DYNAMICS OF PRIMARY/SECONDARY CHILLED WATER SYSTEMS

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Abstract

The purpose of this paper is to bring some additional understanding to the dynamics of variable flow chilled water systems. The literature has had several articles in recent months on this subject with some disagreement regarding a check valve in the bypass line. Reference (1) gave an example of a very positive result after the installation of a check valve. This paper will show a similar result and try to illustrate the reasons for the improvement. The Reference (1) article also presents information on load degradation as a chilled water system ages and, therefore, requires colder supply water and greater flow. This paper will present a study of the dynamics of a new and aged primary/secondary system based on a computer simulation which includes the characteristics of a specific chiller and the laws of thermodynamics.

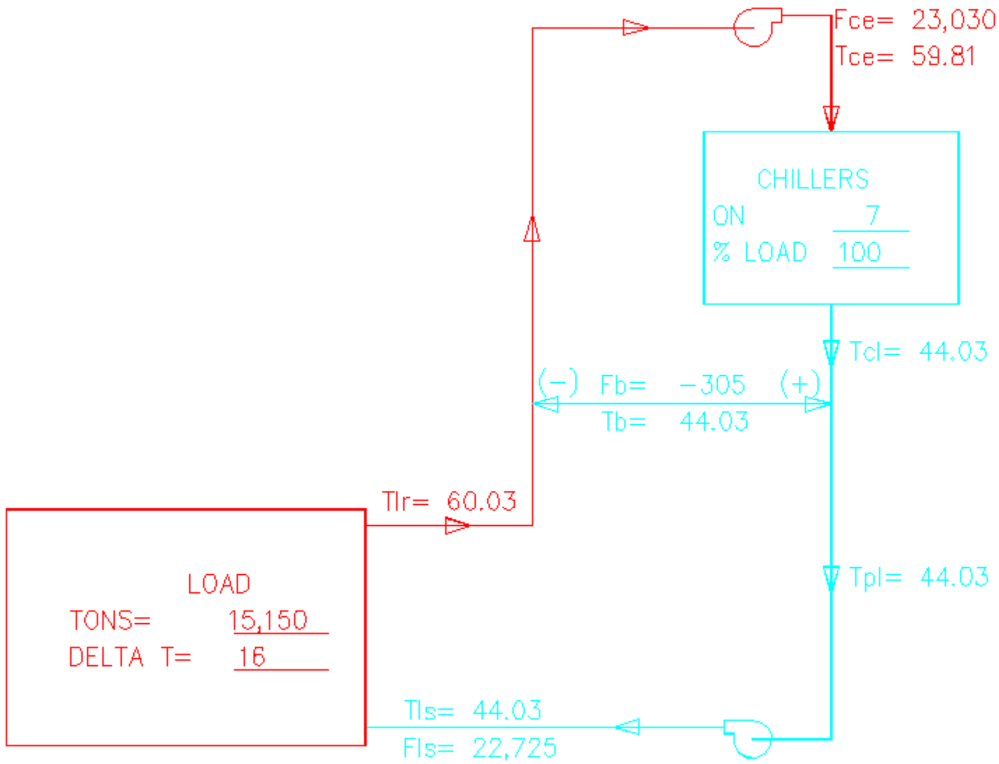
We will analyze the effects of restricting flow in the bypass line and also look at the dynamics of adding thermal storage to the system.

BALANCED SYSTEM

We define the balanced system to be essentially zero flow in the bypass line at peak cooling load. We will assume the load is designed for a delta temperature of 16°F and a peak design load of 15,150 tons. The primary pumps provide constant flow through the chiller with variable flow to the load. Our selected chiller is a 2,165-ton unit at peak conditions. Therefore, seven chillers will meet the peak load. Figure 1 illustrates the temperatures and flows at this near-balanced condition. Note that there is a small negative flow in the bypass line of 305 gpm due to the difficulty of exactly matching a chiller system to the load. Table 1, Column 1 shows the same data for this balanced condition. (See References 2 and 3 for additional discussion.)

The chiller is modeled as providing about 2,165 tons for a chiller entering temperature of 60°F and 1,700 tons for an inlet temperature of about 48.5°F.

Figure 1 - Balanced System



Nomenclature

Load in Tons

Delta T	= Tls - Tlr (°F)	Fce	= Required flow entering chillers (gpm)
Tls	= Temperature load supply (°F)	Tce	= Temperature entering chillers (°F)
Fls	= Flowload supply (gpm)	Tcl	= Temperature leaving chillers (°F)
Tlr	= Temperature load return (°F)	Tpl	= Temperature after bypass (°F)
Fb	= Flow in bypass (gpm)	Chillers On	= Number Running
Tb	= Temperature of bypass flow (°F)	% Load Assumes Chillers Share Load Equally	

BALANCED PLUS ONE CHILLER

If the project was built with eight chillers, then it's probably safe to assume that the plant operator would turn on the eighth chiller as the load approached 15,150 tons. Table 1, Column 2 illustrates the effect which is increased flow to the chillers from 23,020 to 26,320 gpm, which must be accommodated by negative flow in the bypass line if constant flow through the chiller is maintained. The resulting lower temperature into the chillers results in a little less chiller efficiency, and therefore the total capacity on line is 2,164 tons x 8 x .89 = 15,408 tons operating at 15,150 tons to meet the 15,150-ton load. In other words, seven chillers would meet the load, but once the eighth chiller is turned on and flow through that eighth chiller occurs, then seven chillers cannot meet the load.

LOAD DEGRADATION - 8 CHILLERS

Reference 1 presents a typical degradation of the load which results in a required supply temperature of 37.8°F versus 44°F when the system was new, and a ΔT of 14.8°F versus 16°F, when the system was new. The first law of thermodynamics requires an increase in flow for this decrease in ΔT. Table 1, Column 3 illustrates that our eight chiller system can only meet a 14,000-ton load under these conditions; therefore, an additional chiller would have been added as the system aged in order to meet a 15,150-ton load.

LOAD DEGRADATION - 9 CHILLERS

Nine chillers at 96% load would meet the aged conditions of the system. Table 1, Column 4 illustrates the flow and temperature conditions. Note that, in all cases shown above, the temperature of water leaving the chillers is the supply temperature to the load because flow in the bypass line is negative, i.e. the chillers require more flow than the load. This negative flow in the bypass means that the temperature entering the chillers (Tce) is less than the temperature returning from the load (Tlr), resulting in decreased capacity of the chillers.

A shut-off valve in the bypass will be considered next.

BYPASS VALVE

A valve to stop the negative flow in the bypass line (Fb = 0) will improve the efficiency of the chillers as illustrated by Table 1, Column 5. Forcing all flow through the chillers increases the temperature entering the chillers from 50.08°F to 52.62°F which results in increased chiller capacity; and therefore, chiller loading is decreased from 96% (Column 4) to 92% (Column 5). For this system at these conditions, stopping negative flow in the bypass improved plant performance, i.e. the chillers are unloaded about 4%. References 1, 4, 5, 6 and 7 are recommended reading on this subject.

EXCESS FLOW

A condition to consider is that plant operators may have a tendency to pump more flow to the load than required. If this condition exists, the result is a decrease in load delta temperature and decreased negative flow or positive flow in the bypass line. Column 6 of Table 1 assumes about 35% over pumping which results in 3,445 gpm of positive flow in the bypass line and a ΔT of 11.0°F. The nine chillers are 99% loaded and must supply 36.5°F water to mix with the 48.78°F bypass water to provide the required 37.78°F supply to the load as shown by Table 1, Column 6. Note that for this condition, if the plant operators increased flow a little more, the load could not be met and reducing flow would reduce the load on the chillers and improve plant performance. A shut-off valve in the bypass line will force all excess flow to the chillers and improve performance just as it did in Column 5 of Table 1 for negative flow in the bypass line. We must, of course, be sure that the flow to the chillers does not exceed the manufacturer's requirement, nor reduce the flow below the chiller manufacturer's requirement.

SHUT-OFF VALVE WITH EXCESS FLOW

Let's assume a shut-off valve which eliminates the 3,445 gpm positive flow in the bypass and forces all flow to the nine chillers operating at 99% capacity. Column 7 illustrates that the load supply temperature (Tls and Tpl) reduced from 37.78°F to 37.07°F which means that the chillers can be unloaded; i.e., the shut-off valve improves performance of this system. Unloading the chillers will raise the load supply temperature to the desired 37.8°F.

Column 8 illustrates unloading the chillers from 99% to 97% to provide the required 37.82°F supply to the load; i.e. the shut-off valve improved performance by a 2% unloading of the chillers. Over pumping still exists in our Column 8 system; and it will be difficult for the plant operators to determine how much over pumping is occurring without a good simulation of the total system including the load. Because we have set up the problem, we know that the system required flow (Fls) is 24,568 gpm, as shown by Columns 4 and 5. The plant typically would like to minimize pumping and provide as high a value of temperature supply as possible. Defining this optimum operation without a dynamic model of the existing system may be difficult, if not impossible.

The Column 5 System of Table 1 illustrates the optimum operation of the system requiring 92% loading of nine chillers. This is accomplished by eliminating excess flow to the load and eliminating flow in the bypass line.

OPTIMUM OPERATION

We suggest that the procedure for defining optimum operation of an existing system consists of first defining the dynamic characteristics of the plant equipment, and then by observing the dynamic characteristics of the real system, incorporate these characteristics into a system computer model. This procedure will define the characteristics of the load which will typically be the source of making major improvements to the efficient operation of the system. As changes are made on the load side, the computer simulation would be updated; and therefore always provide the plant operators direction on how to optimally control the plant.

Simply stated, we are suggesting that without a computer simulation of the existing system that is updated as the system changes, optimum operation of the plant is not achievable for reasons including the tendency of plant operations to pump excess flow and to turn on more chillers than required.

For the purpose of this paper, let's assume that the plant operation as defined by Column 8, could be returned to the conditions of Column 4, wherein the flow and supply temperature to the load are optimized to the load we have assumed without a shut-off valve in the bypass line. (See References 8, 9, 10, 11, and 12.)

THERMAL STORAGE - AGED SYSTEM

Thermal storage is a part of many chilled water systems; and therefore the dynamics of this feature will be considered in our modeled system, see Table 1, Column 9.

Figure 2 illustrates that the peak load of 15,150 tons for an aged system can be met with seven chillers and a 6,200 ton-hour storage tank and a 306-ton ice slurry generator versus nine chillers of Column 4, i.e. a 306-ton ice slurry generator and a storage tank replaces two 2,164-ton chillers.

Column 1 is for a balanced system and requires seven chillers. The degradation in load, as defined by Column 4, resulted in the need for two additional chillers. One conclusion is to be drawn from System Column 1 and System Column 9 is that thermal storage could have been the original plan for meeting the load as it degraded; i.e. replacing the need for two additional chillers. (See References 13, 14, 15, 16, and 17.)

FIGURE 2

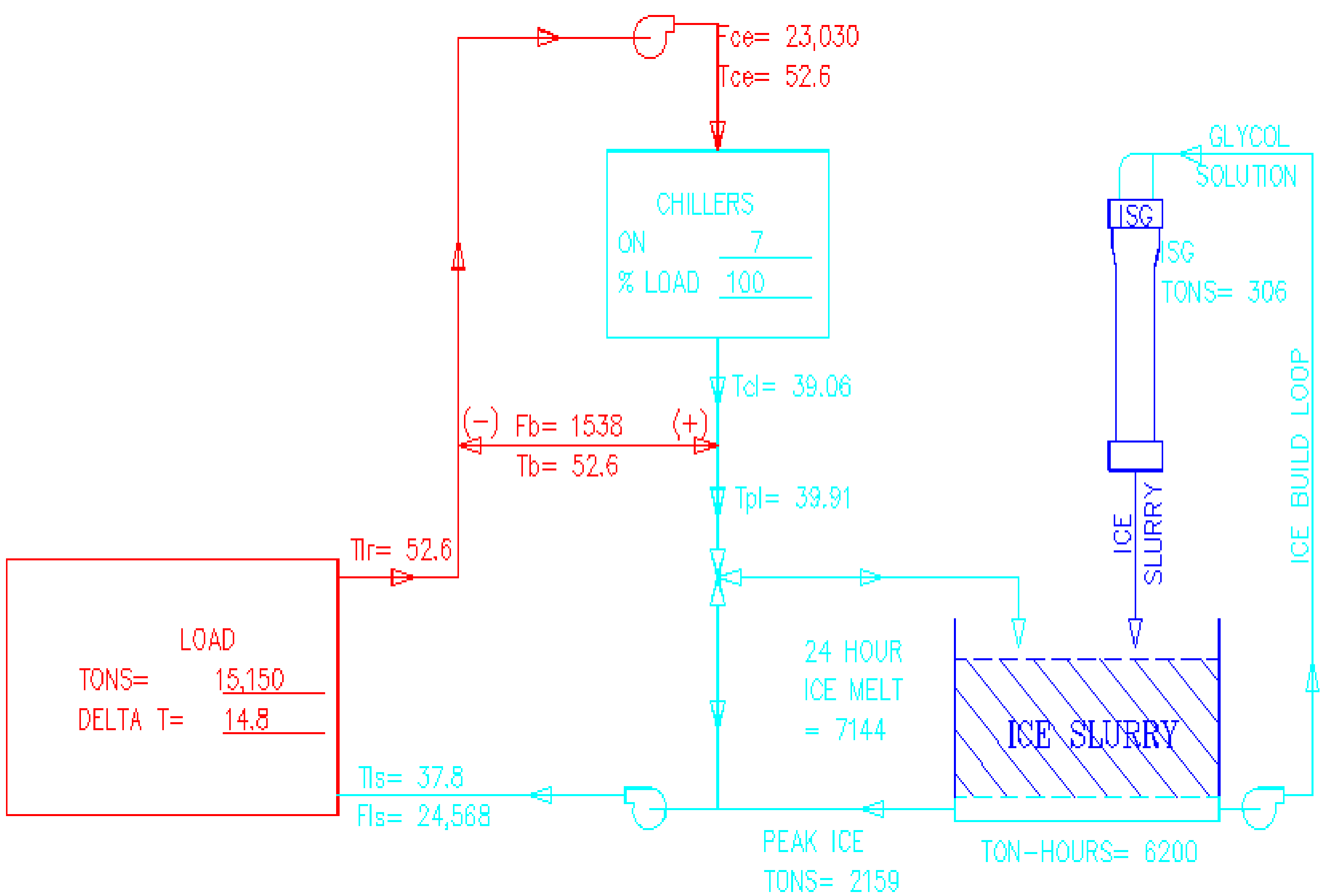
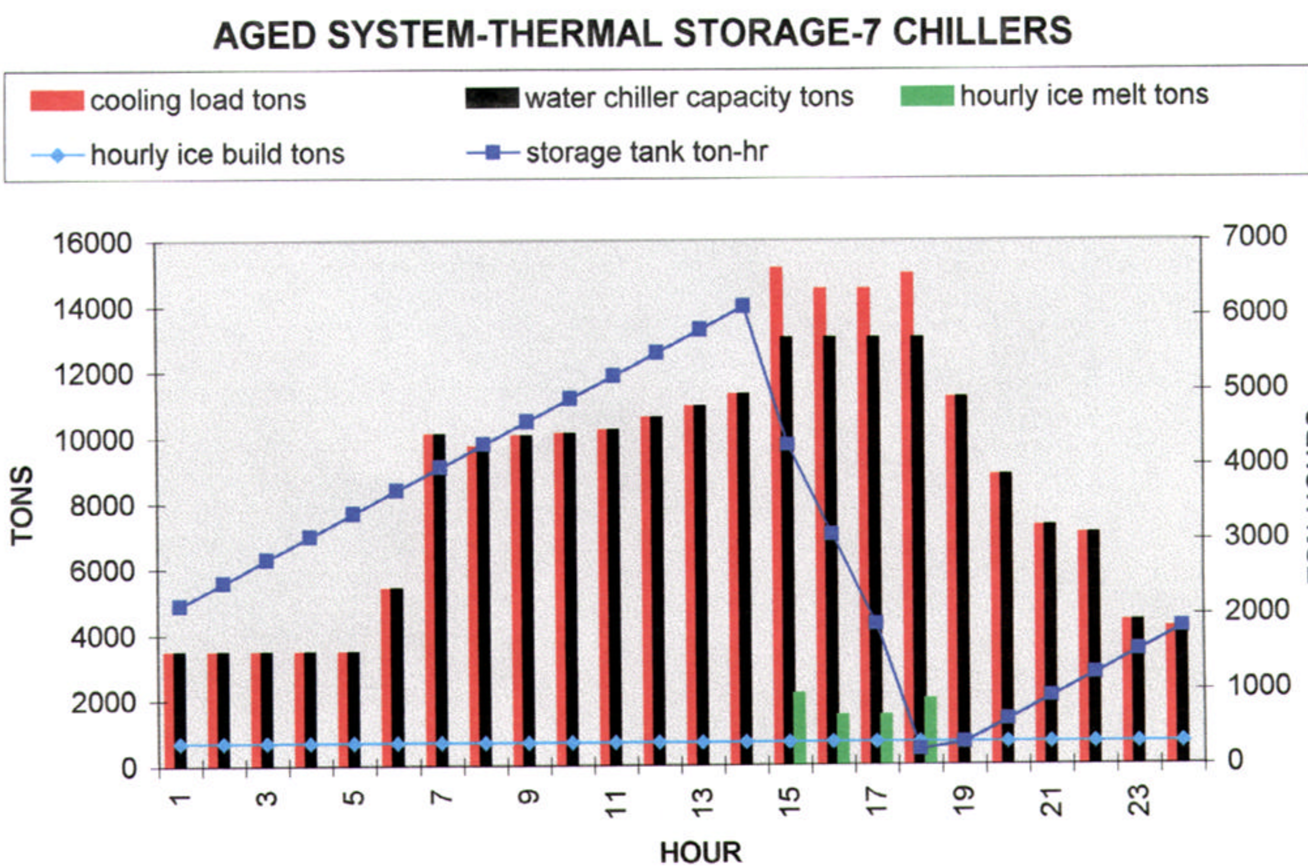


Figure 3 illustrates the 24-hour operation of the system. The seven chillers can meet the cooling load for all but four hours; therefore, ice melting occurs during four hours for a total melt of 7,144 tons. The 306-ton ice slurry generator makes ice all 24 hours, with storage peaking the 14th hour at about 6,200 ton-hours. The storage tank is essentially depleted the 18th hour and begins to build up on the 19th hour. (See References 18, 19, 20, and 21.)

LOAD DYNAMICS

This paper illustrates the positive effects offered by thermal storage, especially in a system that has experienced decreased delta temperature. However, it must be remembered that fixing the load is also an alternative. Reference 3 presents some basic concepts and Reference 22 is a case history of a successful effort to fix the load along with decreasing the supply temperature to the load. Also, References 23, 24 and 25 present an alternative approach to thermal storage.

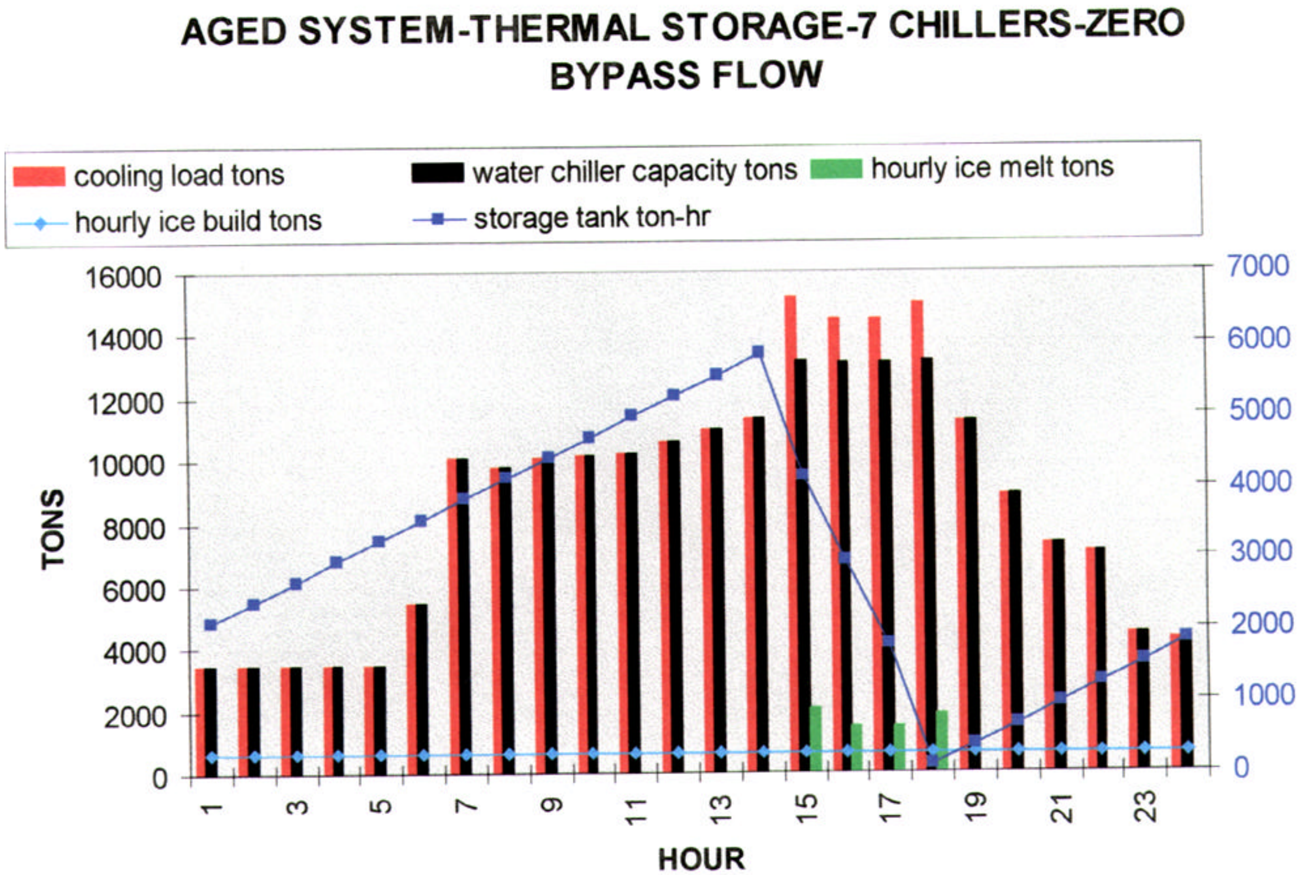
FIGURE 3



THERMAL STORAGE - AGED SYSTEM - WITH SHUT-OFF VALVE

The Column 10 system with thermal storage and a by-pass shut-off valve is equivalent to the Column 5 System with a shut-off valve and no thermal storage. A by-pass shut-off valve slightly reduces the peak thermal storage requirement from 2,159 tons to 2,016 tons because the Column 9 system conditions include 1,538 gpm of bypass flow which gives a temperature going to the thermal storage tank of 39.91°F, versus 39.77°F with a shut-off valve installed. The size of the ice slurry generator can be reduced from 306 tons to 288 tons. The 24-hour ice melt is reduced from 7,144 tons to 6,794 tons and storage is reduced from 6,200 ton-hours to 5,900 ton-hours, all improvements provided by the bypass shut-off valve. Figure 4 illustrates the 24-hour operation of the system.

Figure 4

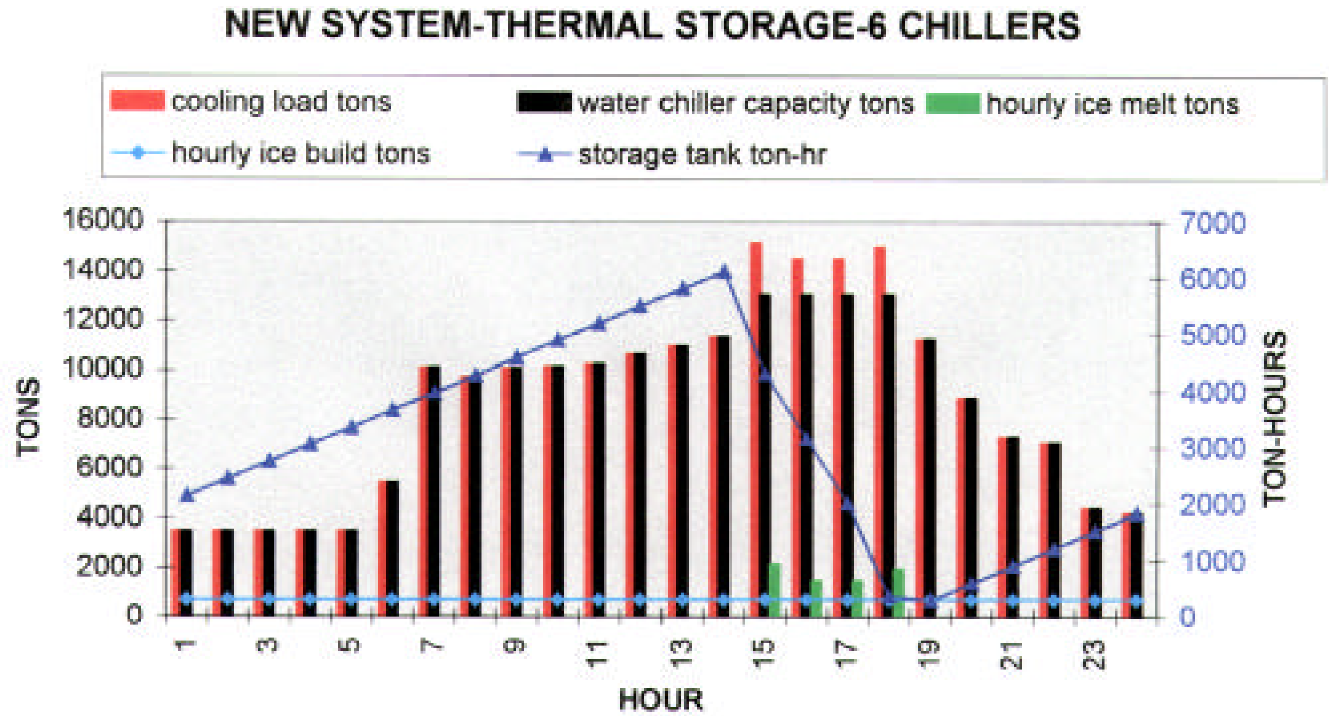


NEW SYSTEM - THERMAL STORAGE - SIX CHILLERS

Column 11 illustrates the conditions of a new system with thermal storage versus Column 1 or 2 of Table 1. Six chillers can meet the load with 2,117-tons of peak thermal storage cooling. For 24-hour operation, the required tank storage would be 6,200 ton-hours, and a 306-ton ice slurry generator could provide this daily requirement. The thermal storage is used for four hours for a total of 6,975 tons over the 24-hour period.

Figure 5 illustrates the 24-hour operation of the system. A 306-ton ice generator and 6,200 ton-hour storage tank replaces one or two 2,164 chillers depending if the new design was installed with seven or eight chillers. Note that this system has flow of 2,985 gpm in the bypass. Let's assume the new system was built with six chillers and thermal storage and see how it performs when aged.

FIGURE 5

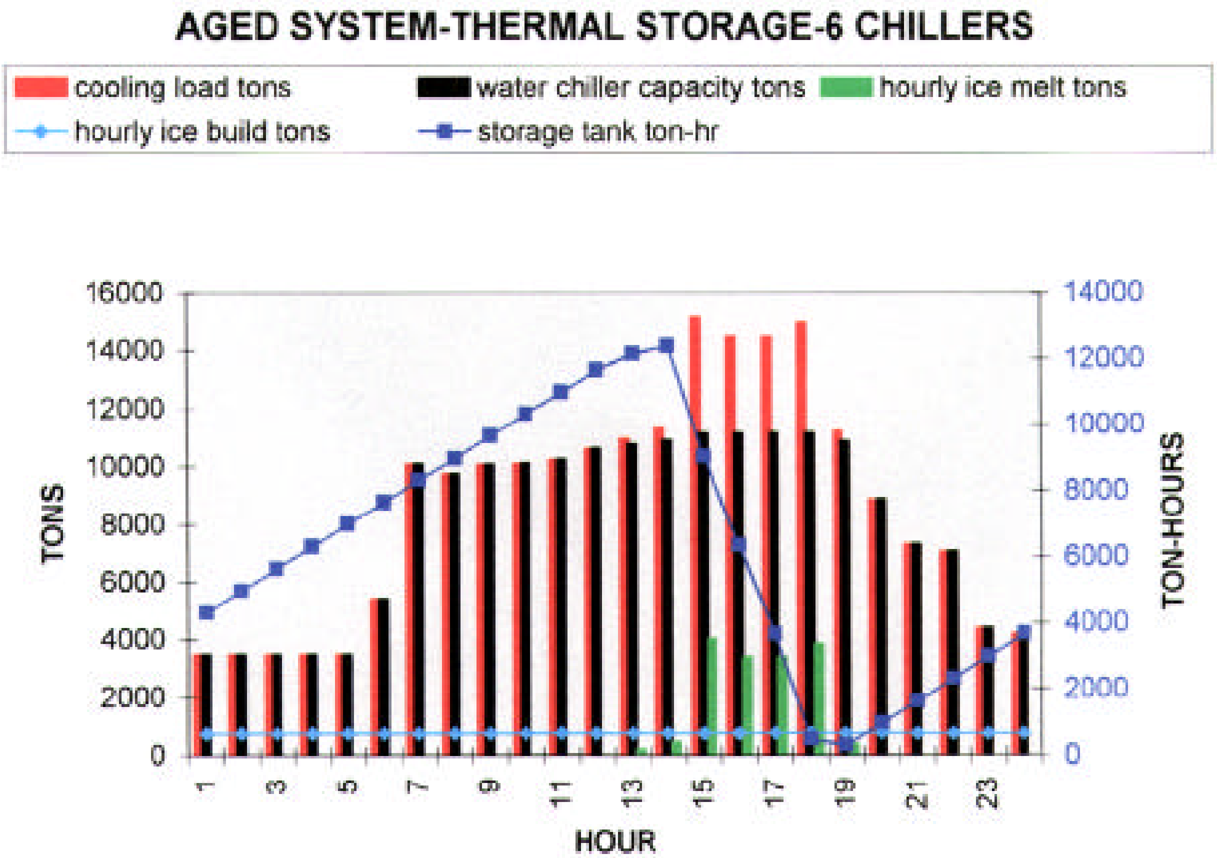


AGED SYSTEM - THERMAL STORAGE AND SIX CHILLERS

Aging of the new system with six chillers and thermal storage increases the thermal storage load as shown by Column 12 of Table 1. Note that the equivalent system without thermal storage is represented by Column 4 which consists of 9 chillers.

Twenty-four hour operation requires seven hours of ice melting for a total of 15,543 tons. A storage tank capacity of about 12,400 ton-hours would be required and a 670-ton ice slurry generator would replace 3 x 2,164 = 6, 492 tons of chiller capacity. Figure 6 illustrates the 24-hour operation.

FIGURE 6

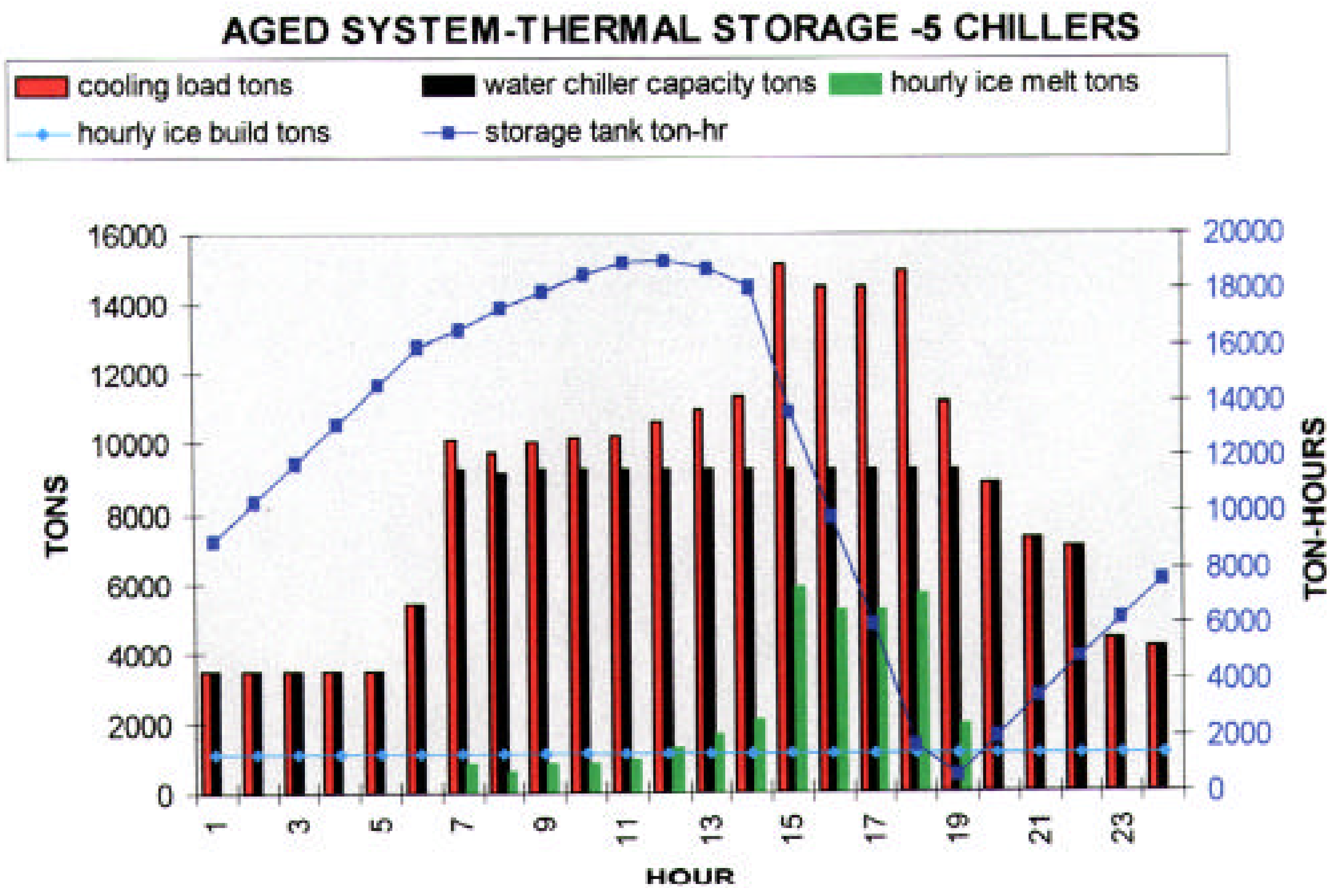


AGED SYSTEM - THERMAL STORAGE AND FIVE CHILLERS

Reducing the number of chillers from six to five for the aged system further increases the thermal storage load as shown by Column 13 of Table 1 to be 5,871 tons.

Figure 7 illustrates 24-hour operation showing 13 hours of ice melting for a total of 32,897 tons. A storage tank capacity of about 19,100 ton-hours would be required and a 1,400-ton ice slurry generator would replace 4 x 2,164 = 8,656 tons of chiller capacity.

FIGURE 7



AGED SYSTEM-THERMAL STORAGE -5 CHILLERS
cooling load tons
water chiller capacity tons
hourly ice melt tons
hourly ice build tons
storage tank ton-hr
TONS
0
2000
4000
6000
8000
10000
12000
14000
16000
TON-HOURS
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
HOUR
1
3
5
7
9
11
13
15
17
19
21
23

The following table illustrates the 13 conditions we have considered. The author suggests making copies of Figures 1 and 2 and writing in the values of Table 1 for each condition for ease of studying the dynamics of this assumed system.

Table 1

	Balanced	Balanced + One	Load Degradation -8 Chillers	Load Degradation -9 Chillers	Shut-Off Valve	Excess Flow	Excess Flow with Shut-Off Valve	Excess Flow w/Shut-Off Valve	Thermal Storage Aged System	Thermal Storage Aged System w/Shut-Off Valve	Thermal Storage New System 6 Chillers	Thermal Storage -6 Chillers Aged System	Thermal Storage -5 Chillers Aged System
Load	15,150	15,150	14,000	15,150	15,150	15,150	15,150	15,150	15,150	15,150	15,150	15,150	15,150
Delta T	16.0	16.0	14.8	14.8	14.8	11.0	11.0	11.0	14.8	14.8	16.0	14.8	14.8
Tls	44.03	44.03	37.36	37.80	37.82	37.78	37.07	37.82	37.80	37.80	44.00	37.80	37.80
Tlr	60.03	60.03	52.16	52.60	52.62	48.78	48.07	48.82	52.60	52.60	60.00	52.60	52.60
Fls	22,725	22,725	22,703	24,568	24,568	33,055	33,055	33,055	24,568	24,568	22,725	24,568	24,568
Fb	-305	-3595	-3617	-5042	0	3445	0	0	1538	0	2985	4828	8118
Tb	44.03	44.03	37.36	37.80	0	48.78	0	0	52.60	0	60.00	52.60	52.60
Fce	23,030	26,320	26,320	29,610	24,568	29,610	33,055	33,055	23,030	24,568	19,740	19,740	16,450
Tce	59.81	57.84	50.12	50.08	52.62	48.78	48.07	48.82	52.6	52.6	60	52.6	52.6
Tcl	44.03	44.03	37.37	37.8	37.82	36.5	37.07	37.82	39.06	39.77	44.15	39.06	39.06
Tpl	44.03	44.03	37.37	37.8	37.82	37.78	37.07	37.82	39.91	39.77	46.24	41.72	43.53
Chillers On	7	8	8	9	9	9	9	9	7	7	6	6	5
% Load	100	89	100	96	92	99	99	97	100	100	100	100	100
Peak Ice Tons	0	0	0	0	0	0	0	0	2159	2016	2117	4015	5871
24-hr Ice Melt	0	0	0	0	0	0	0	0	7144	6794	6975	15,543	32,897
Tank Storage Ton-Hours	0	0	0	0	0	0	0	0	6200	5900	6200	12,400	19,100
Ice Slurry	0	0	0	0	0	0	0	0	306	288	306	670	1400
Column	1	2	3	4	5	6	7	8	9	10	11	12	13

SUMMARY

The paper makes three points:

Point One: A shut-off valve in the bypass line can improve system performance, but the amount of improvement is a function of the characteristics of the system and how it is being operated.

Point Two: This paper suggests that a dynamic math model simulation of a system, verified by existing plant operational data, is the first and necessary step in improving operational performance or modifying an existing system for increased capacity. (See References 26, 27, 28, 29 and 30.)

Point Three: We have shown that thermal storage can offer some significant system characteristics for new or modified systems. For the system of this study, we have shown the following:

Table 2

	Tons Chilling Required Aged System	Chilling Tons Not Purchased with Thermal Storage	Required Ice Generating Capacity Tons	Ratio Ice Capacity to Chilling Tons Not Purchased	Required Tank Thermal Storage Ton-Hours
System without Thermal Storage					
9 Chillers	19,476				
System with Thermal Storage and					
7 Chillers	15,148	4328	306	.07	6200
6 Chillers	12,294	6492	670	.10	12,400
5 Chillers	10,820	8656	1400	.16	19,100

For the systems studied here, unless the cost of space for a storage tank is very high, the five-chiller system with thermal storage should have an attractive return on investment and the six-chiller and seven-chiller systems will have an even more attractive return on investment.

CONCLUSION

Simulating the dynamics of physical systems by applying the laws of physics and thermodynamics is a well established procedure in the design of military products which the author participated in until the mid-1970s. The oil embargo in the fourth quarter of 1973 presented the challenge of simulating energy systems, including buildings and its contents, for the purpose of defining energy waste and systems to eliminate that waste. A fundamental rule of system simulation is that the simulation must give the same results, within reasonable accuracy, as the real system.

This paper presents a simulation based on the first law of thermodynamics. Other features provided by a computer simulation of a central chilled water system include:

- The system energy use and KW demand
- Chiller dynamics of various type chillers
- Pumping dynamics
- Load dynamics

The purpose of a computer simulation of a physical system is to understand the dynamics of the system so that correct decisions about the system can be made. A computer simulation is not required to understand many HVAC systems; however, the author suggests that a primary/secondary chilled water system is sufficiently complex to require a simulation for purposes of operating, changing and expanding the system. Reference 31 is an example of the approach.

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