

Analysis and System Design of a Large Chiller Plant for Korea, with or without Thermal Storage

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ABSTRACT

A 625,600 ft² (58,120 m²) office building with retail in South Korea has a total cooling load of 3,330 tons refrigeration (11,712 kW). In order to evaluate the most economical manner to provide cooling, a simulation program was used. Five different configurations of chiller plants were investigated; each configuration was carefully described so that the computer model was a good representation of the intended plants. This paper outlines the design and analysis procedure, and the results show the difference in energy consumption between the configurations.

BACKGROUND

A forty-story building with 625,600 ft² (58,120 m²) net area -- approximately 40% retail space and 60% office space -- is to be built in Seoul, South Korea. The majority of the building is of rather light construction, insulated metal panels with low-E glass in double-paned windows. The glazing area ranges from 95% in the retail spaces to 10 - 60% on various facades of the office space. Design conditions include 50 ft² (4.6 m²) per person occupancy, 25 CFM (12 L/s) per person ventilation air, and 10 - 14 W/ft² (110 - 150 W/m²) lights and equipment load for the retail areas. Corresponding conditions for the office areas are 50 ft² (4.6 m²) per person, 15 CFM (7.1 L/s) per person ventilation air, and a more modest 4.5 W/ft² (48 W/m²) lights and equipment load.

Seoul, South Korea, experiences summer and winter outdoor design conditions of 88°F (31.1°C) db / 79°F (26.1°C) wb and 11°F (-11.7°C) db respectively. The city's summers could be compared to Florida's for their heat and humidity, while its winters are colder than those of New York City. This paper will focus on design and analysis of cooling equipment, however, rather than considering heating as well.

Because the location suffers from a shortage in electric capacity, indoor design conditions are set at 80°F (26.7°C) and 55% relative humidity (RH) in an effort to reduce the building's required cooling capacity. Furthermore, a local code requirement mandates that a maximum of 60% of the peak cooling load be satisfied by electricity. This leads to consideration of alternatives such as natural gas fuels and use of thermal storage in the design and selection of the refrigeration plant.

FAN SYSTEM DESCRIPTION

The building is divided into two air distribution systems, retail and office, based on building geometry -- all retail spaces are grouped together in the lower floors of the building, while all office spaces are located on the upper floors -- and on operating schedules. Fan powered variable air volume (VAV) boxes, or powered induction units (PIU), were used to distribute and circulate air in both systems.

"The PIU system is basically just a VAV terminal box with a small fan that pulls some amount of air from a ceiling plenum. PIU's have two functions:

- 1) to move warm air from a core area through the plenum to exterior zones requiring heat; this conserves heating energy; and
- 2) to provide increased air movement in zones normally served by VAV terminals; such zones often suffer from stagnant air when the primary air damper is in its minimum position.

(DOE-2.1 Manual Supplement--
2.1E Update, Systems p. 3.16)"

The retail floors have mechanical rooms on the perimeter of the building, thus making air-side

economy cycles feasible. On cool days, outside air volumes greater than the minimum required amounts will be drawn into each floor's air handling unit to reduce the mechanical cooling capacity. On the office floors, however, mechanical rooms are located in the core, and ceiling plenum heights are so tight that air-side economy cycles are not feasible for these floors. Rather, water-side free cooling from the rooftop cooling towers is used as an economy measure for the office system.

Based on the design conditions described previously and using the DOE-2.1E simulation program, the building was determined to have a cooling load of 3,330 tons refrigeration (11,712 kW). (This was rounded up to 3,400 tons [11,958 kW] for the purposes of sizing plant equipment.) The maximum daily integrated cooling load was found to be 39,283 ton-hours (138,158 kWh). For a graph of the summer design day cooling load profile for occupied hours, see Figure 1.

CHILLER PLANT SCHEMES CONSIDERED

Five different configurations of chiller plants were investigated for this project:

A. Gas-Fired Absorption Chillers: To meet 100% of the building's cooling load, four (4) 850-ton gas-fired absorption chillers were simulated.

B. Two-Stage Steam Absorption Chillers: To meet 100% of the building's cooling load, four (4) 850-ton two-stage steam absorption chillers, with steam from gas-fired boilers, were simulated.

C. Electric Centrifugal Chillers with Thermal Storage: Local code requires that a maximum of 60% of the peak cooling load be satisfied "real-time" by electricity. Therefore, two (2) 1,020-ton electric centrifugal chillers provided 2,040 tons refrigeration in this plant scheme. The remaining 1,360 tons required to cool the building (40% of the peak cooling load) were supplied by thermal storage -- circulating water through tanks of encapsulated ice generated at night. The 1,360-ton cooling supply rate for fourteen hours of building operation required 19,040 ton-hours of ice storage. The cooling storage rate required during the ten hours of nighttime tank-charging was 1,904 tons, well within the electric centrifugal chillers' capacity.

D. Mixed Plant -- Gas-Fired Absorption Chillers and Thermal Storage: The fourth scheme

considered was a mixed plant. 60% of the building's peak cooling load was provided by two (2) 1,020-ton gas-fired absorption chillers, while the remaining 40% was provided by thermal storage as in the previous scheme. Electric centrifugal chillers, two (2) at 950 tons each, were still required to charge the ice tanks at night, because gas-fired absorption chillers cannot make the 28°F (-2.2°C) glycol solution temperatures used to make the ice.

E. Mixed Plant -- Gas-Fired Absorption Chillers, Electric Centrifugal Chillers, and Thermal Storage:

The fifth scheme considered was also a mixed plant. 60% of the building's peak cooling load was provided by two (2) 1,020-ton gas-fired absorption chillers, 24% was provided by two (2) 408-ton electric centrifugal chillers, and thermal storage provided the remaining 16%. The 544-ton cooling supply rate for fourteen hours of building operation required 7,617 ton-hours of ice storage. The cooling storage rate required during the ten hours of nighttime tank-charging was 762 tons, well within the electric centrifugal chillers' 816-ton capacity. For a graph of this plant scheme's cooling capacity by source, see Figure 2.

For a summary of the five chiller plant schemes considered, see Table 1.

COMPUTER MODELING OF THE PLANTS

In developing the computer models of the plants, the following DOE-2.1E equipment types were used: ABSORG-CHLR for the gas-fired absorption chillers, ABSOR2-CHLR for the two-stage steam absorption chillers, OPEN-CENT-CHLR for the electric centrifugal chillers, CTANK-STORAGE for the thermal storage component, and OPEN-TWR for the rooftop cooling towers. The quantity and capacities of the chillers were as described above. The ice tanks' storage capacities, cooling supply rates, and cooling storage rates were as also as described above. The cooling towers were specified at quantity eight (four units of two cells each) with sizes to be calculated by the simulation program.

Operating efficiency curves for the equipment were left at the program defaults, but some equipment and plant parameters were changed to more closely model the intended plant designs. For example, to model a 25% glycol solution circulating in the ice tanks, CTANK-BASE-T and CTANK-T-RANGE were specified such that a 28°F (-2.2°C) temperature low would be allowed in the tank charging cycle.

The desired chilled water temperature was set at 44°F (6.7°C). The cooling towers' design wet bulb temperature was set at 79°F (26.1°C) to agree with the summer design day's wet bulb temperature. Load assignments were specified such that the number of chillers running would be appropriate to the cooling load, thus maximizing plant efficiency and reducing operating costs.

Finally, fuel and electricity meters set for each item of plant cooling equipment tallied the plants' energy consumption as distinct from the building's lights, electric equipment plug load, and fan system consumptions.

RESULTS

One of the major criteria for evaluating the various plant schemes under consideration was the cost of electricity and natural gas consumed over the course of a year. Using the DOE-2.1E simulation program, annual energy costs (for cooling only) were found to range from \$420,335 for Plant Scheme C, Electric Centrifugal Chillers with Thermal Storage, to \$530,013 for Plant Scheme B, Two-Stage Steam Absorption Chillers. For a summary of annual cooling energy consumption and costs of each chiller plant scheme, see Table 2.

DISCUSSION

In terms of annual cooling energy costs, the least expensive plant was Scheme C, Electric Centrifugal Chillers with Thermal Storage. This was surprising at first considering the monthly charge of \$6.70 per kW of the year's peak electric demand, but evidently putting even 40% of the peak cooling load into thermal storage -- with electricity usage during off-peak nighttime hours at more favorable utility rates -- was enough to reduce the electric demand and associated charges to manageable levels. This scheme also has the advantage of lowest capital cost and least floor space required. However, in this area short on electric capacity, a blackout would cut out the majority of the building's cooling capacity. Emergency generators would only be sufficient to run circulation pumps for the ice tanks, not to run the electric chillers.

The second least expensive plant to run was Scheme A, Gas-Fired Absorption Chillers. This scheme has the benefit of using natural gas as the power source rather than electricity. Also, choosing a chiller/heater option in the gas-fired absorption units would

provide heating in the winter from the same equipment, thus minimizing capital costs. However, disadvantages are that this scheme requires the largest floor area, and that it is often difficult to control the chemistry of the absorption cycle; crystallization of the lithium-bromide solution is always a concern.

The third least expensive plant to run was Scheme E, Gas-Fired Absorption Chillers, Electric Centrifugal Chillers, with Thermal Storage, with a 60% / 24% / 16% contribution from each. As with plant schemes C and D, this plant's use of thermal storage shifts some electricity usage from peak daytime hours to off-peak nighttime hours and takes advantage of favorable utility rates. Scheme E's use of 16% thermal storage rather than 40% reduces the required electric centrifugal chiller sizes -- thus saving on capital costs -- and also reduces the ice tank volume -- thus saving on real estate opportunity costs. Scheme E's use of natural gas as a partial power source is an improvement over scheme C's all-electric plant. And finally, unlike scheme D, scheme E's running of the electric centrifugal chillers during the day, rather than leaving them to stand idle, uses equipment that has already been paid for.

The fourth least expensive plant to run was Scheme D, Gas-Fired Absorption Chillers with Thermal Storage from Electric Centrifugal Chillers. This scheme has the advantage of using electricity during off-peak hours and of having natural gas cooling available in case of blackouts. Emergency generators could make the thermal storage cooling available, too. However, this scheme has the disadvantage of high capital costs for two sets of chillers.

And finally, the most expensive plant to run was Scheme B, Two-Stage Steam Absorption Chillers. Like the gas-fired absorption chillers, these have the benefit of using natural gas as the power source rather than electricity. Also, the same boilers used to produce steam for the steam absorption chillers can provide heating in the winter, thus minimizing capital costs.

CONCLUSIONS

Based on annual cooling energy costs alone, Scheme C, Electric Centrifugal Chillers with Thermal Storage would be the preferred plant scheme. However, other costs to consider are capital costs,

opportunity costs of mechanical space required, and operating costs such as labor, maintenance, insurance, and depreciation. All of the above could contribute to determination of a present worth dollar value for each plant scheme. However, there are also non-monetary considerations such as complexity of plant operation, versatility in plant power source, and local constraints such as utilities' capacity and reliability.

It is these latter considerations that finally influenced the building owner to select Plant Scheme E, Gas-Fired Absorption Chillers, Electric Centrifugal Chillers, with Thermal Storage. In spite of the high capital costs associated with two sets of chillers, the large mechanical space required, and the complexity of operation, the cost and reliability of natural gas, the off-peak electric usage of thermal storage, and the versatility in power source of a mixed plant turned the scales in favor of Scheme E.

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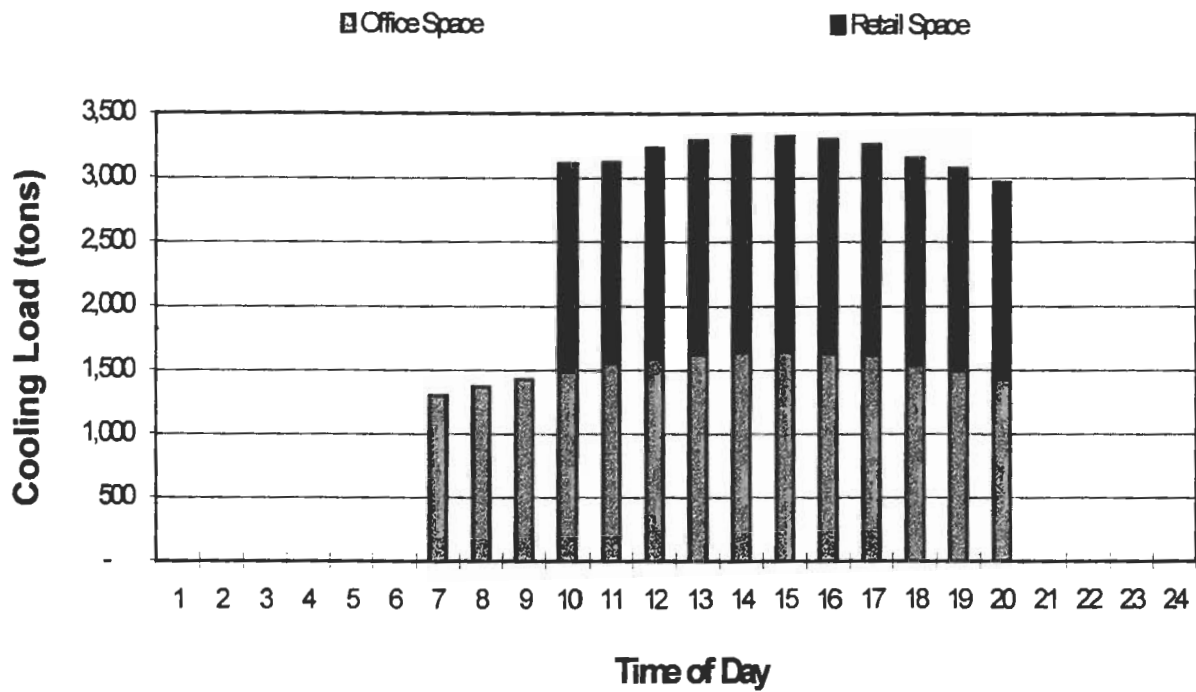


Figure 1: Summer Design Day Cooling Load Profile

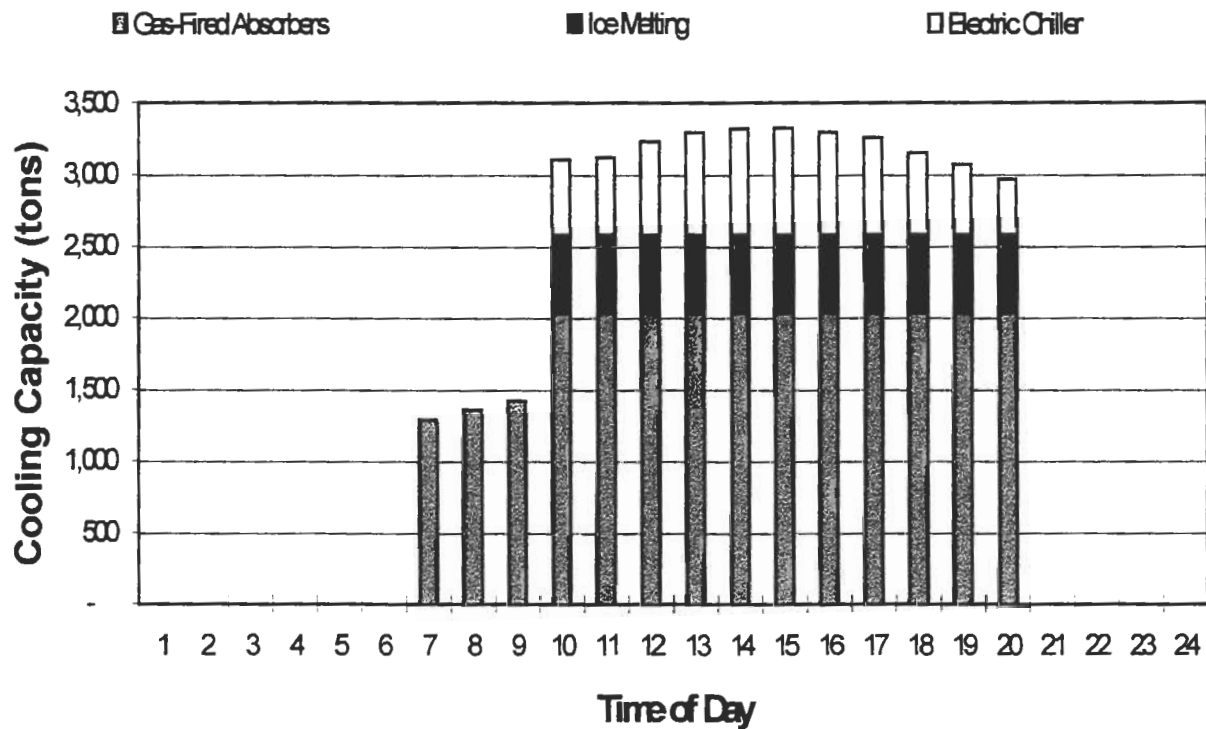


Figure 2: Scheme E -- Mixed Plant Cooling Capacity by Source

CHILLER PLANT SCHEME	REFRIGERATION SOURCE			INSTALLED CAPACITY (tons)	ANNUAL CONSUMPTION (ton-hrs)
	Gas Absorbers (tons)	Electric Chillers (tons)	Thermal Storage (tons)		
A Gas-Fired Absorption Chillers	3,400 (100%)	N/A	N/A	3,400	3,839,648
B Gas-Fired Boiler Plant Steam Absorption Chillers	3,400 (100%)	N/A	N/A	3,400	3,839,648
C Electric Centrifugal Chillers with Thermal Storage	N/A	2,040 (60%)	1,360 (40%)	3,400	3,839,648
D Gas-Fired Absorption Chillers with Thermal Storage from Electric Centrifugal Chillers	2,040 (60%)	(1,900) (ice generation) (night-time only)	1,360 (40%)	3,400	3,839,648
E Gas-Fired Absorption Chillers, Electric Centrifugal Chillers, and Thermal Storage	2,040 (60%)	816 (24%)	544 (16%)	3,400	3,839,648

Table 1: Summary of Chiller Plant Schemes

CHILLER PLANT SCHEME	ELECTRICITY			NATURAL GAS			ANNUAL ENERGY COST (U.S. \$)	RANKING, LEAST TO MOST COSTLY
	Demand (kW)	Consumption (kWh)	Cost (U.S. \$)	Demand (Btu/h x 10 ⁶)	Consumption (Btu x 10 ⁶)	Cost (U.S. \$)		
A Gas-Fired Absorption Chillers	623	813,208	126,487	50	42,707	301,567	428,054	2
B Gas-Fired Boiler Plant Steam Absorption Chillers	635	794,678	125,837	61	57,217	404,176	530,013	5
C Electric Centrifugal Chillers with Thermal Storage	1,728	3,143,125	420,335	N/A	N/A	N/A	420,335	1
D Gas-Fired Absorption Chillers with Thermal Storage from Electric Centrifugal Chillers	1,353	1,072,167	197,037	29	39,927	282,836	479,873	4
E Gas-Fired Absorption Chillers, Electric Centrifugal Chillers, and Thermal Storage	1,068	978,452	178,493	30	40,485	287,081	465,574	3

Table 2: Annual Cooling Energy Consumption and Costs