Chapter Two { TC "Chapter Two " \l 1 }

Detailed System Description

2.1 Power Plant{ TC "2.1 Power Plant" \l 2 }

2.1.1 The Steam Power Plant and the Clausius - Rankine Cycle{ TC "2.1.1 The Steam Power Plant and the Clausius - Rankine Cycle" \l 3 }

The Columbia Generating Station of the Wisconsin Power & Light Company is a conventional coal fired steam cycle power plant. Such a plant works on the basis of a Clausius - Rankine steam cycle. The basic principles of this thermodynamic cycle are shown in figure 2.1, in their simplest form.

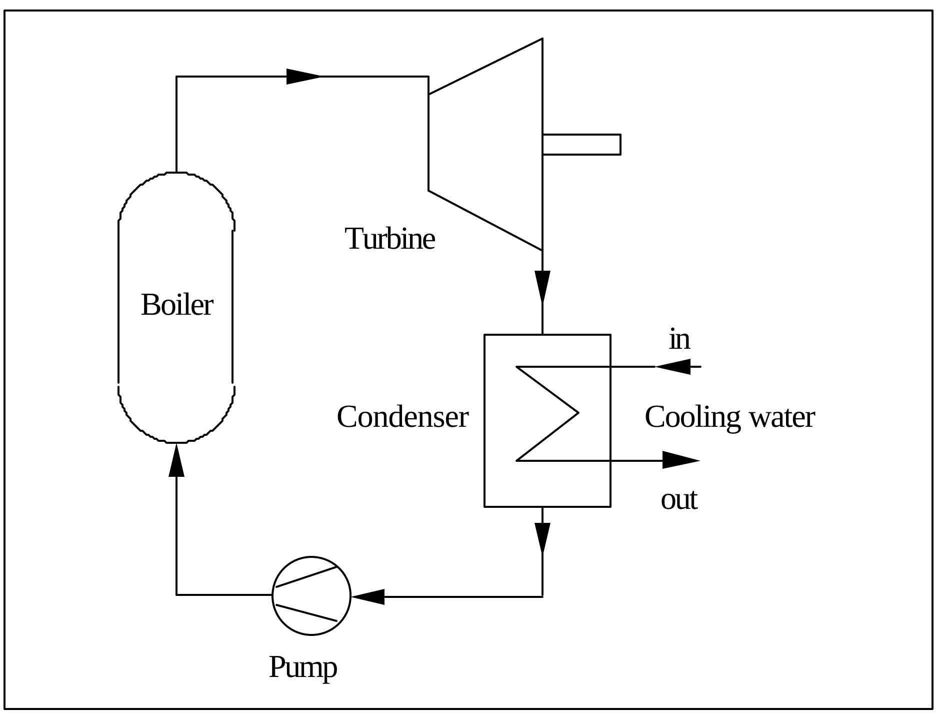

Figure 2.1 Simple steam cycle{ TC "Figure 2.1 Simple steam cycle" \l 5 }

Liquid water is brought to a high pressure by a feedwater pump. The pressurized water enters the boiler, where the water boils completely and leaves in a superheated state. The heat source for the boiler is combustion of fuel in this case. The steam is led to a turbine, where it expands and work is extracted from the turbine. After the turbine, the steam is at a low pressure and temperature, close to a saturated state. Steam quality should be less than one after the turbine. The steam is led to a steam condenser, where the steam condenses completely. The condenser is a heat exchanger, which rejects the waste heat to the environment by means of a coolant, water in this case. The condensate is then led back to the feedwater pump. This is a very simple description of the processes in a modern steam power plant as it neglects completely all sorts of refinements intended to improve the overall efficiency (see 2.1.2 to 2.1.3).

To explain the importance of the condenser cooling water temperature, which determines the temperature at which the waste heat is rejected to the environment, the overall efficiency limit of a heat engine can be calculated, assuming a fully reversible cycle, by evaluating the Carnot efficiency:

$$\eta_c = \left(1 - \frac{T_c}{T_h}\right) \qquad \text{(Eq. 2.1)}$$

This equation shows, that a lower condenser cooling water temperature leads to a higher possible efficiency, as it means a lower temperature at which heat is rejected. The hot temperature, basically the temperature in the boiler, is limited mainly by the capabilities of the materials that are used, for example for the high pressure pipes. Again, this is a very simple approach to determine the overall plant efficiency and a more detailed analysis of the effects of a high condenser cooling water temperature is given in the following chapters.

2.1.2 Steam Generation{ TC "2.1.2 Steam Generation" \l 3 }

The Columbia Generating Station consists of two identical units, each rated at 525 MW electrical output. The fuel for the furnace, which provides the energy to the boiler, is coal with a low sulfur content, in order to meet environmental regulations. Before the coal is burned it is pulverized and then fed into the furnace by using preheated air.

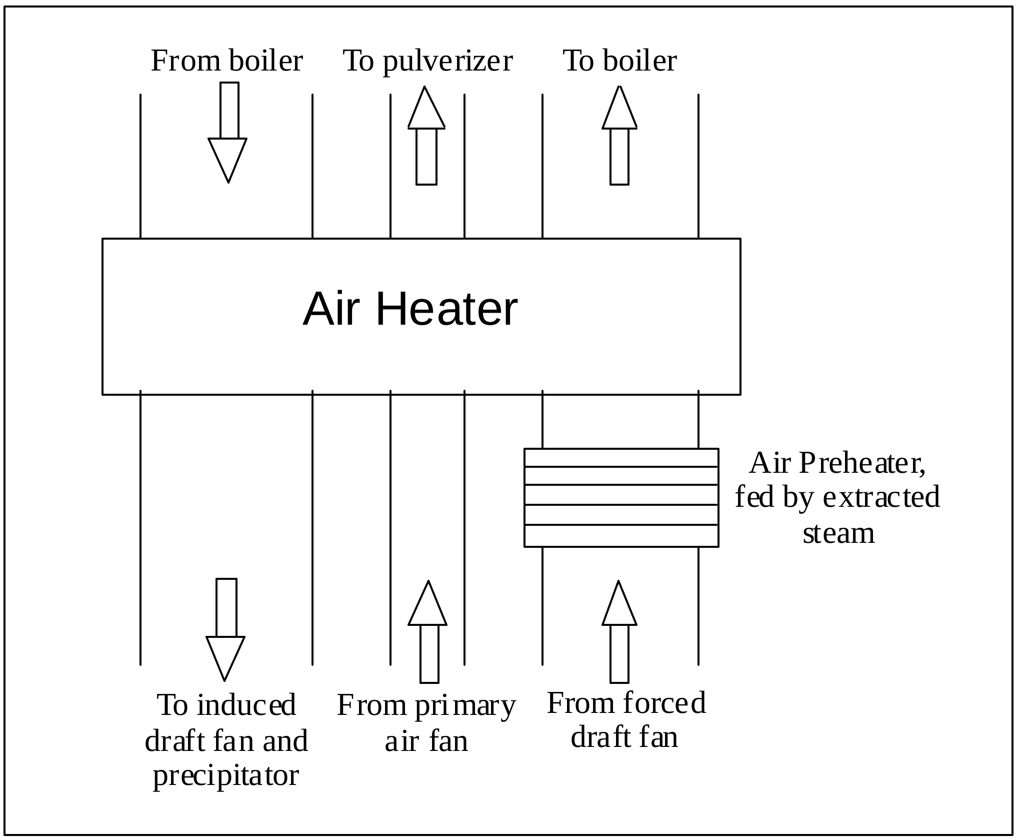

Figure 2.2 Main air streams of combustion process{ TC "Figure 2.2 Main air streams of combustion process" \l 5 }

Figure 2.2 shows the different air streams and how they are led. Only one half of the air stream per unit is shown in the figure as every unit has two devices. The air that flows to the pulverizers is taken from the environment by two fans per unit that blow the air to the air preheaters from where it flows to the pulverizers and transports the coal into the furnace. Two separate fans provide the main air stream for the combustion. The main combustion air stream and the air that goes to the pulverizers is preheated in two air preheaters per unit, where the hot combustion gases from the furnace are used to heat the intake air. Two additional air preheaters per unit use extracted steam from the intermediate pressure turbine to preheat only the main combustion air before it reaches the air preheaters that are supplied by combustion gases. The combustion gases are induced from the furnace by two induced draft fans that are located after the preheaters, while the primary fans mentioned above are forced draft fans. The exhaust gases of the furnace are treated in an electrostatic precipitator, which cleans the exhaust of small particles.

Each unit has a boiler which produces, at design conditions, steam at 1000 F, 2415 psia and a mass flow rate of 3,585,000 lb/hr. The boiler also provides heat for a reheater that heats the exhaust steam of the high pressure turbine from about 600 F back up to 1000 F, at a mass flow rate of 3,200,000 lb/hr and a pressure of 583 psia. The difference in steam flow between main steam and reheating flow represents that used to supply the last feedwater preheater. Figure 2.3 shows the different stages of feedwater heating (see also figure 2.4, which shows where the steam is extracted).

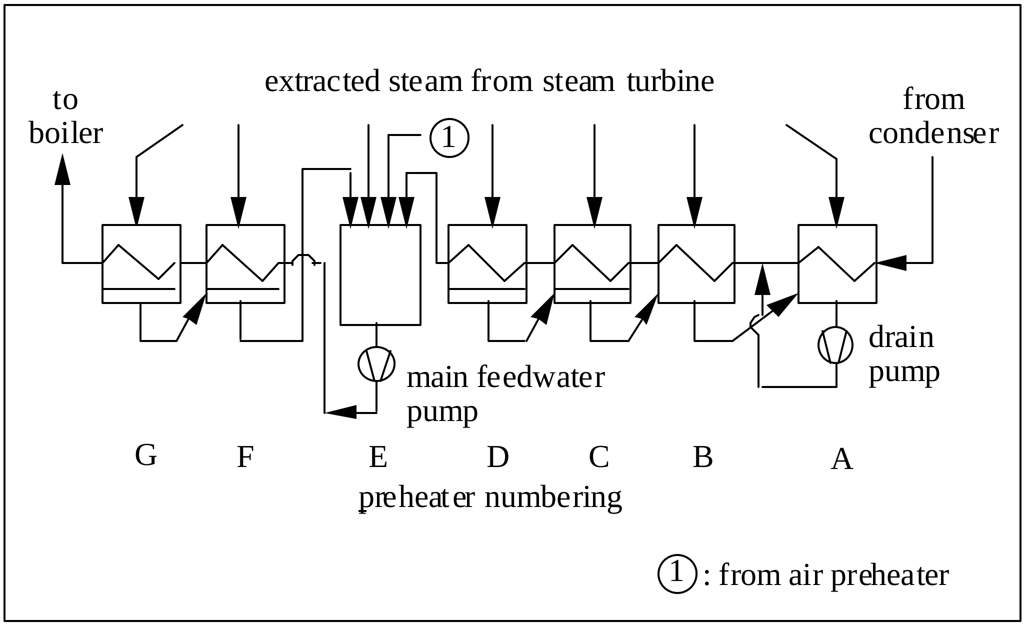

Figure 2.3 Feed Water Preheating{ TC "Figure 2.3 Feed Water Preheating" \l 5 }

The boiler feedwater is preheated in five low pressure (denoted A to E) and two high pressure (denoted F and G) feedwater heaters, where the high pressure preheaters are located behind the main feedwater pumps. The fifth preheater, named preheater E in the figure, is designed as a deaerator. In contrast to the other preheaters, where the extracted steam and the feedwater are separated, the deaerator is constructed as an open shell.

The main function of the deaerator is to remove noncondensable gases from the water in the main steam cycle. The deaerator also functions as a storage tank and receives the drain water that comes from the air preheaters. The drain from each preheater, which is the condensed extraction steam, is led to the preceding preheater. The collected drain from preheaters A to D is pumped back into the main feedwater line by a drain pump. Two main feedwater pumps per unit, which bring the feedwater to approximately 2900 psig after the deaerator and before it enters the next preheating stages, are driven by steam turbines, the steam for which is extracted from the main turbines, too (see 2.1.3).

2.1.3 Steam Turbine{ TC "2.1.3 Steam Turbine" \l 3 }

The Columbia Generating Station utilizes two steam turbine sets, one for each unit, manufactured by the General Electric Company. The turbines are of tandem compound four flow type, which means, that each set consists of a high pressure, an intermediate pressure and two double flow low pressure turbines.

Figure 2.4 shows a schematic of the steam turbines. Superheated steam from the boiler expands in the high pressure turbine. The exhaust of the high pressure turbine flows to the reheater, where the steam is superheated again. The reheated steam then enters the intermediate pressure turbine, the exhaust from which is divided into two flows. Each exhaust steam flow from the intermediate pressure turbine enters a low pressure turbine. In the low pressure turbines the exhaust steam leaves the turbine at two different locations (see figure 2.4). The exhaust steam is divided because at the low exhaust pressure the steam has a high specific volume. Therefore a large opening is required to keep the velocity of the exiting steam low. Another important reason for dividing the steam flow in the low pressure turbine is to eliminate axial thrust, as a high pressure drop occurs across the low pressure turbine stages. There is a total of four exhaust steam flows per unit, which defines the turbine set type that is specified as 'tandem compound four flow'.

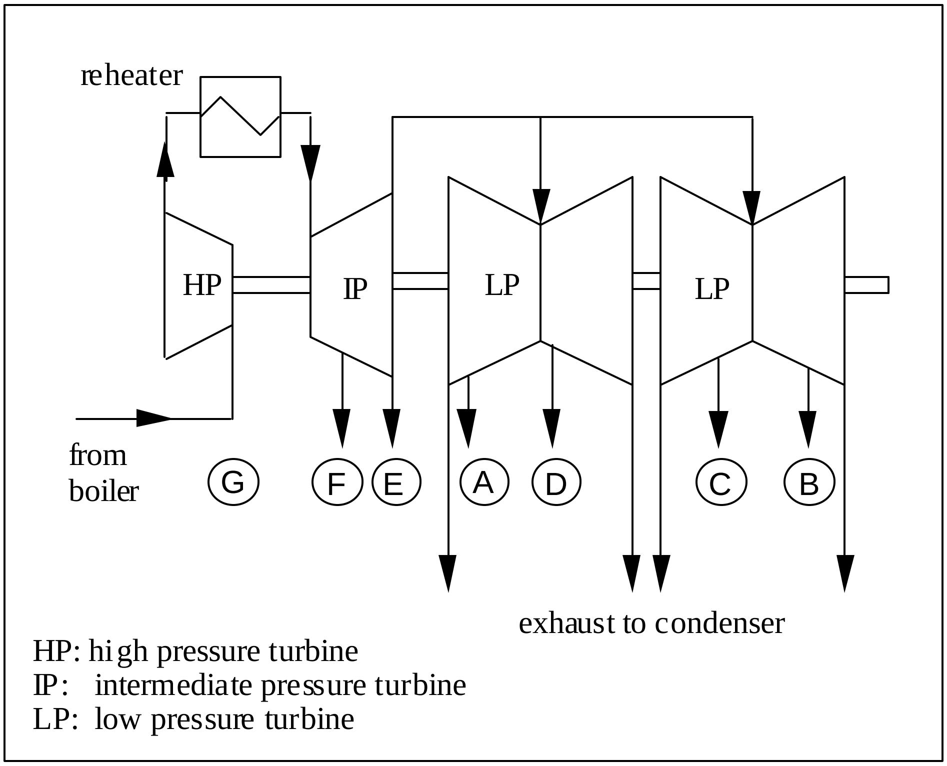

Figure 2.4 Steam Turbine Set and Steam Extraction Positions**{** TC "Figure 2.4 Steam Turbine Set and Steam Extraction Positions" \l 5 **}**

Steam is extracted for seven stages of feedwater heating from different locations in the turbine, corresponding to the temperatures of the respective feedwater heaters. Figure 2.4 shows the locations of steam extraction, corresponding to the nomenclature in figure 2.3. At point E there is, aside from the steam for preheater E, steam extracted to drive the main feedwater pumps and to supply the air preheaters.

The overall turbine design conditions are summarized in Table 2.1. The turbines are designed for a speed of 3600 rpm (**r**evolutions **p**er **m**inute), which corresponds to a grid frequency of 60 Hz. The design steam properties entering the high pressure turbine are a pressure of 2415 psia at a temperature of 1000 F. The steam temperature after reheating is 1000 F. An electric generator is driven directly by each turbine set. Each set is rated at 560 MW power output.

Manufacturer	General Electric Co.
Type	Tandem four flow
Speed	3600 rpm
Initial steam pressure	2415 psia
Initial steam temperature	1000 F
Steam temperature after reheating	1000 F
Design back pressure	1.0" Hg
Back pressure limit	6.0" Hg
Capacity at valves wide open	560 MW

Table 2.1 Summary of turbine design conditions{ TC "Table 2.1 Summary of turbine design conditions" \l 4 }

Back pressure is a main parameter that influences the turbine power output and efficiency. Back pressure defines the exhaust pressure of the steam when it leaves the low pressure turbine, which is also the pressure in the condenser shell, neglecting the pressure loss between turbine outlet and condenser. In general, a higher back pressure leads to a lower efficiency and lower output, if the inlet conditions remain the same (see 4.5).

There is also a mechanical warranty limit, specified by the manufacturer, that limits the back pressure at which a specific turbine can be safely operated. This mechanical limit is given as the turbine blades are only designed for a certain maximum density of the working fluid, steam in this case. When the back pressure limit is reached, the steam flow rate and therefore the load has to be reduced, to keep the back pressure below its limit. The mechanical limit of the turbine was raised in an overhaul to six inches of mercury, from the original limit of four inches. This allows the turbine to run at a higher steam flow rate and therefore higher load during summer months, when the back pressure rises due to higher cooling water temperatures. The back pressure can be used to determine the heat rate and output of the turbine, using a specific procedure outlined in 4.5.

c3.**2.1.4 Condenser**

Each unit has a surface steam condenser consisting of two shells. In addition to the exhaust of the low pressure turbines the condenser receives the exhaust of the feedwater pump drives plus some smaller amounts from other flows or emergency lines. Three condensate pumps per unit pump the condensed water to the steam packing exhauster from where it flows to the first preheaters. Figure 2.5 illustrates in principle, how the condenser works. The exhaust steam enters at the top of the shell and flows perpendicular to the cooling water pipes. The condensed steam is collected at the bottom of the shell, from where it flows to the condensate pumps. Dependent on the cooling water inlet temperature and on the amount of steam to be condensed, a certain back pressure is developed in the condenser shell.

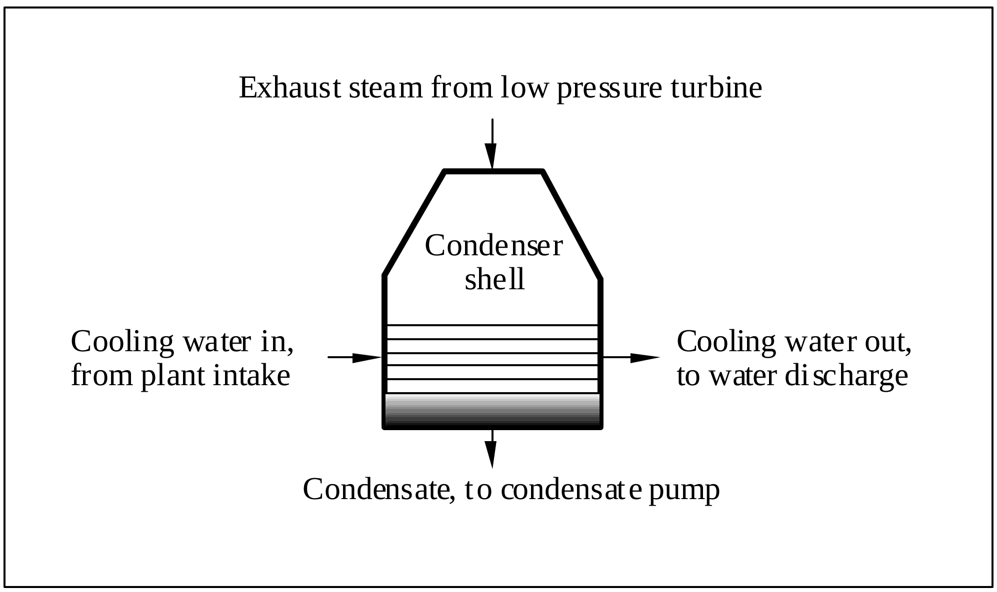

Figure 2.5 Schematic of main steam condenser{ TC "Figure 2.5 Schematic of main steam condenser" \l 5 }

Circulating pump	
Manufacturer	Ingersol Rand
Type	Vertical Mixed Flow

Size	50 APMA-1
Flow rate	92,500 gpm
Speed	440 rpm
Head	33.5 ft
Pump motor	
Manufacturer	Louis Allis
Rated Power	1250 hp
Speed	445 rpm

Table 2.2 Summary of circulating water pump design data{ TC "Table 2.2 Summary of circulating water pump design data" \l 4 }

Condenser circulating water pump data is summarized in table 2.2. Two circulating water pumps for each unit, rated at a water flow of 92,500 gpm (**g**allons **p**er **m**inute), supply the cooling water to the two condenser shells. The pumps are driven by electric motors. The pump power for driving the main cooling water pumps is not included in the heat rate calculation discussed in section 2.1.5.

The amount of cooling water flow that goes to the condensers can be varied by using one or two pumps, thereby providing approximately 100% or 50% of the design flow rate. The reason to switch to one pump operation may be a low unit load and therefore low heat load on the condenser.

The back pressure is mainly fixed by the heat load on the condenser, the cooling water inlet temperature, and the amount of cooling water flow. This relation is discussed in more detail in section 4.5. Also the cleanliness of the pipes within the condenser has an influence on the performance, as the cleanliness influences the heat transfer coefficient.

The design data of the main steam condensers are given in table 2.3. Each condenser has a total surface area of 250,000 ft^2 with a total of roughly 13,300 tubes of a diameter of 1". The design mass flow rate of steam to be condensed is 2,432,000 lb/hr, which is considerably lower than the steam flow rate provided from the steam generator. This is due to the many extraction steam flow rates in the cycle. At a water inlet temperature of 68 F the condenser should develop a back pressure of 3.047 "Hg. The design cleanliness factor of the tubes is already at 90% as the assumption is made, that the tubes will be covered by a layer of oxide as soon as the condenser is used the first time. A heat transfer rate of 970 Btu/lb, with respect to the mass flow rate of steam to be condensed, accounts for a certain quality of the exhaust steam, which is usually on the order of 90 % or below. The latent heat of vaporization for water at 1.5 psia is 1028 Btu/lb, which would be the heat transfer rate for an exhaust steam quality of 100 %.

Manufacturer	Westinghouse
Type	Radial flow, two pass, twin shell condenser
Surface area	250,000 ft^2
Number of tubes:	
Admiralty metal, 1", 18BWG	12,470
Stainless steel, 1", 20BWG	868
Steam condensed	2,432,000 lb/hr
Water inlet temperature	68 F
Absolute pressure	3.047" Hg = 1.5 psia
Condensate temperature	115.64 F
Design criteria	
% clean tubes	90%
Heat transfer rate	970 BTU/lb, referred to flow rate of steam condensed
Circulating water flow	185,000 gpm
Friction loss	18.04 ft of water at a water velocity of 6.96 ft/s
Water discharge temperature	85 F (unit 1), 95 F (unit 2)

Table 2.3 Summary of condenser design data{ TC "Table 2.3 Summary of condenser design data" \l 4 }

2.1.5 Heat Rate Calculation{ TC "2.1.5 Heat Rate Calculation" \l 3 }

The heat rate (HR) of the plant is defined as the ratio of the total amount of energy supplied to the system to the useful output of the system. Units of plant heat rate are Btu/kWh, as the supplied energy in the boiler is measured in **B**ritish-**t**hermal-**u**nits (Btu), and the electrical output in **k**ilo-**W**att-**h**ours (kWh). The heat rate can also be expressed in terms of an efficiency, where a heat rate of 3412 corresponds to an efficiency of unity (3412 Btu = 1 kWh). There are several definitions of heat rate which are defined as follows [1]:

$$\text{Net station HR} = \frac{\text{rate of heat added to steam generator, Btu/h}}{\text{net station power, kW}} \qquad \text{(Equ. 2.2 a)}$$

$$NHR = \frac{\dot{Q}_{st}}{P_{net}}$$

$$\text{Gross station HR} = \frac{\text{rate of heat added to steam generator, Btu/h}}{\text{gross generator power, kW}} \qquad \text{(Equ. 2.2 b)}$$

$$GHR = \frac{\dot{Q}_{st}}{P_{gr}}$$

$$\text{Net turbine HR} = \frac{\text{rate of heat added to cycle, Btu/h}}{\text{net station power, kW}} \qquad \text{(Equ. 2.2 c)}$$

$$NTHR = \frac{\dot{Q}_{cyc}}{P_{net}}$$

$$\text{Gross turbine HR} = \frac{\text{rate of heat added to cycle, Btu/h}}{\text{gross generator power, kW}} \qquad \text{(Equ. 2.2 d)}$$

$$GTHR = \frac{\dot{Q}_{cyc}}{P_{gr}}$$

The rate at which heat is added to the steam generator can be computed by evaluating the total amount of fuel that is burned. By using the heating value of the fuel the mass flow of fuel can be converted into an equivalent rate of heat added to the steam generator.

The rate of heat added to the cycle can be determined by the amount of energy that is transfered in the boiler to the main steam flow and reheat flow. This is the only energy input into the system. Net station power is the power that leaves the plant, or that can be sold in this case. The gross generator power is the power that the generator produces. The difference in net station power and gross generator power is the auxiliary power that is needed to drive auxiliary components such as condenser cooling water pumps, forced and induced-draft air fans, drain pumps, cooling tower pumps and fans, fuel supply and handling devices, to name the most significant. The main feedwater pumps are driven by extracted steam, originally coming from the same boiler, so that the feedwater pump drive is not an auxiliary power consumption. Typical net station heat rate values of the Columbia Generating Station are in the range of 10200 Btu/kWh, which corresponds to an efficiency of approximately 33.5 %.

2.2 Condenser Circulating Water Cooling{ TC "2.2 Condenser Circulating Water Cooling" \l 2 }

2.2.1 Cooling Pond{ TC "2.2.1 Cooling Pond" \l 3 }

The cooling pond was designed originally as the primary heat sink of the power plant. The hot circulating water is discharged into the cooling pond after it comes from the cooling equipment inside the power plant. The water then flows around the pond from plant discharge to intake. The circulation time depends on the amount of total cooling water flow and on the amount of water which is taken from the plant discharge to the cooling towers (see 2.4).

Circulation time defines the time the water needs to flow from discharge to intake. During the circulation time, the water cools down and is then pumped back into the power plant.

Aside from the condenser cooling water flow, an additional flow of hot water is discharged into the pond. This is the so called low head circuit water, which is supplied by up to four pumps. Low head refers in this case to the water pressure in the circuit that is in the range of 70 to 90 psia. By employing different numbers of pumps, the flow rate can be varied. The average flow rate for one pump is about 16,000 gpm, depending on the discharge pressure. This water is used for auxiliary cooling, such as oil cooling or Hydrogen cooling for the generators. The hot water is discharged at the same location as the hot condenser cooling water and the cold water is taken out of the pond at the same place. The range of temperature rise in the low head circuit is usually about 5 F lower than in the main circuit.

Losses from evaporation in both cooling pond and towers are compensated for by a make-up water flow that is taken from the Wisconsin River. The magnitude of the losses depends mainly on weather conditions. Four make-up pumps, each rated at 10,000 gpm, are available to feed the needed amount of make-up water into the pond.

During three pond surveys that were intended to measure the temperature distribution within the pond, the depth of the pond was measured, too (see 3.2.2). Figure 2.6 shows the depth of the pond following the flow path of the water. The depths shown are measured near the middle of the flow path. Near the shore the pond gets shallower. It can be seen that the discharge and intake sections are among the deepest parts while the rest of the pond varies in depth. An average depth of approximately 6.5 ft is determined by taking the shallower shore areas into account.

The physical shape and orientation of the cooling pond is shown in figure 2.7. It can be seen, that the flow channel is not of uniform width, especially in the first half. The figure shows an island on the northeast side of the pond and a shallow area in the same region that restrict the flow path. A spillway limits the water level and the water overflows when the level reaches a certain value. Before the make-up water mixes with the pond water it is pumped into a settling basin where small particles carried with the river water can sink to the ground. The overall surface area of the pond is approximately 490 acres, with a length of approximately 9500 ft and an average width of about 1250 ft. The irregular shape of the pond is due to the way in which the pond was constructed. The pond was not excavated but it was taken advantage of a natural depression on the site of the pond. A levee was constructed and the resulting basin then filled up with water.

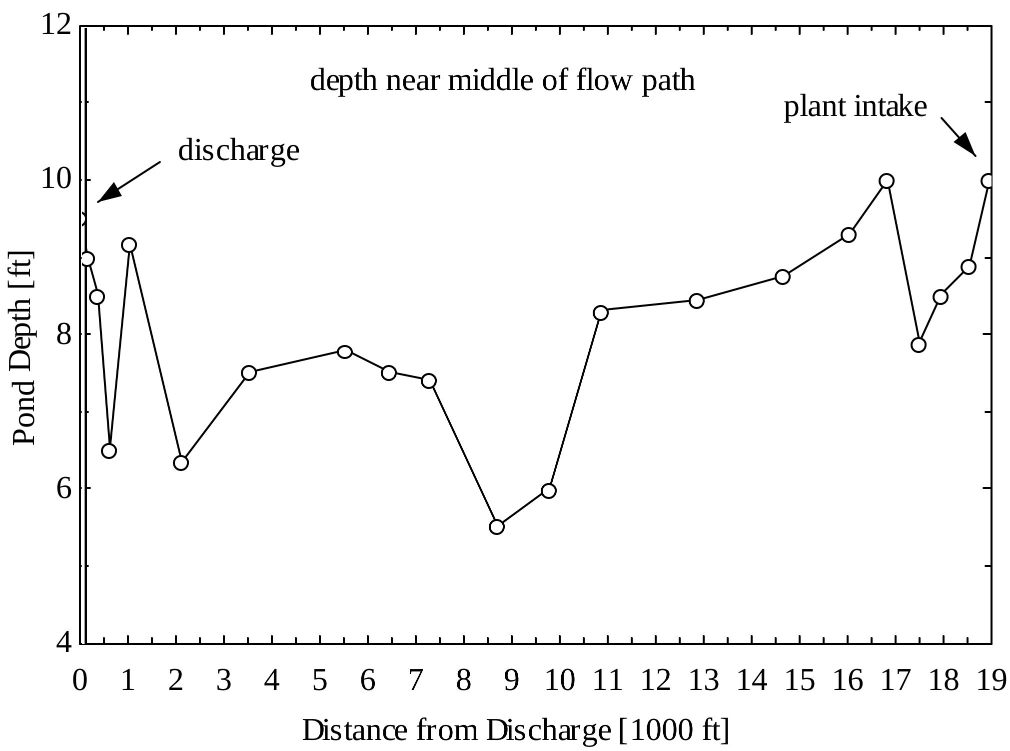

Figure 2.6 Cooling pond depth distribution near middle of flow path{ TC "Figure 2.6 Cooling pond depth distribution near middle of flow path" \l 5 }

Figure 2.7 Cooling pond shape{ TC "Figure 2.7 Cooling pond shape" \l 5 }

2.2.2 Cooling Towers{ TC "2.2.2 Cooling Towers" \l 3 }

In addition to the cooling pond, two cooling towers manufactured by the Marley Company are employed for heat rejection. The towers are denoted tower A and tower B, where tower A is located on the east side of the plant intake section of the pond. The towers are of cross flow induced draft type. Each tower consists of seven separate tower cells. Figure 2.8 shows the crossection of a tower cell and the side view of a whole cooling tower. The fan is mounted on top of the tower and 'sucks' the air through the fill (see crossectional view in figure 2.8). Induced draft refers to this type of fan location while a forced draft fan would be located before the air enters the fill. The cooling towers are of crossflow type as the incoming air flows perpendicular to the down falling water. After the ambient air takes up heat and moisture the hot and humid air is discharged at the top of the tower. The hot water is brought to the header pipes by two equally sized risers on the front end of each tower cell row (see sideview in figure 2.8). The water flow is then distributed to the several cells through two header pipes, one on each side of the tower. To maintain an equal flow rate for each cell, the flow can be regulated individually for each cell by discharge valves. However, it is difficult to maintain an equal flow distribution with the same valve position if the total water flow rate is changed in order to control the tower operation. From the top of the tower, the water falls through diffusers into the tower fill. The fill consists of splash bars. The function of the splash bars is to increase the overall contact surface between water and air by distributing the water into small droplets. The original fill consisted of asbestos cement splashbars. In a recent tower upgrade the asbestos fill was replaced by coated sheet metal bars. The fill of tower A was replaced completely while only the fill of four cells of tower B was replaced.

The cold water is collected in the tower sump. From the sump the water flows back to the plant intake section of the pond. There is no direct inflow of make-up water into the sump that would compensate for losses, as the make-up is added directly to the pond.

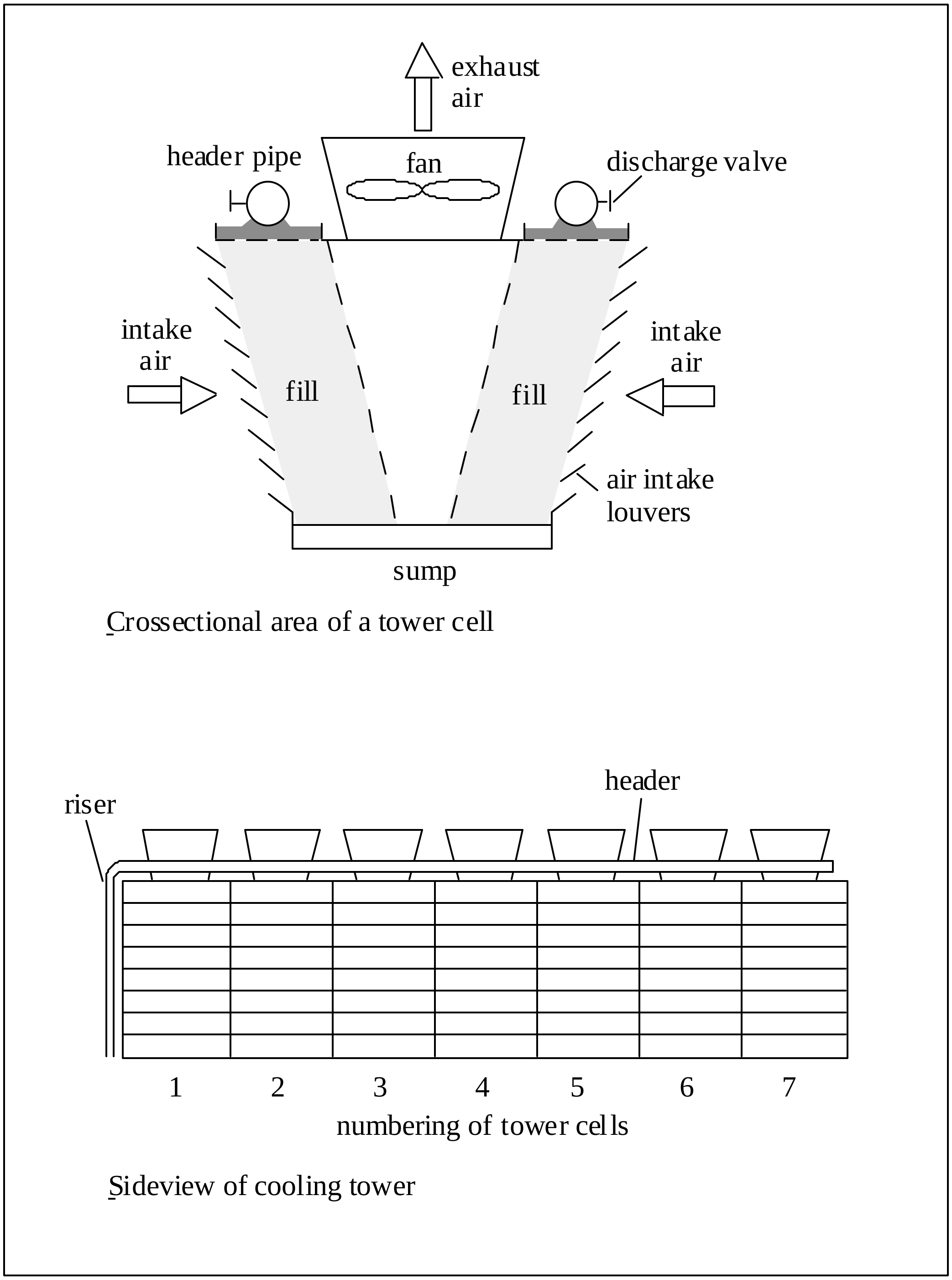

Figure 2.8 Cooling tower{ TC "Figure 2.8 Cooling tower" \l 5 }

The fans are driven by electric motors located on top of the tower outside the shell and the torque is transferred by a shaft and gear to the fan. Table 2.4 summarizes the fan and fan motor information. Originally the fans were constructed with eight blades, but in an upgrade the number was increased to nine. The intention was to increase the air flow while not increasing the fan motor power. Unfortunately, there is no actual measurement of the air flow rate with the 'old' fans, but in the process of a cooling tower performance test the actual value after the upgrade could be determined (see 3.2.3).

Motor nameplate information for the fan drives is given in table 2.4. The motors are rated at a speed of 137 rpm and a power requirement of 178 kW . The real power requirement differs slightly from the design value (see 3.2.3). The actual fan power was measured in the performance test, too. The fan drive power is a major energy consumption and will be included in the further analysis of the cooling cycle.

Fan	
Number of blades	9
Fan Diameter	336”
Original Design Airflow	$1.3656 \cdot 10^6$ cfm
Fan Motor	
Type	Three phase
Voltage	460 V
Current	223 A
Speed	137 rpm
Rated Horsepower	178 kW

Table 2.4 Cooling Tower Fan Data**{** TC "Table 2.4 Cooling Tower Fan Data" \l 4 **}**

The hot water that is cooled down in the towers is taken from the plant discharge site into the pond, so that the temperature of the hot water is equal to the plant discharge temperature. The towers are supplied by two water pumps that can be run separately. By running one or two pumps, the water flow can be controlled. However, the pumps discharge the water into the same main pipe, that leads to the cooling towers. The flow is then almost equally distributed to each of the two towers. It is also possible to run only one tower while shutting the flow to the second tower off. Table 2.5 summarizes the design cooling tower pump data. The pumps are rated at 92,500 gpm each so that a total flow of 185,000 gpm can be achieved, which accounts for roughly half of the total circulating water flow. Exact flow measurements are given in 3.2.3. The rated power requirement to run the pumps is 1922 bhp (**b**rake **h**orse **p**ower) for each pump. This power requirement is significant and will also be included in the further analysis. All 14 fan drives and two pump motors together account for a power requirement of about 6300 hp or 4.7 MW.

Manufacturer	Foster Wheeler Corp.
Pump Type	VA-I (F) K-4.8 R.S.
Size of Discharge	66”
Stages	1
Flow rate	92,500 gpm
Speed	352 rpm
Dynamic Head	72 ft
Pump Efficiency	87.5 %
Brake Horse Power	1922 bhp

Table 2.5 Summary of Cooling Tower Pump Design Data{ TC "Table 2.5 Summary of Cooling Tower Pump Design Data" \l 4 }

2.3 Configuration of Generating Unit and Cooling Cycle{ TC "2.3 Configuration of Generating Unit and Cooling Cycle" \l 2 }

The configuration of the whole cooling cycle and the two power plant units is shown in figure 2.9. The hot water from the power plant is discharged into the cooling pond at the discharge section. Unit 1 and unit 2 discharge the water at the same location. The hot water is the discharge from both the low head and the main cooling cycle. The water then flows around the pond to the plant intake section. Makeup water is added in the second half

Figure 2.9 Cooling circuit and plant set up**{** TC "Figure 2.9 Cooling circuit and plant set up" \l 5

}

Figure 2.10 Map of the power plant site{ TC "Figure 2.10 Map of the power plant site" \l 5 } of the pond. The water that flows to the cooling towers is taken from the pond discharge section by two pumps that are located in a screen house right near the discharge of the plant. The towers are placed on two different sides of the intake channel, so that tower B is further away from the pumps and a longer supply pipe is required. In the arrangement shown towers and pond are in parallel, which corresponds to the present configuration in the site. From the intake channel the water is pumped back into the plant by the main condenser cooling pumps and low head circuit pumps. There is a total of four condenser and four low head pumps that are all located in the same screen house. Unit 1 is further away from the screen house and requires therefore a longer supply pipe for both cooling cycles. Figure 2.10 shows a scaled map of the plant site. The Wisconsin River that supplies the make-up water is located on the west side of the plant. A technically irrelevant but interesting fact is the nomenclature of the cooling pond. On the map shown in figure 2.10 the cooling pond is denoted Columbia Lake that is a publicly accessible body of water. The Wisconsin Power & Light Company claims the pond as its property, as it is indeed, and the company's nomenclature is cooling pond instead of lake.

2.4 Current Operation Mode of the Plant{ TC "2.4 Current Operation Mode of the Plant" \l 2 }

2.4.1 Unit Load{ TC "2.4.1 Unit Load" \l 3 }

The Columbia Generating Station is a base load plant. That means it is used to supply the base load that is needed through the whole day. The fact that the plant has low production costs is one main reason that the units are run at almost maximum power at every time of the day. One other reason is that the Columbia Station is a steam cycle power plant. This type of plant is not able to react to changes in load quickly. For example, the system needs about one hour to reach a stationary state again after an increase in power of about 100 MW. A so-called cold start, that means starting power production after a unit was completely shut off, takes several hours. Therefore the plant is only seldom taken off the grid and an almost constant turbine power output is maintained.

2.4.2 Operation Mode And Control of the Cooling Cycle{ TC "2.4.2 Operation Mode And Control of the Cooling Cycle" \l 3 }

Average water flow rates of the cooling cycle

The total cooling water flow rate is fixed by the cooling needs of the plant corresponding to the load and can not arbitrarily be changed. As mentioned in 2.4.1, the Columbia Generating Station is a base load plant and therefore almost always operated close to the maximum power. Thus the maximum cooling water flow rate for the condensers is needed, too, and all four condenser circulating pumps are usually operated, providing a total cooling water flow of 370,000 gpm.

The times of operation of the low head circuit pumps are given in table 2.6. Operation data only for summer months 1992 were available. The table shows the number of hours in which two, three or four low head pumps were operated. A minimum of two pumps is always required, four pumps were never on at the same time. The column for two pump operation shows the sum of hours for two pumps while the next columns only show the actual operation time for the third and fourth pump, respectively. For further calculations an average number of pumps was determined by dividing the sum of pump hours by the sum of hours in the months.

$$n_{lh,av} = \frac{n_{lh,sum}}{n_{hr,sum}} = \frac{8724\,hr}{3672\,hr} = 2.37 \approx 2.4 \qquad \text{(Equ. 2.3)}$$

Taken this average number of low head pumps, the total amount of cooling water flow that the system has to handle is app. 408,000 gpm, assumed four main cooling water pumps are on and each low head pump provides a flow rate of 16,000 gpm.

Year: 1992	2 pumps	3 pumps	4 pumps	Sum of pump hours	Hours in month
May	1488 hr	190 hr	0	1678 hr	744 hr
June	1440 hr	461 hr	0	1901 hr	720 hr
July	1488 hr	191 hr	0	1679 hr	744 hr
August	1488 hr	151 hr	0	1639 hr	744 hr
September	1440 hr	387 hr	0	1827 hr	720 hr
Sum	7344 hr	1380 hr	0	8724 hr	3672 hr

Table 2.6 Low Head Pumps Operation Times{ TC "Table 2.6 Low Head Pumps Operation Times" \l 4 }

Possibilities of controlling the performance of the cooling cycle components

The most effective way of controlling the performance of the cooling cycle in the current set up is to change the operation mode of the cooling towers and cooling tower pumps. There are several options for operating the towers:

- no tower operation and only usage of the cooling pond
- operating one cooling tower pump and both towers
- operating two cooling tower pumps and both towers
- operating only one cooling tower and one pump

In addition to these four possibilities the number of fans that are operated can be changed. The fans can individually be turned on or off. There is no way of adjusting the fan speed and thereby changing the volumetric air flow rate through the towers. Thus, if a fan is operated, it operates at its maximum power. The effect of air flow rate on tower performance will be discussed in chapter 4.

There are two effects of changing the number of tower pumps that are operated. On the one hand, the water velocity in the pond is changed and on the other hand, the cooling capability of the towers is influenced by different water flow rates. In general a lower flow rate through the towers leads to a lower tower outlet temperature, if all other parameters, such as air flow rate and ambient conditions, remain constant. When the towers are not operated at all, the cooling pond is the only source for heat rejection from the plant to the environment. In the case of no tower operation, the whole amount of cooling water flows through the pond, thereby leading to a high velocity in the pond and low circulation time.

When the cooling tower pumps are turned on, a portion of the total cooling water flow is pumped to the cooling towers. In this way the flow rate of water into the pond and therefore the water velocity within the pond is changed. In the case of two tower pump operation the velocity within the pond would be the least.

Table 2.7 shows approximate circulation times in the pond for different tower operation modes. A total cooling water flow rate of 408,000 gpm is assumed and the design tower pump flow rates are taken as a basis for the calculation. It can be seen that the tower flow rate has a major impact on the circulation time in the pond. The effect of circulation time and tower flow rate on cooling cycle behavior will be discussed in more detail in chapter 4.

Number of tower pumps	Flow rate to towers	Flow rate into pond	Approximate circulation time
No tower operation	no flow	408,000 gpm	45 hr
One pump	92,500 gpm	315,500 gpm	59 hr
Two pumps	185,000 gpm	223,000 gpm	84 hr

Table 2.7 Water flow rates in cooling pond and tower and circulation times for different tower operation modes{ TC "Table 2.7 Water flow rates in cooling pond and tower and circulation times for different tower operation modes" \l 4 }

Another way of influencing the behavior of the cooling cycle is to vary the amount of make-up flow that is added to the pond water. The number of make-up pumps can be varied to change the total make-up flow rate. Up to four pumps can be turned on although at the time of this study only three pumps were available and one pump was not in operation condition. Each make-up pump is rated at 10,000 gpm water flow so that a total make-up flow of 40,000 gpm can be achieved. If the amount of make-up is larger than the amount of losses, mainly due to evaporation, the pond overflows. The spilled water is warm pond water that is replaced by colder river water. In this way an additional cooling can be achieved, although environmental restrictions have to be considered that limit the amount of make-up water taken from the river. When the water level in the river is low, drawing a large amount of water from the river can harm the river fauna. Also, the cooling effect that can be achieved by make-up is limited, as the maximum amount of make-up water is only ten percent of the total cooling water flow in the cycle and the temperature difference between pond and make-up water at the location of the make-up inflow is in the range of 5 to 10 F.

Current Operation Mode

At the time of the study the operation mode of the cooling towers is such that in summer months the towers are on all the time. During night time two pumps are operated and in the morning the water flow is cut back to one pump operation. In the late afternoon the second pump is turned on again. The intention for operating the towers in this way is not to heat up the pond outlet water with warmer tower outlet water. Thus the time for switching to one pump operation in the morning is determined by monitoring tower outlet and pond temperature. When the tower outlet temperature exceeds the pond temperature, one tower pump is shut off. In late afternoon the second pump is turned on again as during the night the tower water is colder than the pond water even if two tower pumps are operated. The intention to run two tower pumps during the night is to slow down the flow to achieve a lower pond outlet temperature and to 'store' or 'save' the pond for the next day. A basic assumption for this control strategy is that less flow in the pond increases the cooling potential by increasing the circulation time and leads to colder water temperatures at the outlet. This control strategy will be studied in chapter 5.

When the towers are operated, all fans are on all the time. The fans are only turned off for maintenance purposes. Also both towers are operated together. Only in spring or fall or for maintenance is one tower shut off.

During winter months, the cooling potential of the pond is sufficient and the towers are not operated. Another reason not to operate the towers in very cold weather is to protect the equipment from freezing.

Usually the make-up pumps are only used to compensate for losses. But during summer 1995, a very hot summer and the time period during which the study was done, the make-up flow was increased to its maximum to use the additional cooling effect.

2.5 Options For Performance Improvement Of The Cooling Cycle{ TC "2.5 Options For Performance Improvement Of The Cooling Cycle" \l 2 }

2.5.1 Optimization Of Control Strategy{ TC "2.5.1 Optimization Of Control Strategy" \l 3 }

The present control strategy, as outlined in 2.4, is based on the assumption that a longer circulation time in the pond leads to a lower water temperature at the pond outlet. A closer examination of the behavior of cooling tower and cooling pond for different flow rates is supposed to yield the optimum times to switch between one and two pump operation. The optimum has to be a compromise between a possibly cold water inlet temperature and the necessary auxiliary power that is used to reach this temperature. It is also possible that switching the number of pumps is not useful at all and the best performance can be achieved by running a constant water flow rate through the towers.

Another possibility to change the operation mode is to vary the amount of make-up flow. It has to be evaluated whether the cooling effect of more make-up water justifies the required higher auxiliary power for running a higher number of make-up pumps.

The effects of switching the number of pumps and of pumping a variable amount of make-up water into the pond will be studied in chapter 5 by using a model of the whole cooling system. In this way the most cost effective control strategy will be found.

Variation of the air flow rate through the towers by changing the number of fans that are operated is generally another option. But, as the fans can only be turned on and off, it is considered not to be an advantage at any time, to run the towers without fan operation. Natural convection is not sufficient to provide enough air to achieve a considerable cooling effect. Therefore the fans will be turned on every time the towers are operated. The effect of changing the number of fans that are operated will not be examined in the further study, but instead the assumption is made that the fans will always be on during tower operation.

2.5.2 Upgrading The Available Equipment{ TC "2.5.2 Upgrading The Available Equipment" \l 3 }

Upgrading of a cooling tower could include changing the fill of the tower to increase its heat transfer capability by providing a higher surface area for heat transfer between water and air. As the fill was replaced recently, in winter 1994/95, this option will not be considered further. Another way of improving cooling tower performance is to increase the air flow rate by upgrading the fans. An upgrade of the fans was done recently, too, so that with the present available fan drives it seems not to be possible to increase the air flow rate further. The water flow rate is another parameter that influences tower performance and also the pond flow rate (see 2.4). But, in order to change the water flow rate, the pumps or water supply system would have to be altered. An upgrade of the cooling tower pumps would mean replacing the present impellers with more effective ones. This possibility is considered together with an addition of cooling devices (see 2.5.3). Adding another pump is not considered, for design and economic reasons, as the screenhouse where the tower pumps are located can not hold another pump. It seems also not economical to install an additional separate water supply pipe for the towers that would come from a third pump.

Upgrading the cooling cycle could also include changing the arrangement of towers and pond. In the present arrangement, pond and towers are in parallel. In order to speed up the flow velocity in the pond and, by doing so, making presumably better use of the cooling potential of the pond, towers and pond can be connected in series. That means that the water is first led through the pond. The cold pond water is then pumped to the towers and cooled further down. After that it is mixed with the remaining pond water flow again, as not the whole amount of cooling water required can be cooled in the towers, and pumped into the plant. The background idea for connecting pond and towers in series is that the pond water may reach equilibrium before it reaches the plant intake section. Practically this would mean that the pond is too long or longer than it has to be. If this is true, speeding up the flow would be an advantage. But, changing the arrangement of the cooling cycle would require a new connection between the cold side of the pond and the cooling tower pumps, which is not easily done. It has to be mentioned that the idea of too long a pond contradicts the concept mentioned above, that a longer circulation time leads to lower outlet temperatures. Further examination has to show whether connecting pond and towers in series proves to be beneficial.

An alternative of changing the pond is to alter the depth of the flow channel. This can be done uniformly by rising the water level in the entire pond by blocking the spillway. But the practical limit to an increase in depth is in the order of one to two feet, if only the spillway is blocked. Another alternative of increasing the depth is to dredge the pond. The advantage of dredging is, that it can be done in selected areas. For example, the depth could only be increased in the second half of the pond while the first half remains unchanged to enable the pond water to cool down quickly in the first part and then to store the cold water in the second half.

2.5.3 Adding cooling devices{ TC "2.5.3 Adding cooling devices" \l 3 }

To increase the capacity of the cooling cycle, additional cooling devices can be added. One way to accomplish this is to construct another cooling tower or to enlarge the present ones. It seems not to be possible to add another complete cooling tower with seven cells of the same size and design as the present ones as there is not sufficient room on the site. Another complete cooling tower would interfere with the two existing towers, mainly with respect to air flow. It is important to avoid a situation in which one tower gets its fresh air from the exhaust air stream of another tower. Considering these restraints, the one reasonable alternative is to add cells to the existing towers, which would basically make the towers longer. Without upgrading the pumps, the water flow is then distributed over more cells, thereby reducing the flow rate for every single cell. This can be an advantage. Also, increasing the water flow rate in a way mentioned in 2.5.2 can provide an improvement as in total more water is handled by the cooling towers.

It is also possible to include different cooling devices in the system. The primary device considered is an atmospheric cooling spray. Such a spray works in that water is sprayed into the air through vertically upward facing nozzles that are placed above the pond surface. During the time the droplets fly through the air, the water is cooled down, mainly by evaporation similar to a cooling tower, and the cold water drops fall back into the pond. A spray requires no fan as it depends solely on wind and natural convection. But its reliability as a permanently and efficiently working device is in question. Sprays are considered more efficient for cooling than a pond surface, as a spray provides a greater surface area for heat transfer. But there is also a considerable amount of pumping power required and in addition a new set of pumps and pipes is needed to install a spraying system. A short analysis of sprays will be given in chapter 4. In order to keep construction costs low, that means primarily pipes and power supply lines, the only location considered for a spray or any other additional cooling device is the plant intake or discharge section of the pond.

A shading structure for the pond is not really a cooling device in its usual meaning. Shading off solar radiation shuts the only major energy input, besides the power plant, off and promotes the process of cooling down of the pond water. A disadvantage of a shading structure is that it would also shut off radiation from the water to the sky. At night time radiation is a major source of heat rejection from the pond water to the environment. A calculation has to show whether a shading structure can be an advantage. In any case it seems not realistic at the present time to build a shading structure over a flow channel that is at average over 1200 ft wide. Only for slightly futuristic thoughts, namely that photovoltaic cells may become economical to use them for shading the pond, the option of shading is included in the further analysis, however only briefly.

2.6 Conclusion{ TC "2.6 Conclusion" \l 2 }

The condenser cooling cycle of the Columbia Generating Station consists of a number of different components that were described in the preceding chapters. A number of options exist, as discussed in section 2.5, to improve the overall performance of the cooling cycle with the goal of increasing plant efficiency and lowering production costs. In sections 2.1 to 2.4 the system properties were described and the limits discussed that the plant operators have to consider in operating the power plant. The whole system of power plant and cooling cycle can not be evaluated by looking at components individually as the components interact with each other. Thus there is the need to develop a model that describes the whole system. This model will be used to find optimum operation conditions and to study the benefits that new components would add to overall plant performance. This strategy will be described in chapter 4 and 5, as the purpose of chapter 2 was to outline in detail the task of this work.