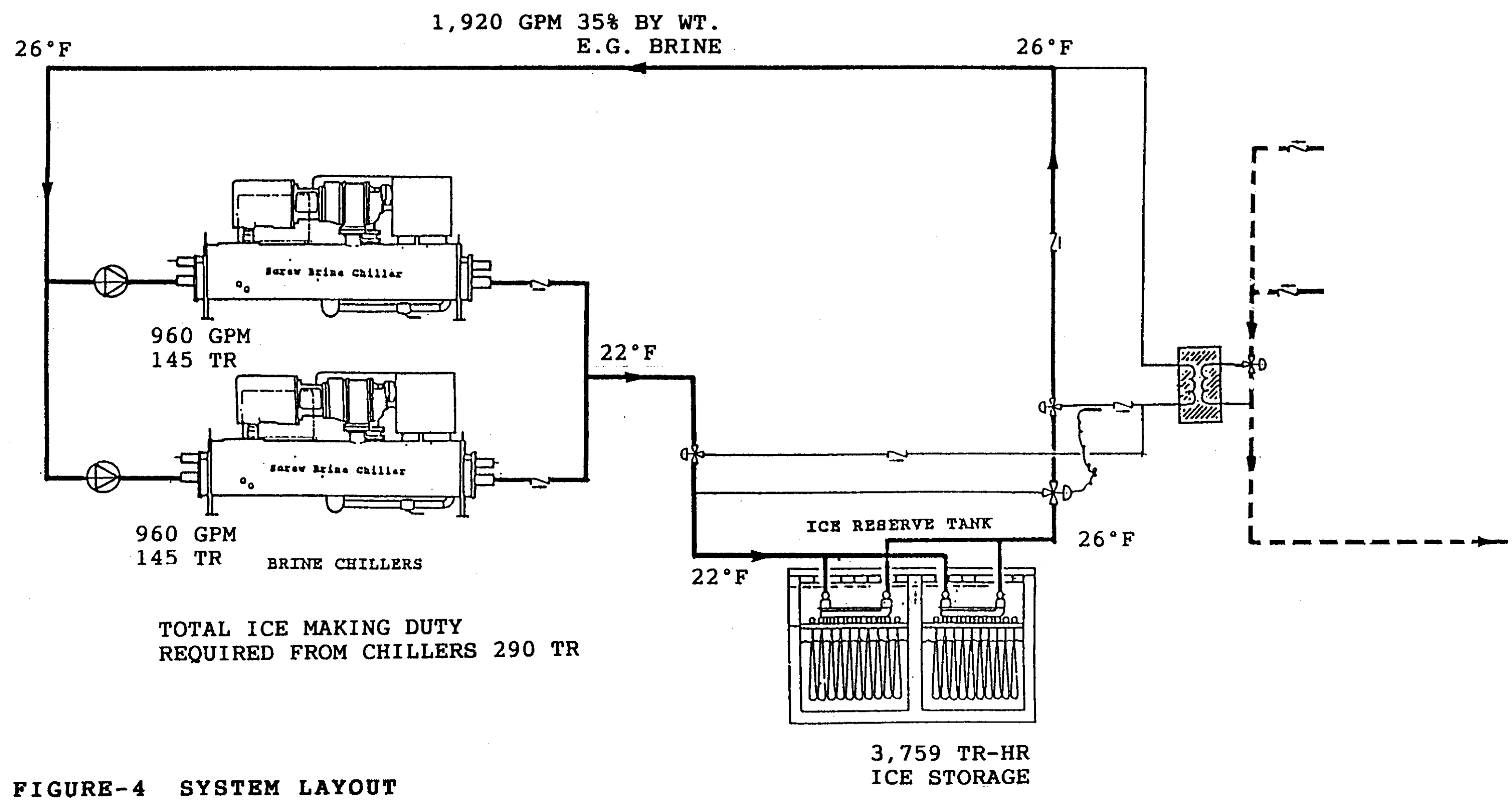

**FIGURE-4 SYSTEM LAYOUT
NIGHT TIME
ICE MAKING OPERATION
CHILLER PRIORITY**

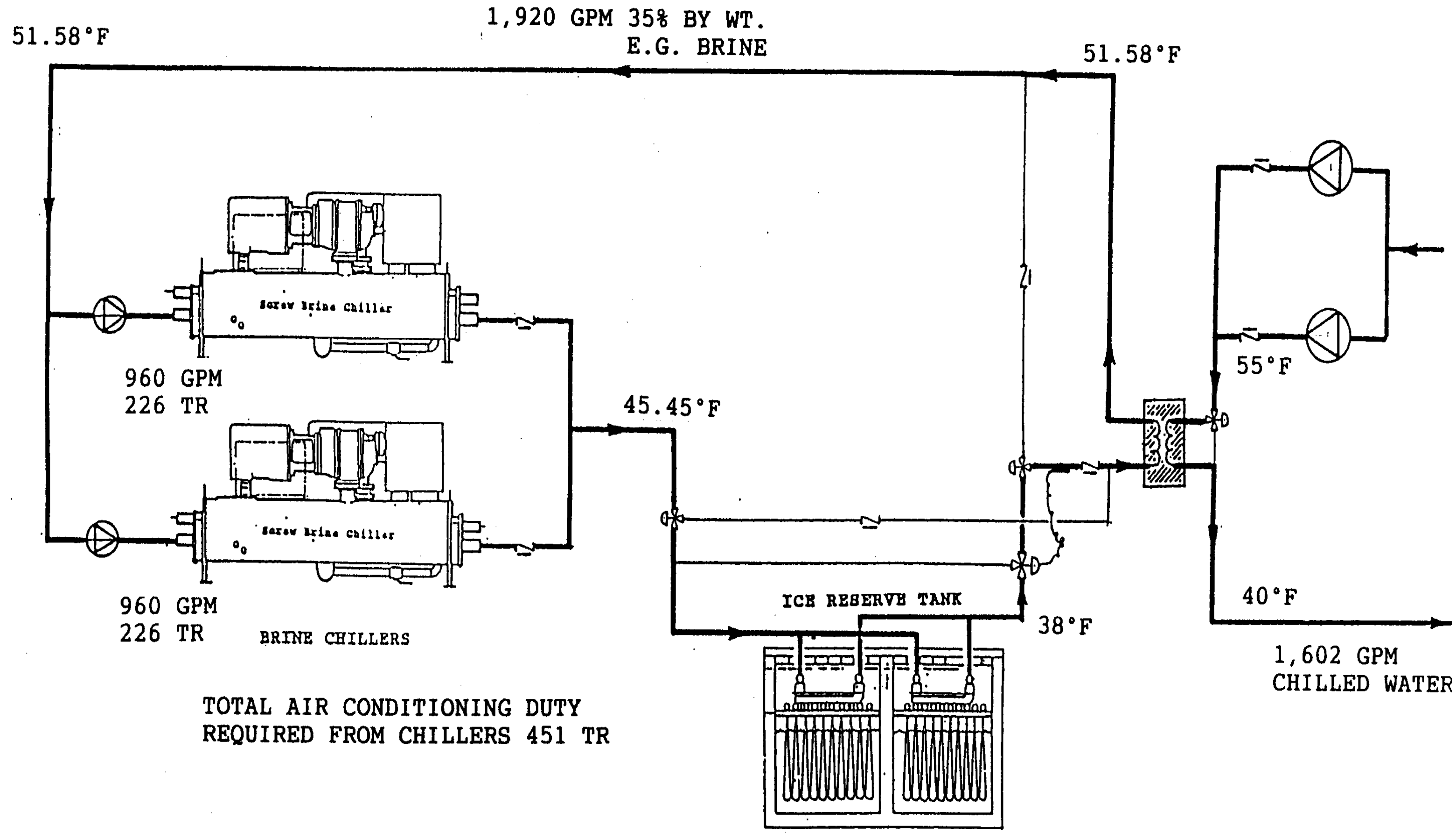

FIGURE-5 SYSTEM LAYOUT
DAY TIME A/C OPERATION
CHILLER PRIORIT

Based on the brine flow of 1,920 gpm which is determined for the night duty of brine circuit, same brine flow rate has to be used for day time design. the reasonable lowest brine temperature leaving from the ice builder is 38°F. Also, 2°F approach is necessarily required to produce the 40°F chilled water through the plate type exchanger.

Ice melting from the ice builder is 549 TR as allocated at the design hour, therefore, with brine flow of 1,920 gpm and leaving brine temperature of 38°F, the entering brine temperature to the ice builder is calculated at 45.45°F.

The brine temperature leaving the brine chillers is same temperature as the brine entering to the ice builder, i.e. 45.45°F. The capacity of the two brine chillers is 451 TR. Therefore, the brine entering temperature to the chillers with 1,920 gpm is calculated at 51.58°F. The total brine temperature range is about 13.6°F at the design condition during day time air conditioning operation.

With 55°F return to 40°F leaving, 15°F temperature range for the chilled water at peak design load of 1,000 TR, the chilled water flow is calculated at 1,602 gpm.

THE MODES OF OPERATION:

The Figure-6 shows the mode of chiller priority operation. The chiller delivers a fix amount of 451 TR cooling, if the cooling is not enough for the building, the cooling is supplemented by the ice. This is the mode of the system operation for the chiller priority and it is being designed for the design day and for the entire cooling of the season.

The Figure-6 shows the Temperature and Capacity chart. The scale on the top is the 100% load line. The return chilled water temperature is 55°F and the leaving chilled water temperature is 40°F. The vertical line on the right is the system load from 0% to 100%. This system chart provides the capacity, the operating conditions, the supplement cooling from the ice and the main cooling from the chiller. This chart provides the information for load conditions from any partial load to the 100% design load.

At 100% load, 451 TR is provided by the chillers, it is equivalent to cool the 1,602 gpm chilled water from 55°F to a intermediate temperature (Ti) of 48.24°F. The ice builder provides 549 TR, it is equivalently to cool the 1,602 gpm chilled water from 48.24°F to 40°F by the ice melting.

At 80% partial load, a horizontal line is drawn at 80%. The chilled water return temperature is 52°F instead of 55°F. The chilled water is equivalently to be cooled down by chiller from 52°F to 45.23°F and is equivalently further cooled down to 40°F by ice melting. Actually, from the brine circuit, the brine temperature leaving the ice builder is kept at 38°F. The chiller is still producing 451 TR. The brine temperature leaving the heat exchanger is 48.86°F at 80% load instead of 51.58°F. The brine leaving the chillers is 39.1°F at 451 TR, 1920 GPM.

The chiller load and the ice load of the system at various building cooling load are tabulated as shown in Table-5.

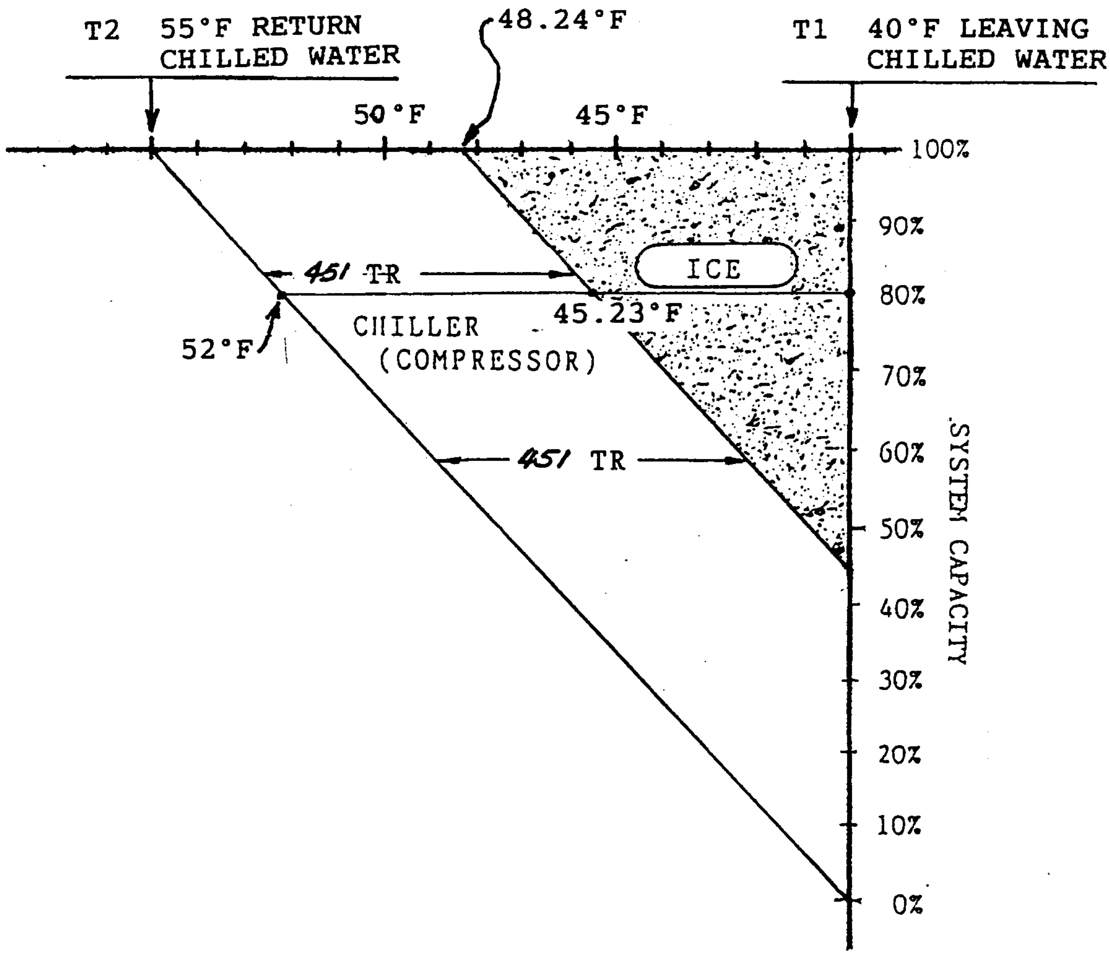

FIGURE-6 TEMPERATURE & CAPACITY CHART CHILLER PRIORITY

Table-5 Cooling Load Sharing, Chiller Priority

Cooling Load	Cooling By the Chiller Unit	Supplement Cooling From Ice Unit
1,000 TR (100%)	451 TR	549 TR
830 TR (83%)	451 TR	379 TR
735 TR (74%)	451 TR	274 TR
540 TR (54%)	451 TR	89 TR
350 TR (35%)	350 TR	0 TR
250 TR (25%)	250 TR	0 TR

The chiller is to be operated with lowering leaving brine temperature during the day time operation even after the ice is totally melted. Therefore, the chiller is to be selected not only to satisfy the cooling load with the leaving brine temperature at the design hour, it is very important that the chiller is to be selected also to produce the lowest leaving brine temperature as the ice builder leaving temperature, i.e. 38°F for the chiller priority mode system.

At 45.1% partial load (see Figure-6), the ice is completely melted, the chiller is to produce 451 TR at 38°F leaving brine at this hour. The figure-7 shows the operating conditions of this point. **It is very important that for chiller priority arrangement, the chiller should be sized not only for 100% system load, it also should be sized for this system partial of 45.1%; that means the chiller should be sized for leaving brine temperature of 38°F.**

The discharge efficiency of ice builder for chiller priority system is usually no problem, because the tr-hr required from ice builder is decreasing during the final hours of air conditioning operation. This is exactly what ice builder prefers. Usually a smaller size ice builder can be used in a chiller priority mode ice thermal storage system. However, the chiller is bigger and oversized; the power consumption is much higher for the compressor if chiller priority is used.

ICE BUILDER SPECIFICATION
AND REQUIREMENTS
CHILLER PRIORITY SYSTEM

The specification for the ice builder is very important to tie down the performance of the ice builder. The criteria of the specifications are as the following:

THE CRITERIA OF PERFORMANCE OF THE ICE RESERVE UNITS:

A. ICE STORAGE CAPACITY:

3,759 TR-HR OF NET LATENT HEAT OF THE ICE. THE TR-HR OF CHILLED WATER SHOULD BE EXCLUDED.

B. CHARGE CYCLE:

THE CHARGING TIME IS 13 HOURS. THE DESIGN CONDITIONS FOR THE ICE RESERVE UNIT DURING THE ICE MAKING CYCLE ARE:

BRINE:	35% BY WEIGHT OF ETHYLENE GLYCOL.
BRINE INLET:	24°F.
BRINE OUTLET:	26°F.
REFRIGERATION CAPACITY:	290 TR.
BRINE FLOW:	1,920 USGPM.
CHARGE TIME:	LESS THAN 13 HOURS.

C. DISCHARGE CYCLE:

THE DISCHARGE TIME IS 10 HOURS. THE DESIGN CONDITIONS FOR THE ICE RESERVE UNIT DURING ICE MELTING CYCLE ARE:

BRINE:	35% BY WT. ETHYLENE GLYCOL
DISCHARGE TIME:	10 HOURS.
DISCHARGE BRINE TEMP.:	38°F CONSTANT
BRINE FLOW:	1,920 USGPM

THE DISCHARGE TR AND THE LEAVING BRINE TEMPERATURES REQUIRED FROM THE ICE RESERVE UNIT FOR THE LAST SIX HOURS OF DISCHARGE OPERATION:

6TH HOUR: 529 TR38°F

7TH HOUR:	549 TR38°F
8TH HOUR:	484 TR38°F
9TH HOUR:	338 TR38°F
10TH HOUR:	89 TR 38°F

BRINE CHILLER SPECIFICATION
AND REQUIREMENTS
CHILLER PRIORITY SYSTEM

THE TWO BRINE CHILLERS ARE TO BE USED. THE CHILLERS ARE TO BE DESIGNED FOR THREE (3) DUTIES AS THE FOLLOWING:

(1) MAKING ICE IN THE NIGHT TIME.

(2) TO PROVIDE COOLING FOR AIR CONDITIONS DUTY AT THE DESIGN HOUR.

(3) TO PROVIDE COOLING AFTER THE ICE IS MELT DURING THE DAYTIME OPERATION.

THE DESIGN OPERATING CONDITIONS OF THE TWO BRINE CHILLERS ARE TO COOL 35% BY WEIGHT OF ETHYLENE GLYCOL BRINE. THE DUTIES OF EACH UNIT ARE AS THE FOLLOWING:

I) NIGHT TIME ICE MAKING OPERATING CONDITIONS:

CAPACITY, EACH:	145 TR
BRINE FLOW:	960 GPM
INLET BRINE TEMP:	26°F
LEAVING BRINE TEMP:	24°F
COOLING WATER FLOW:	713 GPM
INLET COOLING WATER TEMP:	89°F
OUTLET COOLING WATER TEMP.:	95.3°F

II) DAY TIME OPERATING CONDITIONS:

The chillers should be selected for two operating conditions; one is for system 100% load and another is for the system partial load at 45.1% system load when the ice is completely exhausted.

(A) AT 100% SYSTEM LOAD:

CAPACITY, EACH:	226 TR
BRINE FLOW:	960 GPM
INLET BRINE TEMP:	51.58°F
LEAVING BRINE TEMP:	45.45°F
COOLING WATER FLOW:	713 GPM
INLET COOLING WATER TEMP:	90°F
OUTLET COOLING WATER TEMP.:	99.1°F

(A) AT SYSTEM PARTIAL LOAD:

CAPACITY, EACH:	226 TR
BRINE FLOW:	960 GPM
INLET BRINE TEMP:	44.14°F
LEAVING BRINE TEMP:	38°F
COOLING WATER FLOW:	713 GPM
INLET COOLING WATER TEMP:	90°F
OUTLET COOLING WATER TEMP.:	100°F

SYSTEM OPERATING MODE AND CONTROL:

Same as the ice priority, after the system is designed, the designer should specify the operating mode for the system and the control which either by manual or by microprocessor automatic control system is to be designed and installed in accordance with the functions as specified in the operating mode. The control system for chiller priority mode system is more complicated than ice priority mode system. It must be layout to reflect the characteristic of chiller priority.

CHAPTER OF DISCUSSION AND COMPARISONS

1.0 ICE PRIORITY OR CHILLER PRIORITY:

The comparison of ice priority and chiller priority system at **design point** is as the following:

	Ice Priority System	Chiller Priority System
Refrigeration Equipment	Larger	Smaller (**might be larger at partial load**)
Ice builder	Larger	Smaller
Power Consumption	Lower	Higher
Annual Energy Cost	Lower	Higher

The main purpose of using ice thermal storage system is to lower the operating cost and might be conserve energy. The chiller priority mode system will consume more energy than ice priority mode system. **The most important of all is that the chiller should be selected to base on the system partial load conditions instead of at the design point. The power consumption for the chiller for a chiller priority system is much higher because the ET of the chiller is lower at the system partial in most cases.** Therefore, chiller priority mode system should be avoided if all possible.

2.0 PARALLEL OR SERIES ARRANGEMENT:

Many installations arranged in such way that the brine chiller and the ice builder are in parallel during air condition operation. The control and the piping arrangement for this type of application is very complicated. When the chiller and the ice builder are arranged in parallel, there are two cases of operation as the following:

(I) If the brine chiller is to produce 38°F leaving brine temperature to match the ice builder leaving brine temperature as design in the example, the power consumption of the chiller will be much higher.

(II) It wastes cold energy from the ice builder, if the chiller is to produce higher leaving brine temperature.

In view of the above, the parallel arrangement cannot take the advantages of both the cold energy of the ice and at the same time to run the chiller with higher leaving brine temperature.

The parallel arrangement will always result in high power consumption as compare to series arrangement on similar leaving design brine temperature basis. It has no advantage in energy saving consideration by using parallel arrangement and therefore, the parallel arrangement should be avoided.

3.0 UP-STREAM OR DOWN-STREAM LOCATION OF CHILLER TO THE ICE BUILDER IN SERIES ARRANGEMENT:

The chiller is a unit which is the main power consumption center of the ice thermal storage system. On the other hand, the ice builder is just a heat exchanger and it consumes no energy. Therefore, it is the good engineering practices to follow the rules as the following:

(A) The chiller should be arranged to be operated at a higher leaving brine temperature during air conditioning operation during the day time to conserve annual power consumption. In order to obtain this objective, the chiller should always be located before the ice builder in the brine circuit, so the chiller is working at higher leaving brine temperature before entering the ice builder.

(B) The ice produced in the ice builder is already at 32°F. Therefore, it is the best to use of the cold energy of the ice to provide the lowest possible leaving brine temperature for the application. In order to obtain this objective, it is very nature that the ice builder should be located at the down stream of the chiller.

The brine circulated ice builder has poor discharge efficiency at the final hours of discharge, therefore, the ice builder discharge efficiency should be checked and the ice builder should be selected large enough to produce the leaving design brine temperature. It makes no sense to locate the ice builder at the up-stream of the chiller just for the purpose to accommodate the poor discharge efficiency characteristics of the ice builder.

The comparisons of advantages and disadvantages of up-stream and down stream location of the chiller are tabulated as the following:

	Brine Chiller Up Stream of Ice Builder	Brine Chiller Down Stream of Ice Builder
Chiller Unit Size:	Smaller	Larger
Brine Unit Cost	Cheaper	More Expensive
Power Consumption	Lower	Higher
Annual Energy Usage	Much Less	Much More

The advantages and disadvantages of up-stream and down-stream location of the ice builder are as the following:

	Ice Builder Up Stream of Chiller	Ice Builder Down Stream of Chiller
Ice Builder Discharge Eff.	Good	Poor
Ice Builder Size:	Smaller	Larger
Ice Builder Price:	Cheaper	More Expensive
System Power Consumption	Higher	Lower
System Annual Energy Usage	Much More	Much Less

(4) **CHILLER SELECTION:**

Some standard centrifugal chillers which are basically designed for air conditioning application might have difficulty for series arrangement because of the performance characteristics and the surge problem associated with the centrifugal compressor. Therefore, considerations should be given as what type of chiller to be used when making the system design. Generally, screw chiller can be used for any type of arrangement, because the screw compressor has no surge problem. It would be even better and further to improve the power consumption if the screw compressor is with variable internal volume ratio control in additional to the sliding vane control.

(5) **AIR HANDLING UNIT SELECTION:**

There is no problem at all to select the air handling unit with chilled water temperature difference range (Leaving chilled water temperature minus entering chilled water temperature) as small as 5°F and to large range even more than 25°F.