CHAPTER

ONE

INTRODUCTION

1.1 Absorption Cooling Cycle

Ferdinand Carré, a Frenchman, invented the absorption system in 1860, with its first use during the Civil War (Stoecker and Jones, [1982]).

A mechanical vapor compression refrigeration system requires shaft-work to transform a low pressure vapor from the evaporator into a high pressure vapor. Typically, the work input is provided by an electric driven compressor. It is possible to replace the vapor-compression process with an absorber/generator combination and an absorbent solution. A basic absorption unit is given in Figure 1.1. The low pressure refrigerant vapor is absorbed by a liquid solution in the absorber. Since the refrigerant changes state from a vapor to a liquid, energy must be transferred to the surroundings, similar to condensation. The liquid solution is pumped to a higher pressure. The shaft-work required is much less than the compression of the vapor due to the lower volume of the liquid. Heat transfer to the generator boils the solution thereby removing the refrigerant. The refrigerant vapor is sent to the condenser and the evaporator, and the solution from the generator is sent to the absorber to repeat the process. The absorption cycle is referred to as a heat-operated cycle because the operating costs are mainly associated with providing heat to boil off the refrigerant. The cycle COP is defined as the ratio of the refrigeration heat rate to the rate of heat input to the generator, Q_{evap}/Q_{gen}.

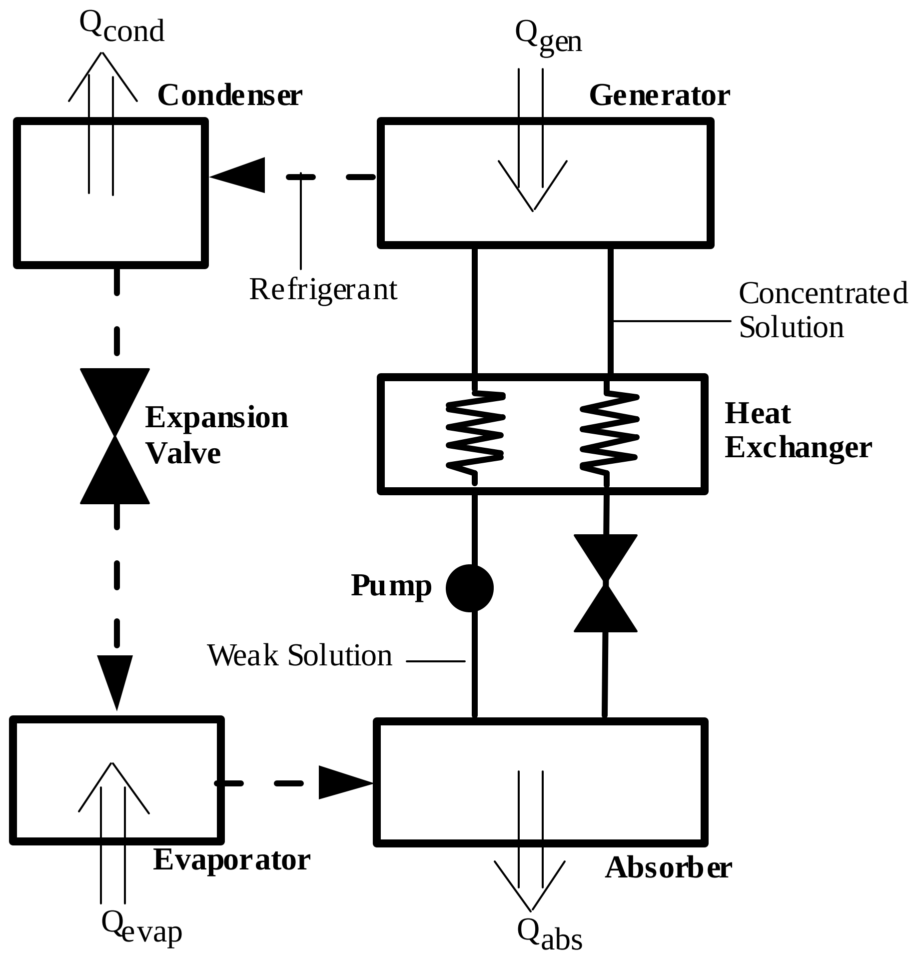

Figure 1.1 Basic absorption unit.

The cycle investigated in this research is a double-effect water-lithium bromide cycle for which a diagram is given in Figure 1.2. Water is used as the refrigerant and lithium bromide (LiBr), which has a strong affinity for water, as the absorbent. The cycle in Figure 1.1 is referred to as a "single-effect" cycle. The "double-effect" cycle is commonly used for commercial cooling applications due to a higher rated COP (~0.9-1.0) than the single-effect cycle (~0.6-0.7). A very brief description of the cycle is given here, but the cycle is discussed in further detail in Chapters 2 and 3, were a computer model of the chiller is described. Refrigerant vapor is absorbed by the water-lithium bromide solution in the absorber. The solution is pumped to a higher pressure where a parallel flow arrangement splits the solution flow, sending a fraction to a high temperature generator and the rest to the low temperature generator. Energy is supplied to the high temperature generator (by combustion of natural gas) to boil off the refrigerant. This refrigerant vapor condenses in the low temperature generator boiling off further refrigerant, thus creating the "double-effect." The strong solutions leaving the two generators are mixed together before entering the absorber.

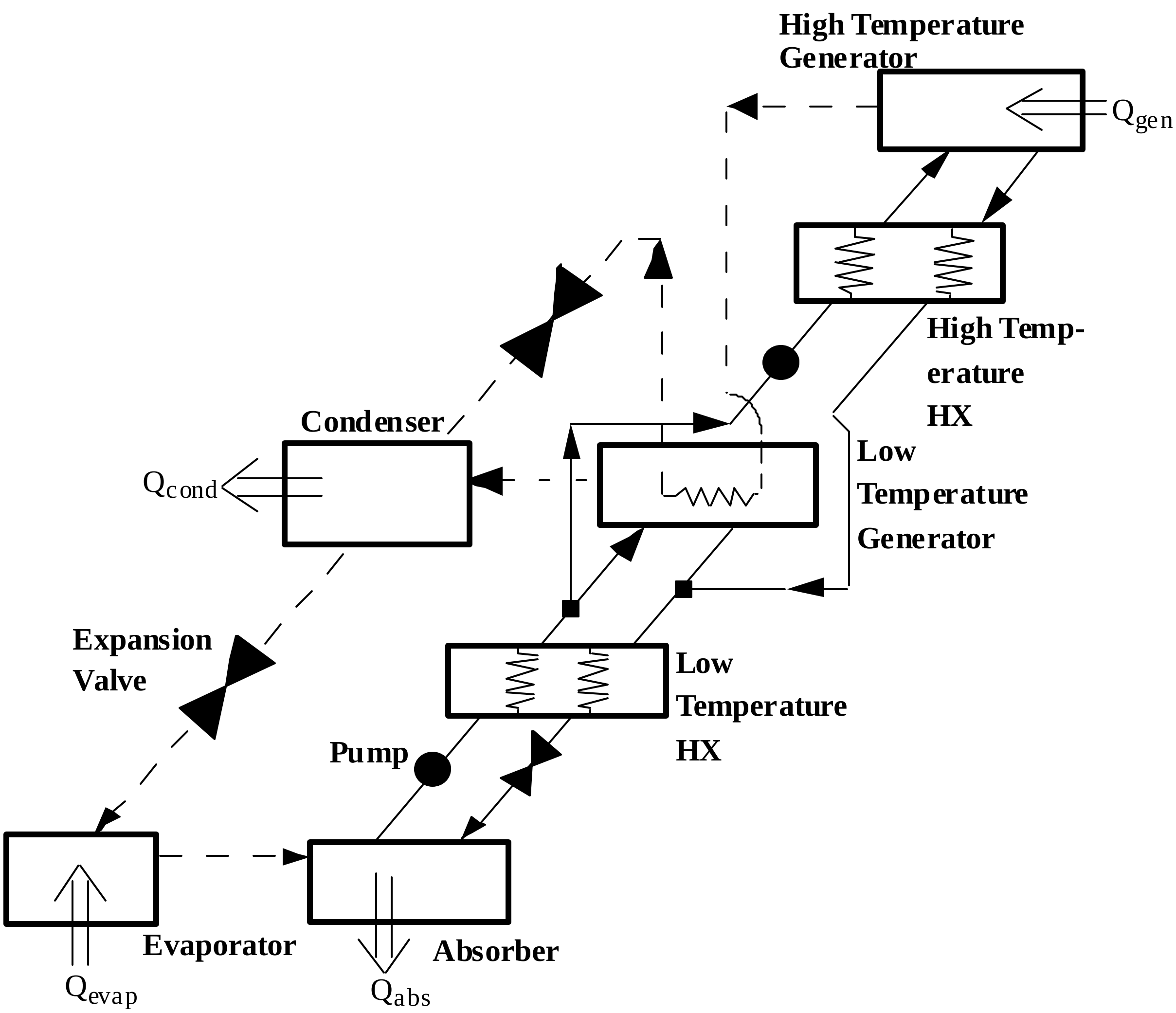

Figure 1.2 Double-effect absorption cycle diagram. Solid lines represent the solution flow and broken lines the refrigerant flow.

1.2 Background

Absorption gas cooling technologies are an alternative to electric driven vapor compression cooling for commercial cooling and industrial customers. On-peak electrical energy and demand charges have contributed to an increasing interest in absorption chillers. Direct-fired (natural gas) double-effect absorption chillers using water-lithium bromide are commonly used for commercial cooling applications. The benefits are reduced electric demand and a shift from electricity to natural gas during the cooling season. Typically, these absorption chillers have a 15 to 20 percent higher first cost than electric chillers (ASHRAE Air-Conditioning Systems Design Manual [1993]) mainly due to the larger heat exchange surface area. These absorption chillers can be cost effective over a long-term depending on the electric and gas rates and rebates offered by utilities.

Absorption chillers require electrical energy to operate the chiller pumps, the cooling tower fans, and the chilled and cooling water pumps. Figure 1.3 shows a simplified schematic of an absorption chiller system. An absorption chiller rejects more energy than a vapor compression chiller and therefore requires larger cooling water flow rates, which increases the pumping and cooling tower electrical requirements. The absorption chiller performance and the parasitic electrical energy consumption will be investigated and documented in this study.

This research will investigate the chiller system performance and supervisory controls using both simulation and field monitoring data. The system simulation will consist of models of the chiller, cooling tower, and pumps, and will be used to determine the optimal supervisory control of the chiller system with respect to the total energy input cost. Control laws (strategies) were developed from the optimal control investigation and implemented into the chiller system simulation. The optimal and near-optimal control will be compared to the base or current control, and evaluated in terms of potential energy savings.

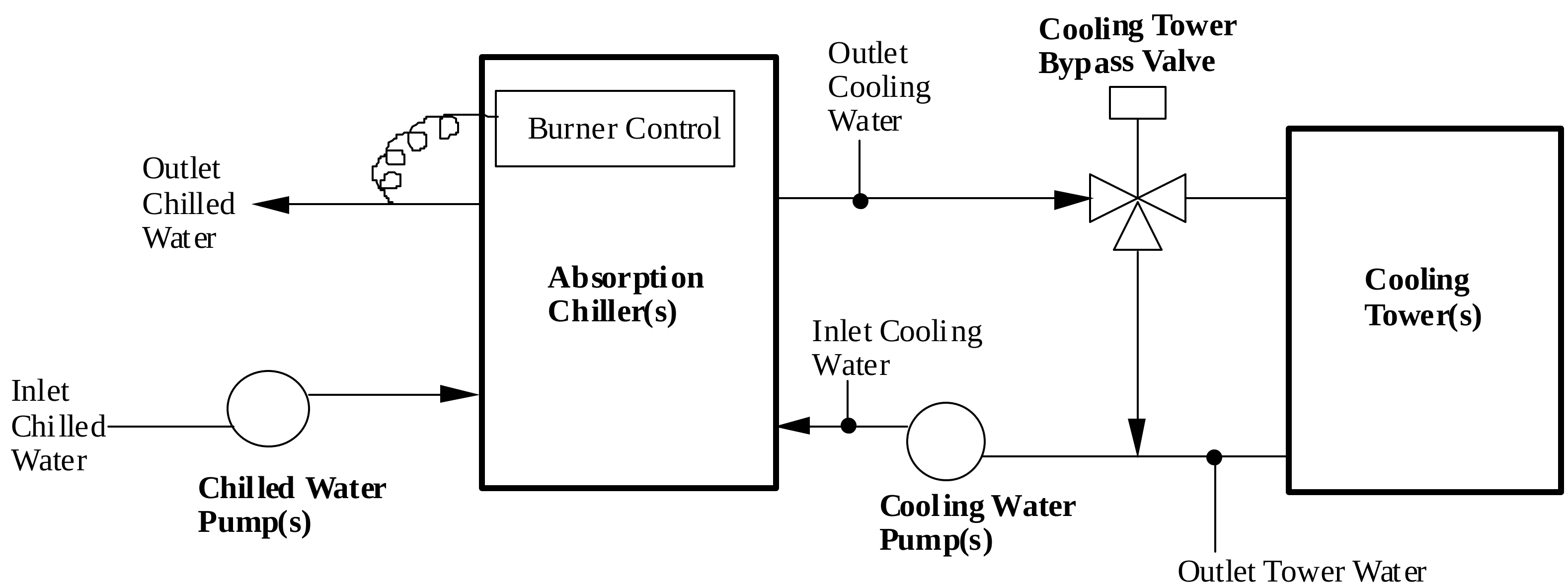

Figure 1.3 Schematic of an absorption chiller cooling system.

Research on absorption chillers has mainly focused on the design and analysis of the components comprising the chiller and not on optimization of the system operation of the chiller with the cooling tower and the external water circuits (chilled and cooling water). It is important to investigate the system performance of the chiller and its supervisory controls, in order to reduce the parasitic electrical energy consumed and improve the total chiller system economics.

The Wisconsin Center For Demand-Side Research, WCDSR, (a consortium of Wisconsin utilities, the Public Service Commission of Wisconsin, the University of Wisconsin, and other sources) has supported the instrumentation and monitoring of a number of gas cooling systems with the objective of providing a base for evaluating their economic and energy viability. Two direct-fired double-effect absorption chillers of 200 and 400 ton capacity at two different sites have been monitored during the 1993 and 1994 cooling seasons, and these data have been made available for this research.

1.3 Research Objectives and Approach

The goals of this research are:

- To assess whether absorption gas cooling systems are performing as expected and whether the monitoring results are representative of what may be expected in practice.
- To develop a calibrated, mechanistic computer simulation model of a direct-fired double-effect water-lithium bromide absorption chiller.
- To determine the optimal supervisory control of an absorption chiller system with respect to the total energy cost (gas plus total electric).
- To evaluate control laws (near-optimal control) compared to the current control and the optimal control.

The results of this study will provide necessary information to owners and operators for decisions on absorption gas cooling systems and their operation and control. The model will be a useful tool for simulations of commercial absorption chiller systems and for comparison to other technologies. Also, the model will provide detailed information concerning the cycle operation (temperatures, pressures, concentrations) and concerns such as crystallization. It is anticipated that the use of optimal control will result in improved system economics. The analyzed field monitoring data will provide information and experience concerning the system performance and operation, and the importance of the supervisory controls. The results from both the monitoring and the control study will be useful for designers and contractors for the system operation, economics and supervisory control.

1.3.1 System Simulation

The transient simulation program, TRNSYS, Klein et al. [1994], was developed over 20 years ago for analyzing the performance of solar energy systems. TRNSYS is a modular program in which models of system components (i.e. collectors, pipes, heat exchangers) are written as FORTRAN subroutines. The user can formulate new models or modify existing models. The models are connected together to form a system simulation model, analogous to the way pipes and wires connect the physical pieces of equipment, and is one particular advantage of the program. Component models currently exist for a cooling tower, pump, valve and mixer. Weather and load data are inputs to the system model. The cooling tower model was developed and validated by Braun [1988] and is important since the power consumed by the tower is influenced by the desired inlet cooling water temperature to the chiller (tower outlet), i.e. the control law. A component model for a commercial absorption chiller has been developed using the results obtained from the calibrated, mechanistic model. Simulations of the system model can be performed for different control strategies and the results evaluated. A general, global optimization component model for TRNSYS has been developed at the Solar Energy Laboratory, University of Wisconsin-Madison, Flake [1994], and uses a statistical algorithm to minimize an objective function with respect to the prescribed independent variables. This optimization component will be used to determine the optimal supervisory control. Analysis of the results of the optimal control will allow for determination of near-optimal control laws that are simple to implement and that will improve the chiller system economics.

1.3.2 Chiller Model Development

A steady state model of a direct-fired double-effect water-lithium bromide absorption chiller in parallel flow configuration was developed from first principles. The model can be used to predict the performance under operating load and environmental conditions. It will be used to assess whether the field monitored units are operating as expected, and to investigate the supervisory control of the chiller system. The model has been calibrated and validated against manufacturer operating data and performance ratings and is a valuable tool for investigation of the cycle operation and performance. The model has been used to optimize the chiller part-load COP, evaluate the performance with a higher cooling water temperature range, and investigate conditions leading to cycle crystallization and to determine the operating limits to prevent crystallization.

The absorption chillers at both sites are York/Hitachi, direct-fired double-effect units. The cycle configuration of the developed model is similar to that of the York/Hitachi units. The model was written using an equation solver program, EES-Engineering Equation Solver, by Klein and Alvarado [1993]. Mass and energy balance equations were written for each of the components, along with the appropriate equilibrium equations. All heat transfer rates are expressed as a function of a log-mean temperature difference. York catalogs (York Applied Systems [1992, 1993] and Aizawa, Nagao, and Kazuo [1981]) provide operating data for various cycle points at full-load, nominal conditions. These data consist of cycle temperatures, pressures and concentrations. Also provided is the nominal cooling capacity, nominal gas consumption, nominal chilled and cooling water flow rates, nominal outlet chilled water temperature and nominal inlet cooling water temperature. The nominal outlet chilled water temperature is 6.7 C (44 F) and the nominal inlet cooling water temperature is 29.4 C (85 F). The manufacturer also gives performance ratings for chiller part-load performance at nominal temperatures, and for chiller full-load performance at various chilled and cooling water temperatures. The unknown parameters in the model, such as heat transfer coefficients, were determined by matching the model's calculated state points and COP against the manufacturer's nominal full-load operating data and COP. The model was then compared to the manufacturer performance ratings.

Vliet, Lawson, and Lithgow [1982] have simulated a double-effect water-lithium bromide absorption chiller in series flow configuration. Gommed and Grossman [1990] have used the computer simulation code developed by Grossman and Michelson [1985] and Grossman, Gommed, and Gadoth [1987], to investigate the performance of both series and parallel flow configuration chillers. Both studies investigated the chiller performance as a function of various design and operational variables. Oh et al. [1994] have modeled an air-cooled, gas-fired double-effect water-LiBr absorption heat pump with a cooling capacity of 2 tons and investigated the performance of the heat pump as a function of the inlet air temperature, and design and operational variables. The model developed for this study differs from the above models in that it was developed with the intention of replicating manufacturer performance ratings for both full and part-load conditions, and to be used to predict chiller performance under different operating conditions for which manufacturer data is not available.

After the model was judged satisfactory by comparison to the manufacturer's data and performance ratings, a component model of a direct-fired double-effect absorption chiller was written for the simulation program TRNSYS. Curve-fits of the steady state EES model COP over a wide range of operation were used to develop the component model. Thermal capacitance effects are not included in the model. The model meets the load for a desired chilled water setpoint.

1.3.3 Optimal Control Investigation

The current supervisory control as implemented at the field monitored sites involves constant chilled and cooling water flow rates which correspond to the nominal flow rates, a constant outlet chilled water temperature setpoint, and a constant inlet cooling water temperature setpoint. Variable and one speed cooling towers are in use at the field sites. The chilled water setpoint is usually 6.7 C (44 F) and the cooling water setpoint is usually 29.4 C (85 F), but it has been lowered by site operators to 26.7 C (80 F) on occasion, to take advantage of improved chiller efficiency. It is noted and displayed in Figure 1.3, that the gas input to the chiller is modulated to maintain a constant outlet chilled water temperature (setpoint). The gas input is modulated continuously between 30 and 100 percent of full-load and cycles off below 30 percent.

Optimal supervisory control involves determining the control of the equipment in a cooling plant in order to minimize the total operating cost. The control depends upon the cooling requirement and environmental conditions. The major independent control variables in a cooling plant consisting of one chiller to meet the entire cooling load are the chilled water and supply air setpoint temperatures, cooling tower cell air flow rate, and chilled and cooling water flow rates. In this study, the chilled water and supply air setpoints were not investigated as control variables. Variable speed electric motors have been used in many HVAC applications and Treichler [1985] concluded that variable speed pumping is economically attractive for both the chilled and cooling water loops of a vapor compression chiller. Variation of the chilled and cooling water flow rates, and the tower cell air flow rate can lower the electric consumption of the system but will have an effect on the chiller performance. Two speed cooling tower fan motors are available from cooling tower manufacturers and are considered in this study.

Optimization of cooling plant control has been performed by Marcev [1980], Sud [1984], Lau [1985], Hackner [1984, 1985], Johnson [1985], and Braun [1988]. The cooling plants investigated in these studies contain electric driven vapor compression chillers. Gas-fired absorption cooling systems are a relatively new technology for commercial cooling applications and there is little experience available to set the controls at optimal values. Bedard [1993] has investigated varying the cooling water flow rate with the cooling load for a gas-fired single-effect absorption chiller. In the analysis, COP losses due to varying flow rates were neglected and the electric consumption of a constant flow system and a variable flow system calculated. An annual operating savings of 32 percent for an Atlanta building, along with a 3 year payback for the variable flow system were calculated.

A methodology for optimal supervisory control of central cooling systems without chilled water storage has been developed by Braun [1988]. A modular, component-based optimization algorithm was developed which is similar in nature to that of TRNSYS. TRNSYS was not utilized in Braun's study because TRNSYS did not have the capability for performing control optimization. Such capability has been recently developed and in this study the optimal control was determined and evaluated through computer simulation (TRNSYS) of the chiller system and a global optimization algorithm implemented by Flake [1994], for use with TRNSYS. The global optimization algorithm called “simulated annealing” (Kirkpatrick et al. [1983], Corana et al. [1987], Goffe et al. [1994]), is a statistically based method for solving global optimization problems. The optimization algorithm has been formulated as a TRNSYS component model in which the inputs are the control variables and the objective function. Its major advantage in application to optimal control of HVAC systems is its ability to handle functions of both continuous and discontinuous variables without any special treatment of the objection function.

From the optimal control investigation, supervisory control laws involving varying chilled and cooling water flow rates, and varying inlet cooling water temperatures were developed with the desire to improve the total chiller system economics. A lower inlet cooling water temperature than the nominal will increase the chiller performance, but may increase the cooling tower electric energy consumed. The use of one, two and variable speed cooling towers to obtain a desired inlet cooling water temperature was investigated. Currently, there is some inconsistency on the part of the manufacturer as to the variation of the chilled and cooling water flow rates. It is stated in one catalog, York Applied Systems [1992], that they may be varied plus or minus 25 percent of nominal and in another, York Applied Systems [1993], the variation is only plus or minus 10 percent. In this research, flow rates are to be varied to a minimum of 50 percent of the nominal for the cooling water and to a minimum 75 percent of the nominal for the chilled water, and to investigate if the operation is possible. The reduced flow rates at part-load will substantially reduce the electrical energy consumed by the pumps. Varying flow rate applications have been used for electric driven vapor compression chillers, Treichler [1985], with limits prescribed for safety. Varying the chilled water flow rate is usually not a factor for the vapor compression chiller efficiency where as varying the cooling water flow rate may be, but the minimum chilled water flow rate is more critical due to the danger of tube freeze-up. The effect of the flow rates on chiller efficiency will be investigated for an absorption chiller. The same concern of tube freeze-up will exist for the chilled water flow and this is the reason for the higher minimum chilled water flow rate, but is within manufacturer limits. For the cooling water variation, cycle crystallization is a concern. The operating conditions with respect to crystallization were investigated with the steady state, mechanistic chiller model.

1.4 Field Monitored Sites

The locations will remain anonymous and will be referred to by the absorption chiller nominal capacity. Two direct-fired double-effect absorption chillers have been monitored during the 1993 and 1994 cooling seasons. These data have been made available by the Wisconsin Center For Demand-Side Research. The monitored data consist of both filtered and unfiltered 15-minute measurements. The data consist of external (to the chiller) points for the chilled and cooling water loops, and the gas and electricity consumed. At the 200 ton site, a single York/Hitachi direct-fired double-effect absorption chiller provides the entire cooling for a 60,000 ft^2 office building located in southern Wisconsin, near Lake Michigan. A site schematic is given in Figure 1.4. The cooling tower utilizes a variable speed fan for control of the inlet cooling water temperature. A bypass valve prevents the inlet cooling water temperature from dropping below 21.1 C (70 F), which is the limit prescribed by the manufacturer. Also, there is a minimum fan speed of 750 rpm, the nominal is 1800 rpm. The rated COP at nominal, full-load conditions is 1.0. The cooling tower fan motor size is 14.9 kW (20 hp), and the chilled and cooling water pump motor sizes are 11.2 kW (15 hp) and 14.9 kW (20 hp), respectively. The absorption chiller is monitored along with the cooling tower electrical power, and pump runtimes. The inlet cooling water temperature was originally monitored and at a later time the cooling water flow rate, the outlet cooling water temperature and the outlet tower water temperature were added to the monitoring to investigate the cooling tower performance and the cooling water loop control.

At the 400 ton site, four chillers are piped in parallel to provide 5843 kW (1660 tons) of cooling capacity for 225,000 ft^2 section of a laboratory building in southern Wisconsin. The site schematic for the chilled water loop is given in Figure 1.5. The absorption chiller is a 400 ton York/Hitachi direct-fired double-effect unit and is baseloaded, and there are also three electric driven vapor compression chillers. The 400 ton absorption chiller is monitored along with the total cooling load to the building. The rated COP for the unit is 0.92, and has a 29.4/37.8 C (85/100 F) cooling water temperature range instead of the nominal 29.4/35 C (85/95 F) temperature range. The cooling water flow rate at the higher temperature range is 77 L/s (1220 gpm). The higher temperature range is reported by the manufacturer to have no loss in capacity or COP. The cooling tower fan speed is constant at full speed and the inlet cooling water temperature is controlled by bypassing a fraction of the water and then mixing it with the outlet water from the cooling tower. The cooling tower fan motor size is 22.4 kW (30 hp) and the cooling water pump motor size is 29.8 kW (40 hp). A 11.2 kW (15 hp) chilled water pump serves just the absorption unit. The common chilled water loop and the three electric chillers are served by two 44.7 kW (60 hp) pumps and one 55.9 kW (75 hp). The absorption chiller is monitored along with the absorption chiller cooling tower electrical power, the pump runtimes, the common load and chilled water flow rate, the common supply and return chilled water temperatures, the inlet and outlet cooling water temperatures of the absorption chiller, and the absorption cooling water flow rate.

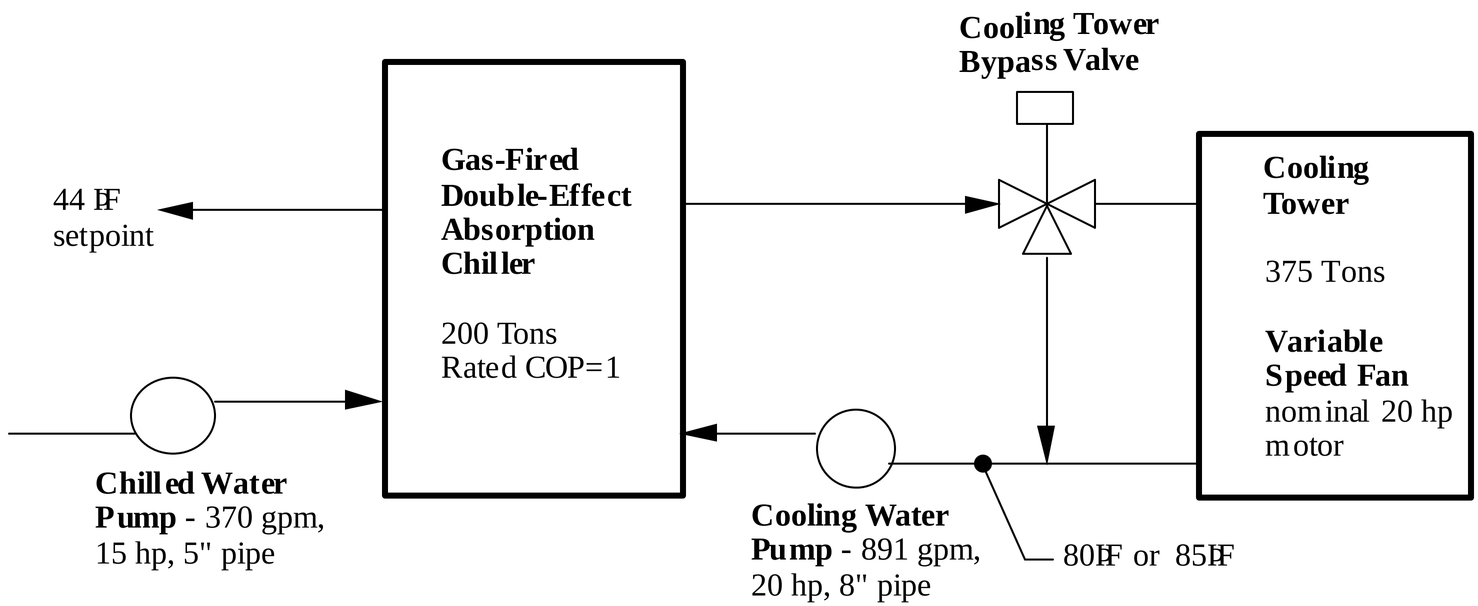

Figure 1.4 Schematic of the 200 ton field site chiller system.

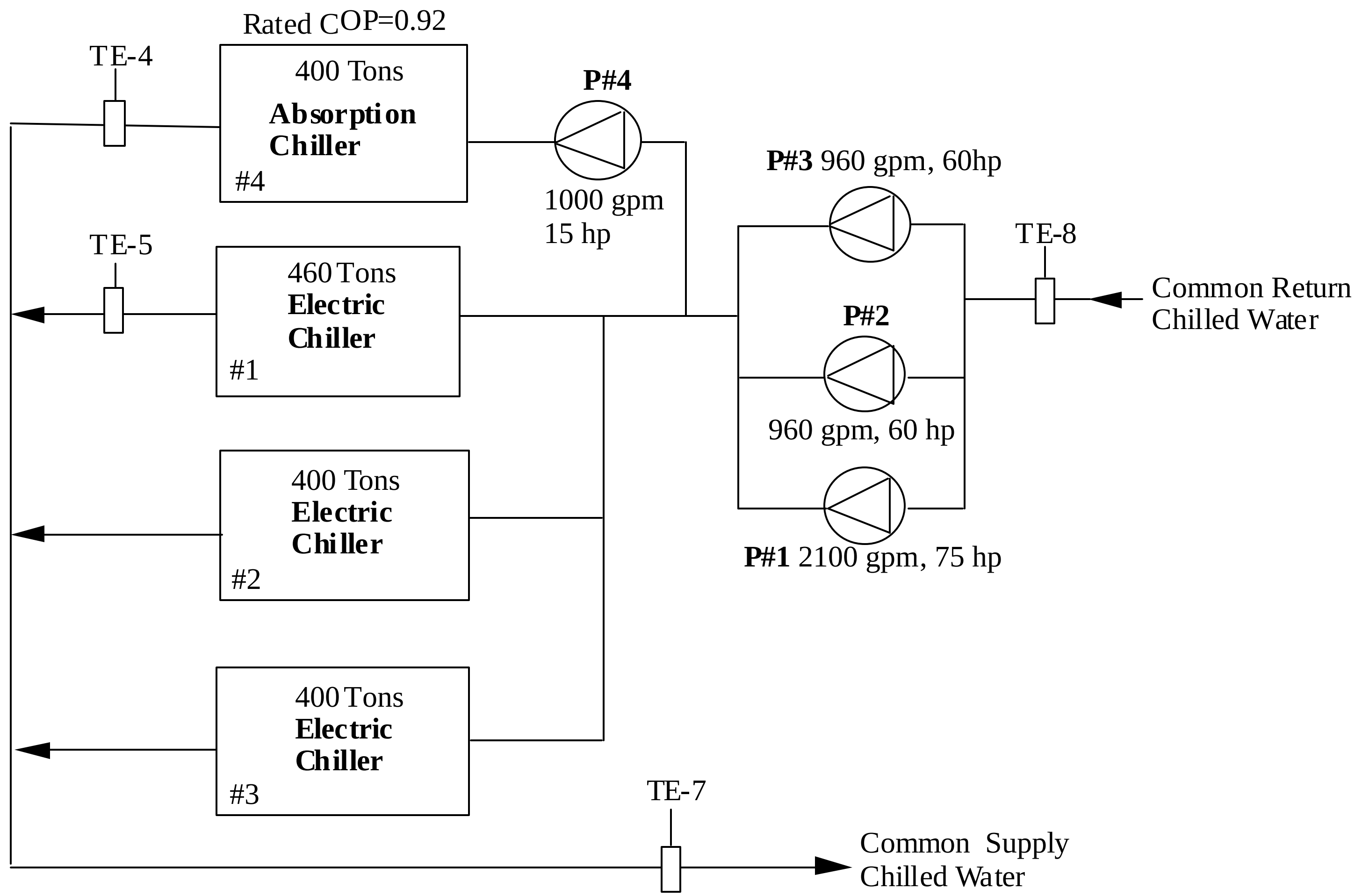

Figure 1.5 Schematic of the 400 ton field site chilled water loop.