J. ENVIRONMENTAL SYSTEMS, Vol. 25(3) 309-330, 1996-97

ENVIRONMENTAL IMPACT EVALUATION AND LIFE-CYCLE COST ANALYSIS OF COOLING TOWER TECHNOLOGIES

BECKY ZIEBRO

DEBORAH I. NELSON

JESS W. EVERETT

The University of Oklahoma, Norman

ABSTRACT

As environmental awareness increases, factors other than economic costs must be considered during product design. A new cooling tower design was compared to more traditional design considering energy usage, environmental impacts, and worker health and safety. The greater control over air flowrates provided by the new design allows for possible energy savings above traditional designs. The reduction in energy not only saves the user money, but carries with it the added environmental bonus of reducing emissions associated with energy production and consumption. Other environmental benefits found included potential reductions in noise and dust emissions, reduced chemical usage, elimination of sludge cleanout/disposal, and increased aesthetic appeal. Finally, the new design places mechanical components near ground level, reducing the risks to maintenance personnel associated with elevated working environments. The enclosed structure also eliminates the potential confined space entry hazards often associated with traditional towers.

INTRODUCTION

Choice of product design is often made with the goal of maximizing the benefit/cost ratio. However, in recent years the need to consider factors other than monetary benefits/costs when choosing a product is becoming increasingly clear.

doi: 10.2190/4URE-84JL-CD1P-3N7M
http://baywood.com

Raw material usage, environmental impacts, and worker health and safety must also be examined. This work compared the external costs associated with conventional cooling tower design to those of a new design. A variable wet-bulb study was conducted to explore the possible energy savings available with the new design. This was followed by a life cycle cost comparison. Environmental impacts were compared for the two designs considering both materials and methods of construction. Finally, the Occupational Safety and Health Administration Integrated Management Information System was queried for accidents involving cooling towers.

Traditionally, cooling towers were massive wooden or concrete structures built over open cold-water basins, and required many months to build. One manufacturer has developed a new design which is completely factory assembled and can be erected on-site in less than one hour. It is constructed from pultruded fiberglass and has many design features which may reduce energy consumption as well as environmental and health and safety impacts. These design features include the use of multiple fans which increase control over airflow, PVC filmpack fill which requires less frequent replacement, a completely enclosed cold-water basin which reduces sediment buildup, and placement of mechanical components at ground level which reduces health and safety risks to workers and reduces the overall tower height, thereby reducing pump costs.

ENVIRONMENTAL EFFECTS OF COOLING TOWERS

The most thorough treatment of environmental effects of cooling towers to date is contained in a study prepared for the National Environmental Studies Project (NESP) of the Atomic Industrial Forum [1]. This study of operational effects of cooling towers concluded that environmental effects are highly design- and site-specific, and that the impacts produced are often negligible. The environmental effects most often associated with cooling towers can be divided into two broad categories: 1) effects due to atmospheric emissions and 2) aquatic and surface effects. The effects associated with atmospheric emissions can include local weather changes (such as fogging and icing) and effects due to the chemical composition of drift. Fogging results when the tower discharge plume returns to ground level. Factors such as the wind speed and direction, and the plume exit height and velocity, are relevant when fog formation is considered. In general, though, fogging is thought to be a problem only in the immediate vicinity of the tower [2]. Another atmospheric emission of concern is the drift that makes its way out of the tower, which will have the same chemical composition as the circulating water. Concerns related to the drift contaminants are "their effects on local vegetation, soil contamination, and hazards to persons, automobiles or plant equipment" [3].

The primary chemicals of concern regarding surface waters are those used to treat recirculating water for prevention of corrosion and microbiological growth.

For many years chromate was widely used to prevent corrosion of the metals in cooling towers; however, its use is gradually being phased out due to the toxicity of hexavalent chromium [4]. In recent years, formulations using other heavy metals, such as zinc and molybdate, have been substituted for chromium compounds; however, concern has arisen over possible bioaccumulation in shellfish [5]. The chemical most commonly used to treat for microbiological growth is chlorine; however, chlorine reacts with organic constituents to produce trihalomethanes, which may be carcinogenic. Both chlorine and trihalomethanes are regulated by the EPA [5]. Bromine is another frequently used microbiocide. Other chemicals that may be present in the water come from the treated wood used for tower construction. Typical chemicals used for treating wood include creosote and chromated copper arsenate [5]. It is known that these chemicals can leach from the wood and, therefore, become part of the chemical makeup of the water. They can also be found in the sludge that builds up on the bottom of the cold water basin. This sludge, and possibly the wood itself upon tower decommissioning, may have to be disposed of as hazardous wastes [6].

HEALTH AND SAFETY EFFECTS OF COOLING TOWERS

There are many health and safety issues of concern to cooling tower workers. The major health concern regarding cooling towers is the possibility of Legionnaires' disease, a rare form of pneumonia, which is caused by the *Legionella pneumophila* bacteria. *Legionella* is a common bacteria, usually isolated in warmer waters [7]. Under appropriate conditions, it can thrive in cooling towers, creating a potential health risk. The most likely mechanism for infection is for the bacterial cell to become entrained in the drift, and subsequently be inhaled by humans. As recently as 1992, however, most drift was not tested for biological content [6]. The best method of controlling the spread of *Legionella* is prudent siting of the tower, so that the exhaust plume is not pulled into the air intakes of buildings.

The main safety concern about cooling towers is the possibility of persons falling from the tower structure. Inspections and maintenance require workers to be on top of towers, often greater than 40 feet above ground. The fan deck can be very slick and hazardous; even the use of a safety belt will not prevent all accidents [6]. The common solution appears to be the installation of structures (or platforms) on which to stand. However, such structures obstruct some of the air flow and decrease tower performance. Another safety concern related to cooling towers is the need to enter the basin for sludge removal. Such confined space entry can be extremely dangerous even when proper precautions are taken against accidents. Potential risks include oxygen deficiency and exposure to chemicals or pathogenic bacteria. A system that would prevent buildup of sludge would eliminate these risks.

METHODS

Variable Wet-Bulb Study

A comparison of yearly fan operating costs, considering the changes in ambient wet-bulb temperatures throughout the year, was made for two types of towers. Traditional towers, equipped with a single fan per cell, may have variable-pitch blades, or (more frequently) a variable-speed motor. These options allow the air flowrate to be adjusted as the ambient wet-bulb temperature changes throughout the year. However, the new design has produced a tower with multiple fans that can be switched on and off as needed (either manually or automatically). This unique feature increases the number of set points from the usual three (full speed, half or two-thirds speed, and off) to a number equal to the number of fans in the cell (N) plus one (to account for "all fans off"). The effect of the increased number of set points with which to control fan speed should be lower annual energy costs. Towers which differed in the number and operation of the fans were compared.

A multiple-fan tower was compared with two nearly identical towers (i.e., the same except for fan configuration) having a single fan and variable-speed motor each. One single-fan tower was assumed to have a motor that could run at full and half speeds, while the other tower was assumed to have a motor that ran at full and two-thirds speeds. The fan static pressure and air flowrate from the multiple-fan tower were used to select a single fan that could do the same duty for that tower. This single fan would be operated by a variable-speed motor as discussed above. Therefore, the single-fan towers were theoretical equivalents of the multiple-fan tower except for the number of fans.

For the given heat load (800 tons), a number of multiple-fan tower configurations exist; the one with the lowest total fan brake horsepower was chosen. Similarly, there were several options for a single fan which would operate at conditions equivalent to those of the multiple-fan tower. Again, the option which used the least horsepower was chosen in order to determine maximum possible energy savings.

The procedure followed was to calculate the ratio of total mass flows of water (designated L) and dry air (designated G) in the cooling tower at design conditions of 95°F hot water, 85°F cold water, and 78°F wet bulb using Equation 1. (For a review of cooling tower theory, the reader is referred to the work by Cherimisinoff and Cherimisinoff [8].)

$$\frac{L}{G} = \frac{GPM \times 8.33}{CFM \times 0.07} \tag{1}$$

where,

GPM = tower capability in gallons per minute

8.33 = lbs. water per gallon of water

CFM = air flowrate at maximum horsepower, ft^3/min
0.07 = density of air, lb/ft^3

Once this ratio was known, L was found by simply multiplying by G, approximately 2400 GPM for an 800-ton tower. The output enthalpy was then determined using Equation 2:

$$h_o = \frac{R \times L}{CFM \times .07} + h_i \tag{2}$$

where,
h_o = air output enthalpy, BTU/lb dry air
R = cooling range, °F
L = waterflow rate through the tower, lb/min
CFM = air flowrate through the tower, ft^3/min
0.07 = density of air, lb/ft^3
h_i = air input enthalpy, BTU/lb dry air

The input enthalpy h_i can be found from any psychrometric chart, given the 78°F input wet-bulb temperature. Once the value for h_o was known, it was assumed to be a constant during the seasonal wet-bulb changes. This assumption is based on the fact that "the amount of heat transferred to the atmosphere by the cooling tower is always equal to the heat load imposed on the tower" [9]. In this study, the heat load imposed on the tower remained a constant 800 tons; thus, if the wet-bulb temperature decreased, less air flow was required to cool the given amount of water. As the wet-bulb temperature changed, the L/G ratio changed.

Next the air flow was determined at each fan set point. For the multiple-fan tower, each fan was assumed to operate independently. Therefore, shutting off fans reduces both the airflow and horsepower in a linear manner, i.e.

$$CFM_{n/N} = CFM \times \frac{n}{N} \tag{3}$$

and,

$$BHP_{n/N} = BHP \times \frac{n}{N} \tag{4}$$

where,
$CFM_{n/N}$ = air flow when n of N fans are operating
CFM = air flow when all fans are operating
$BHP_{n/N}$ = brake horsepower when n of N fans are operating
BHP = brake horsepower when all fans are operating
n = number of fans operating
N = total number of fans

Equations 3 and 4 are appropriate if it is assumed that the pressure loss through the tower does not change as fans are turned off (and the air flow decreases). The assumptions made, fan independence and unchanging pressure loss, are both conservative; i.e., if more realistic assumptions were made, the estimated tower electricity consumption would be lower.

For the variable-speed fan towers, the brake horsepower used to generate the required CFM was taken from fan curves supplied by the fan manufacturer. Brake horsepower requirements at lower speeds were then estimated using Equation 5.

$$\frac{BHP_1}{BHP_2} = \left(\frac{CFM_1}{CFM_2}\right)^{3.2} \tag{5}$$

This is the familiar fan law, as applied to cooling towers [10]. These values represent the theoretical power needed to drive the fans. However, actual motor horsepowers vary as the ratio of the speeds squared. Therefore, a motor turning at two-thirds speed will use two-thirds squared, or 44 percent, of full horsepower [11]. Calculations of annual energy consumption were made using both brake horsepower and motor horsepower for the multiple speed fans. It is presumed that actual energy use will lie between the two values; therefore, both values are reported.

Once the CRMs for each set point were determined, Equation 6 was solved for h_i, the input air enthalpy.

$$h_i = h_o - \frac{R \times L}{CFM \times .07} \tag{6}$$

Again, psychrometric charts can then be used to determine the wet-bulb temperature that corresponds to the estimated input air enthalpies, and corresponding air flows. For a given air flow, the estimated wet-bulb temperature determines the setpoint (number or speed of fans) at which the tower can successfully operate. The number of hours per year for each range of wet-bulb temperatures was obtained from weather data [12].

The energy cost required for each set point was calculated using Equation 7.

$$cost = \frac{BHP \times 0.746 \times hours \times .047}{0.9} \tag{7}$$

where,

cost	= dollars/year
0.746	= kW/HP
hours	= hours/year of operation
0.047	= dollars/kW-hr
0.9	= fan motor efficiency

The annual energy cost was found by summing the cost for all individual set points for a given tower. The entire set of calculations was performed for several cities. Cities were chosen to represent warm and/or humid and cool and/or dry climates.

Life Cycle Costs

The life cycle economic assessment was based on a comparison of initial and operating costs of the appropriate model(s) from five different cooling tower manufacturers. Specific models for each manufacturer were chosen for each of six different cooling loads, based on conditions deemed appropriate for two different markets. For the air conditioning market, towers of 400, 800, and 2500 tons were compared at 95°F hot water, 85°F cold water, and 78°F ambient wet-bulb temperature. For the industrial market, towers designed for three cooling loads (6,000; 10,000; and 30,000 GPM) were compared at 105°F hot water, 85°F cold water, 78°F wet bulb.

The first condition for selection was a noncorrosive construction material. Therefore, fiber-reinforced plastic (FRP) towers with stainless steel fittings were chosen. This essentially limited the choice to one or two specific model lines per manufacturer. Another condition for selection was the use of PVC fill only. When a choice of model lines was available for a particular size, the model with the lowest initial price was chosen. However, for the new design (Manufacturer E), the model which would cool the given heat load with the lowest fan horsepower was also chosen. This allowed for examination of the tradeoffs involved between initial costs and operation costs.

Purchase price and installation are the primary initial costs. Other costs may be incurred, depending on the specific tower purchased and location, and include transportation, support structure, and cold water basin. The manufacturers (or their district sales representatives) were asked to provide the purchase price of the models selected. Many smaller towers can be purchased factory assembled. These are then loaded onto trucks for transportation to their final destination. For these towers, the prices received were quoted as freight on board (FOB) factory, which means that they are loaded on the truck at the factory and then become the purchaser's property. Here, the purchaser is responsible for transportation to the site. For purposes of this study, it was assumed that all FOB towers were to be shipped via a commercial trucking line a distance of 519 miles. Shipping rates were obtained from a local trucking company [13], based upon the shipping weights quoted in manufacturers' catalogs. For field-erected towers, the prices quoted included construction of the tower at the purchaser's site; therefore, no transportation costs were incurred.

Purchase price and transportation costs are not the only initial costs which must be considered. Some towers have a cold water basin as an integral part of the tower, while others require that a basin be built. For towers requiring the construction of a basin, the cost of a concrete basin with dimensions as suggested in the appropriate catalog was included in the initial cost estimate. A price of $200 per cubic yard (including labor and reinforcement) of concrete was chosen as a representative price [14].

The costs associated with tower connection can be significant. For example, the cost of wiring and temperature controls can be in the same order of magnitude as the purchase price, and thus should be considered as part of the tower's "total cost." These costs, along with the cost of plant hot and cold water piping, were not considered in this study due to their highly site-specific nature.

Power consumption comprises the primary cost of operating a cooling tower. The computations in this study focused on fans and pumps, which account for most of the energy used by cooling towers. It should be noted that the calculations performed in this report result in theoretical values of energy consumption. These theoretical values are based upon several assumptions which tend to idealize the results. More realistic, empirical values for energy consumption would be found through repeated tests on actual towers. As this option was not available, theoretical values are reported.

To determine the cost of fan operation per year, the tower capacities (in GPM), air flowrates at maximum fan horsepower (CFM), and total fan horsepower were obtained. Many towers had capacities greater than required to meet the design parameters. The procedure used to adjust the air flowrates to the required capacity is described below.

The capacities and air flows were used in Equation 1 to determine L/G for each tower. This value was then used to adjust the volumetric air flowrate to the amount required to cool at the design capacities, by solving Equation 1 for CFM and using the operating GPM and the calculated L/G ratio. (It is recognized that L/G values do not remain strictly constant; however, they can be assumed to be constant over the small changes in capacity dealt with in this manner.)

Once the required air flowrate was found, the fan laws were used to adjust the brake horsepower for each tower using Equation 5. Horsepower was then converted to costs using Equation 7 and 8760 hours of operation. The assumption of continuous operation (i.e., 8760 hours/year) was based on the responses to a survey of cooling tower operators.

To evaluate the annual cost of operating the pumps, the water flowrate, total dynamic head, and pump and motor efficiencies must be known. The water flowrate is one of the given conditions for the tower size. The total dynamic head (in feet) is the summation of the static lift and the pressure required for the distribution system to operate, less frictional or minor losses from pipes and fittings. Each of these components will be discussed below.

The static lift is the distance from the center of the hot water inlet to the operating level of the cold water in the basin. Data received from the manufacturers will typically quote a height from the top of the basin curb to the center of the hot water inlet. For this comparison, it was assumed that the towers would be operated with full cold water basins. Therefore, the distance from the top of the basin to the center of the hot water inlet was the static lift required for the calculation of total dynamic head.

In order for the nozzles on a counterflow cooling tower to function properly, there must be a minimum amount of pressure across the nozzles. For most manufacturers, an estimate of this pressure is approximately 5 pounds per square inch (psi) [15, 16]. This is equivalent to 11.55 feet of pressure (2.31 ft = 1 psi). However, one manufacturer has developed a nozzle that requires only 1.35 psi for proper distribution. Therefore, for this manufacture a distribution pressure of 3.12 feet was added to the static lift. Information as to the exact pressure required was also available from two other manufacturers, and these values were used in the calculations. For the remainder of the models, the default value of 11.55 feet was used.

Strictly speaking, the frictional losses in the header, riser, and distribution system piping should be included in a calculation of total dynamic head. However, these losses were not included in the calculations for two reasons. First, every tower's external piping will vary depending upon its location, and the purpose of the evaluation reported here was to compare the towers only. Second, while there will be frictional losses due to the internal piping on all of the towers, the losses will be minimal in comparison to the lift and distribution pressures. The term "pump head" will be used here to represent the sum of the static lift and the required distribution pressure in the calculation of pump horsepower.

The final consideration was that of pump and motor efficiencies. Typical efficiencies were obtained by consulting manufacturers' literature, and by examination of typical pump curves [17]. A value of 80 percent was used for the pump efficiency, and 90 percent for the pump motor efficiency. Pump horsepower is given by Equation 8:

$$PHP = \frac{GPM \times HEAD \times 8.33}{33{,}000 \times E} \tag{8}$$

where,

PHP	= pump horsepower, hp
HEAD	= pump head as defined above, in feet
8.33	= lbs. of water/gallon of water
33,000	= ft-lbs/minute/HP, by definition
E	= pump efficiency

Once the horsepower was known, Equation 7 was again used, substituting the pump motor efficiency for the fan motor efficiency, to obtain the annual operating cost of the pump.

There are many other operating costs associated with cooling towers, such as water treatment costs and cleaning costs. Also, the loss of productivity during any downtime would be considered an operating cost. A survey of cooling tower operators showed that these types of costs were essentially the same for all users, regardless of manufacturer. Their primary dependence was upon the particular application of the tower, not the manufacturer. (The cost that seemed to fluctuate most was that of keeping spare parts on hand, but this too was dependent on application rather than manufacturer.) Based upon the site specificity of these costs, they were excluded from this comparison of cooling tower costs.

After all the costs to be studied were quantified, they were totaled. The costs of ownership for each cooling tower were computed assuming five-, ten-, twenty-, and thirty-year lifetimes. For the lifetime cost calculations, the operating costs associated with each tower were assumed constant over the life of the tower; for example, factors such as inflation and changing electricity costs were not considered [18]. Thus, current operating costs were the same in future years except for the time value of money. All operating costs were assumed to be paid at the end of the year. The interest rate used for the calculations was the prime rate of the week ending August 27, 1994 or 7.75 percent [19]. All results represent the amount of money which would need to be invested today (in units of 1994 dollars) in order to pay the initial and operating costs over the assumed lifetimes.

Many methodologies exist for predicting environmental impacts. One such methodology, known as an interaction matrix, has been used for many years. Steps for matrix development are discussed by Canter [20]. An interaction matrix was developed which compares the environmental impacts associated with traditional (wood, concrete, and stainless steel) and new (FRP) construction materials. According to Canter, a qualitative environmental evaluation may be performed by breaking the process, activity, project, etc., into phases and examining the potential environmental impact of each phase. For the environmental assessment of cooling towers, the life-cycle was divided into construction, operations and maintenance, and decommissioning phases. A modified interaction matrix was also developed which allows for a comparison of towers by methods of construction.

Finally, the U.S. Department of Labor (USDOL), Occupational Safety and Health Administration (OSHA), requires that all workplace accidents involving fatalities or catastrophes (five or more employees hospitalized) be reported to OSHA by the employer [21]. Accident investigation reports are then submitted by OSHA compliance officers. These reports, which contain statistics on the employer, cause and outcome of the accident, and OSHA inspection data, have been maintained by OSHA in the computerized Integrated Management Information System (IMIS) since 1984. This database was searched for all federal or state reports from April 1984 to July 1994 that contained the words "cooling tower" [22]. It was not possible to calculate a true risk statistic, i.e., the number of accidents per employee exposed, as the number of employees working on or around cooling towers is not known. However, the accident records were examined for trends in geographical location, year of occurrence, number of employees involved, contributing factors, and type of injuries.

RESULTS

The variable wet-bulb study was undertaken to determine the energy savings possible using the multiple-fan design. This study calculated fan energy use while accounting for the variations in wet-bulb temperature throughout the year for several regions of the country. A multiple-fan tower was compared to two theoretically equivalent towers which differed only in the fan systems used. The results of the variable wet-bulb study for cities with higher 99-percentile wet-bulb temperatures are shown in Table 1. Table 1 shows annual operating costs calculated using both the fan brake horsepower and the actual motor horsepower, as discussed above. For warm and/or humid cities, it can be seen that the multiple-fan tower was the most economical choice regardless of whether fan brake horsepower or motor horsepower is considered. (The calculated actual motor horsepowers for this tower did not vary from the calculated brake horsepowers because motors are simply being turned off as the wet-bulb temperature decreases in both cases.) For extremely humid cities, such as Miami, the multiple-fan tower cost only $5511 per year, while the full/half-speed tower had an annual fan brake horsepower cost of $12,109 and an actual motor horsepower cost of $12,332 per year. In Sioux Falls, the least humid of these cities, the dual speed towers had calculated annual fan brake horsepower costs of $3763 (full/half) and $3820 (full/two-thirds). This is compared to the multiple-fan tower which had a calculated cost of $3379 per year. This difference is even greater when actual motor horsepower usage is compared, as is shown in Table 1.

The results of the variable wet-bulb temperature study for cities with lower 99-percentile wet bulbs are presented in Table 2. It can be seen from the brake

Table 1. Annual Operating Costs (in 1994 U.S. Dollars) for Warm and/or Humid Cities

	Houston		Miami		Sioux Falls		Pittsburgh	
	BHP	Actual	BHP	Actual	BHP	Actual	BHP	Actual
Multiple-Fan	5053*	5053*	5511*	5511*	3379*	3379*	3531*	3531*
Full/ Two-thirds Speed	7500	8880	9412	10353	3820	6045	3853	6070
Full/Half Speeds	9228	9907	12109	12332	3763	5417	3765	5310

Note: BHP = costs calculated using fan brake horsepowers, Actual = costs calculated using actual motor horsepowers, * = lowest cost.

Table 2. Annual Operating Costs (in 1994 U.S. Dollars) for Cool and/or Dry Cities

	Buffalo		Denver		Las Vegas	
	BHP	Actual	BHP	Actual	BHP	Actual
Multiple-Fan	3490	3490*	3203	3203*	3577	3577*
Full/Two-thirds Speed	3825	6048	3692	5946	3692	5946
Full/Half Speeds	3390*	4994	1471*	3379	3389*	4993

Note: BHP = costs calculated using fan brake horsepowers, Actual = costs calculated using actual motor horsepowers, * = lowest cost.

horsepowers that the theoretical tower equipped with a fan which runs at full and half speeds was the most economical choice. The multiple-fan tower had the next least expensive operating costs throughout the year, followed by the theoretical tower with a motor capable of running at half and two-thirds speed. For Denver, the city with the widest variations in operating costs, the annual costs ranged from $1471 for the half-speed motor, to $3692 for the two-thirds-speed motor. For the remaining low wet-bulb cities, the variation was from 9 to 13 percent of the lowest half-speed brake horsepower.

When the costs associated with actual motor horsepower usage were compared, the relative energy usages changed. The multiple-fan tower was the most economical to operate in these dry cities. In the case of Buffalo, the multiple-fan tower cost only $3490 per year, while the two-thirds-speed motor cost $6048 per year. To determine a pattern, the 99-percentile wet-bulb temperatures for the cities used for the variable wet-bulb study were examined [12]. It was found that the "cool/dry" climate cities all had a 99-percentile wet-bulb temperature below 76°F. It was further found that all of the "warm/humid" cities had a 99-percentile wet-bulb temperature above 77°F. It was, therefore, concluded based on both brake and actual motor horsepowers that the multiple-fan tower is more economical than the single fan towers to operate in climates which have a 99-percentile wet-bulb above 77°F. However, in regions with a lower 99-percentile wet-bulb temperature, the results were inconclusive and a determination of which type of tower is more economical to operate cannot be made without actual field tests. However, this conclusion should not be considered a hard and fast rule, as each city will have its own specific variations in wet-bulb temperature which may cause a deviation from the generality presented above.

The lifetime costs, in 1994 dollars, for smaller towers (the air conditioning market) are presented in Table 3. For the 400-ton towers, Manufacturer D had the highest calculated lifetime costs in all cases. The other manufacturers, however, changed in relative positions as the lifetime was increased. This is due to the fact that towers which have high initial costs and low annual operating costs eventually "pay for themselves" as compared to other towers through annual savings in operating costs as assumed lifetimes are increased. This did not happen with Manufacturer D, for the 400-ton towers, because this particular manufacturer had high operating costs for this size tower. However, in comparison of the medium-sized towers (800-ton), Manufacturer D had the lowest lifetime costs for all four lifetimes (except for the low horsepower model of Manufacturer E). No other consistencies were found for this size tower as once again, the relative present costs of towers were different for different lifetimes. For the 2500-ton (lowest initial price) towers Manufacturer E (new design) showed the highest lifetime costs for all assumed lifetimes, due to high fan operating costs. Again, the relative positions of Manufacturers C and D were reversed as one tower "paid for itself" relative to the other as the lifetime was increased. It should be stressed that these analyses assumed full-time operation, i.e., 8760 hours/year. When the low horsepower, multiple-fan model (designated low HP) was considered in the lifetime cost comparisons, this model consistently had the lowest lifetime operating costs. This is not surprising, as the choice of a low horsepower unit would be made in an effort to keep operating costs to a minimum level, as operating costs are a significant portion of lifetime costs.

The lifetime costs for the larger towers (industrial market) are shown in Table 4. For the 6000-GPM towers, Manufacturer D had the highest lifetime costs assuming a 5-year lifetime. However, this situation changed when ten-, twenty-, or thirty-year lifetimes were assumed, again due to higher fan operating costs for Manufacturer E. For the other two sizes, Manufacturer E consistently showed the highest lifetime costs. Once again, when the low horsepower, multiple-fan model was considered, the new design showed the lowest lifetime costs, regardless of the length of the assumed lifetime.

The interaction matrices which were developed for comparison of environmental impacts by materials and methods of construction are presented in Tables 5 and 6. Table 5 shows the potential impacts associated with wood, steel, concrete, and FRP construction. A (+) sign indicates a positive impact, a (–) sign indicates a negative impact, and a (0) indicates little or no impact. The number of signs is indicative of the magnitude of the impact relative to the other construction materials studied. However, while this table treats impacts to different environmental media as separate, it must be remembered that they are all interrelated and what happens in one media may change the magnitude of other impacts.

Wood use may impact the environment in various ways. One positive impact not shown in Table 5 is that wood is a renewable resource, although it may take

Table 3. Lifetime Costs for Air-Conditioning Application Towers[a]

	Mfr. B	Mfr. C	Mfr. D	Mfr. E	Mfr. E (low hp)
5-Year Lifetime Total Costs (Dollars)					
400 ton	$ 66,266	$ 70,799	$ 82,143	$ 67,376	$ 50,268*
800 ton	$158,928	$178,557	$131,738	$133,019	$ 99,687*
2500 ton	n/a	$401,554	$397,888	$404,554	$316,768*
10-Year Lifetime Total Costs (Dollars)					
400 ton	$ 88,382	$ 86,849	$122,163	$ 99,553	$ 65,159*
800 ton	$229,850	$213,593	$182,493	$196,780	$129,334*
2500 ton	n/a	$509,205	$553,073	$596,164	$424,885*
20-Year Lifetime Total Costs (Dollars)					
400 ton	$114,093	$105,508	$168,689	$136,962	$ 82,470*
800 ton	$312,301	$254,325	$241,498	$270,905	$163,822*
2500 ton	n/a	$634,418	$733,486	$818,924	$550,578*
30-Year Lifetime Total Costs (Dollars)					
400 ton	$126,282	$114,354	$190,745	$154,696	$ 90,676*
800 ton	$351,388	$273,634	$269,469	$306,045	$180,166*
2500 ton	n/a	$639,776	$819,011	$924,524	$610,163*

[a]All fans assumed on 8760 hours.
* lowest cost

years for renewal. However, deforestation also has many negative impacts such as erosion, increased runoff, loss of habitat, and an increase in atmospheric CO_2 levels [23]. The magnitude of erosion experienced on land cleared of trees depends on several factors including the slope of the land and the amount of traffic it receives. Surface runoff in cleared areas increases two to tenfold, depending on the amount of clearing [24]. This increased runoff leads to larger and more rapid storm surges. It also decreases the amount of groundwater recharge, adding to the problem of ever declining water tables. The loss of habitat which accompanies deforestation should not be ignored, as many species have precious little viable habitat left in many places. Trees are also an important part of the carbon cycle, converting CO_2 through photosynthesis. It is estimated that 400-2600 million extra tons of carbon are attributable to deforestation [23]. Subsequent increases in anthropogenic CO_2 levels contribute to the serious global climate change problems experienced worldwide. Removal of vegetation can also

Table 4. Lifetime Costs for Industrial Application Towers[a]

	Mfr. D	Mfr. E	Mfr. E (low hp)
5-Year Lifetime Total Costs (Dollars)			
6,000 GPM	$ 423,376	$ 412,536	$ 344,010*
10,000 GPM	$ 627,398	$ 719,250	$ 572,412*
30,000 GPM	$1,882,163	$2,116,081	$1,696,029*
10-Year Lifetime Total Costs (Dollars)			
6,000 GPM	$ 575,514	$ 595,468	$ 465,991*
10,000 GPM	$ 851,373	$1,053,179	$ 775,498*
30,000 GPM	$2,608,530	$3,111,215	$2,308,009*
20-Year Lifetime Total Costs (Dollars)			
6,000 GPM	$ 752,385	$ 808,139	$ 607,802*
10,000 GPM	$1,111,761	$1,441,396	$1,011,599*
30,000 GPM	$3,452,982	$4,268,127	$3,019,478*
30-Year Lifetime Total Costs (Dollars)			
6,000 GPM	$ 836,231	$ 908,957	$ 675,027*
10,000 GPM	$1,235,198	$1,625,431	$1,625,431*
30,000 GPM	$3,853,297	$4,268,127	$4,268,127*

[a]All fans assumed on 8760 hours.
* lowest cost

result in localized microclimate changes, and possibly even modify regional temperatures, humidities, and air circulation patterns [23].

Steel use has been linked to impacts on the soil, surface water, the air quality, habitat, the climate, and waste management. Mining, by its very nature, disturbs the earth and destroys vegetation, causing increased soil erosion. What soil remains is less supportive to revegetation and the problems can quickly compound. Along with this loss of vegetation go the inextricable losses of habitat. The process of mining also contributes a great deal of pollution, particularly fugitive dusts, to the air. Both mining and manufacturing can contribute to surface water impacts. Runoff from mine tailings may carry hazardous materials with it. The manufacture of steel also poses a threat to the water environment. Processing wastes which are directly discharged may contain compounds such as oil and grease, ammonia, nitrogen, cyanide, and lead [23]. Each of these negatively impacts the aquatic environment. Also, surface runoff from manufacturing sites may contain raw materials, coal, or coal breeze which are frequently stored in

Table 5. Environmental Impact Assessment by Materials of Construction

Environmental Media	Wood (Traditional)	Steel (Traditional)	Concrete (Traditional)	Fiber-Reinforced Plastic (Innovative)
Soil	– –	–	0	0
Surface water	– –	– –	–	–
Groundwater	–	0	0	–
Air	0	– –	–	0
Habitat	– –	–	0	0
Global climate	– –	–	–	–
Waste management	0	–	+	0

Note: (+) indicates a positive impact, (–) indicates a negative impact, and (0) indicates little or no impact. The number of symbols indicates the relative severity of the impacts.

piles on the ground at manufacturing facilities. Emissions of SO_x and CO from manufacturing facilities can contribute to global climate change if not adequately controlled. Finally, the mine tailings and process wastes can contain hazardous materials and thus have the potential to contribute to solid waste disposal problems.

On the other hand, concrete manufacture may help reduce waste management problems through the use of kiln dust as filler. Kiln dusts and raw materials pose threats to water, as surface runoff can leach hazardous constituents, polluting the surface waters. Particulate air pollution emitted from plants negatively impacts the air quality. It can also affect the temperature of the air as well as the pH of any entrained water. Gaseous emissions of SO_x, CO, and NO_x from kiln fuels again must be adequately controlled in order to maintain the earth's climate.

The environmental impacts associated with FRP construction result from the manufacture of the chemicals used in the resins. The chemical industry can alter the biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and pH of surface waters through its routine discharges [23]. The major negative impact results from the vast amounts of water used for cooling and washing at chemical plants, again potentially compounding the problem of decreasing water tables. Finally, gaseous emissions of SO_x, CO, and NO_x from plants must be controlled.

The interaction matrix which was developed for comparison of environmental impacts due to design type is presented in Table 6. The design types shown are on-site construction (or traditional, field-erected) towers, and the innovative, modular design. The impacts are grouped according to construction, operations/ maintenance, and decommissioning phases. On-site construction of cooling towers involves heavy equipment, is time consuming, and creates a lot of noise. Factory assembly of modular cooling towers confines the construction impacts to

Table 6. Environmental Impacts by Design Type

Phase	Field Erected (Traditional)	Innovative Design
Construction Phase Impacts	– major heavy equipment creates fugitive dust and noise emissions	+ eliminates heavy equipment impacts
	– more time required	+ less time required
Operation Phase Impacts	– induced draft may result in further plume travel, possibly resulting in fogging or deposition of emissions off-site	+ forced draft design results in better plume containment, and localizes fogging or deposition of any emissions
	– elevated fans normally have greater environmental noise impact	+ ground-level fans normally have less environmental noise impact
	– greater energy use	+ less energy use
	– aesthetic impact	+ aesthetic impact
	– sludge buildup in basin must be removed, possibly disposed of as hazardous waste	+ flow-through design eliminates sludge disposal
Decommissioning Impacts	– porous construction materials must be tested prior to disposal and may require disposal as hazardous waste	+ nonporous construction materials may be disposed of in municipal landfill

Note: (+) indicates a positive impact, while (–) indicates a negative impact.

the manufacturing site, and is faster and quieter. Emphasis at construction sites is often on completing the job in a timely manner and not on protecting the environment. However, the impacts associated with the use of heavy equipment can be significant. Construction activity often destroys the local vegetation, increasing the amount of particulate matter in the air and the amount of sediment carried to streams. The potential to contaminate the soil and groundwater with oil, grease, fuel, and paints used on the equipment has also been documented [23]. A final impact to soil not eroded is that it becomes compacted by the weight of the machines and thus does not support new growth as well. Short-term impacts include increased congestion in densely populated areas and increased noise levels. The new design limits construction phase environmental impacts to the manufacturing site, enabling greater control over them. Placement on site requires only a crane and two persons, and can be accomplished in about an hour, eliminating the need for heavy equipment and its impacts.

Operational impacts occur as a result of a number of factors. The type of air movement used (induced-draft, where the fans are located on the top of the tower or forced-draft, where the fans are located on the bottom of the tower) will influence the distance over which the exhaust plume may be carried, thus determining if off-site environmental impacts such as fogging or chemical deposition are of potential concern. The innovative, forced-draft design, by virtue of its reduced exit velocity, will greatly reduce the chances of off-site contamination occurring. Another benefit of a forced-draft design is a potential reduction in the environmental noise impacts (off-site) due to closer proximity of the fan to the ground. The possible reductions in energy use of the innovative tower can greatly reduce the impacts associated with energy production. Combustion of fossil fuels during energy production is a major contributor to global climate changes. One estimate of carbon contributions is 5208 million tons per year which is then available to become CO_2 [23]. Reduction in overall tower height will also lessen any aesthetic impact due to the tower presence. A newer design feature which further reduces environmental impacts is the deletion of a cold-water basin; the flow-through design eliminates sludge buildup and subsequent requirements for removal and disposal (possibly as a hazardous waste).

Operational phase impacts can also result from the chemicals used in cooling tower water. All towers require treatment to reduce growth of algae and bacteria, and to prevent scale formation. However, wood requires frequent additional treatments to prevent wood rot. Typical chemicals used for this purpose include creosote and copper compounds. Steel towers also require additional water treatments (almost daily) for corrosion prevention, primarily through pH adjustment. The heavy metals used for both of these purposes create a pollution hazard when they accumulate in the soils, and are subsequently taken up by plants and animals.

The impacts which occur during the decommissioning phase are related to the porosity of the construction material used. The components of interest concerning decommissioning a modern tower are the mechanical components, the fill, the structural members, the sides (i.e., walls), and the basin or pad. The materials of primary interest are PVC, FRP, galvanized steel, wood, and concrete. It is necessary to determine whether the components must be handled as non-hazardous or hazardous waste in order to determine the decommissioning impacts. Materials that come in contact with chemicals or fumes may be characterized as hazardous wastes. This includes cooling tower components because they are exposed to chemicals used to treat cooling water. Materials that are classified as hazardous may require disposal in a hazardous waste facility.

Materials can be classified as non-hazardous by two procedures: 1) if testing of the materials demonstrates that concentrations of hazardous chemicals are lower than specified limits; or 2) if it can be demonstrated by knowledge of the process that the components will not contain significant concentrations of hazardous chemicals. The latter procedure involves demonstrating that the waste materials are impermeable or that no hazardous wastes came in contact with the waste materials during operation. Most of the components of a modern cooling tower can be demonstrated to be non-hazardous by knowledge of the process and materials of construction. PVC, FRP, and galvanized steel are all relatively impermeable, thus it is likely that the applicable regulatory agency will allow these materials to be treated as non-hazardous waste. Wood, and to a lesser extent, concrete, however, are relatively permeable and may require testing prior to disposal to determine if hazardous constituents are present.

The OSHA database query revealed a total of nineteen accidents [22]. Examination of the query results revealed several trends. First, Region 6 (South Central) had the highest number of accidents (6), accounting for about 30 percent of the accidents. This region was followed by Regions 4 and 9 (Southeast and Southwest), with four accidents each. There was no apparent trend in the years in which the accidents occurred, however, there was a slight peak in numbers of accidents (8) in 1987-88. The significant trend is that fifteen (79%) of the reported accidents were falls from an average height of 39 feet. (Note that not all reports included the height.) Of the fifteen falls reported, only two did not result in a fatality. All of these accidents involved workers performing routine maintenance on or around the towers. It can be concluded from the query results that the possibility of encountering hazardous working conditions appears high for maintenance personnel on traditional cooling tower superstructures. Of the remaining four reported accidents, one fatality resulted. This accident occurred when a crane being used to replace a motor broke apart and struck a sulfuric acid line believed to be out of service. A worker standing on another line was knocked into the sulfuric acid discharged from the line. Ten additional workers were injured in rescue attempts. This situation underscores the hazards faced by workers involved in cooling tower maintenance.

Worker health and safety hazards are minimized by innovations in cooling tower technology, as seen in Table 7. Manufacture of modular cooling towers occurs proximate to the management, increasing control of worker safety. Operations and maintenance of traditional superstructures presents slip/trip and fall hazards to workers. In contrast, low-profile towers with placement of mechanical components at ground level reduces the risk to operations and maintenance personnel. Confined space entry is another impact which is eliminated in the newer design. Traditionally, workers who are required to enter the tower for sludge removal or operations and maintenance procedures are presented with a potential inhalation hazard of toxic or infectious agents.

Table 7. Worker Health and Safety Impacts by Design Type

	On-Site	Modular	Innovative Design
Worker Health and Safety	– major construction occurs at remote site, simultaneously increasing risk to workers and decreasing management control of worker safety	+ manufacture occurs at controlled site, increasing management control of worker safety	+ manufacture occurs at controlled site, increasing management control of worker safety
	– mechanical components are elevated, increasing slip/trip and falling risks to O+M personnel	– mechanical components somewhat elevated, increasing slip/trip and falling risks to O+M personnel	+ mechanical components at ground level, reducing risk to O+M personnel
	– entry for O+M may present inhalation hazard of toxic or infectious agents	– entry for O+M may present inhalation hazard of toxic or infectious agents	+ entry for O+M not required
	– sludge removal may pose inhalation hazard of toxic or infectious agents	– sludge removal may pose inhalation hazard of toxic or infectious agents	+ sludge removal not required as there is no sludge buildup

Note: (+) indicates a positive impact, while (–) indicates a negative impact. The number of symbols indicates the relative severity of the impacts.

CONCLUSIONS

The cooling tower industry is changing rapidly as many design innovations are introduced. The greater control over air flowrates which is possible due to the many set points available with the multiple-fan design may produce energy savings above those possible with only one or two set points. A reduction in energy not only saves the user money, but carries with it the added environmental bonus of reducing emissions which result from energy production and consumption.

The economic life cycle assessment showed that initial costs are comparable for the tower designs considered. Operating costs were found to depend on the criteria used in tower selection. Tower selection based upon lowest initial cost may not prove to be the most economical. This emphasizes the need for factors other than initial costs to receive equal consideration when product choice is made.

It is possible that the new design will reduce the environmental impacts which are often associated with traditionally designed cooling towers. Possible benefits were found due not only to the materials used, but also due to the construction methods utilized. Finally, the new design may decrease worker health and safety effects such as slip/trip/and fall accidents as well as confined space problems.

REFERENCES

1. K. R. Wilber and R. O. Webb, *Environmental Effects of Cooling Towers,* National Environmental Studies Project of the Atomic Industrial Forum, Inc., Knoxville, Tennessee, 1983.
2. Cooling Tower Institute, Environmental Aspects of Cooling System Operation, in *CTI Cooling Tower Manual,* Chapter 8, Houston, Texas, 1981.
3. G. Mirsky, K. Bryant, and J. Libert, The Latest Worldwide Technology in Environmentally Designed Cooling Towers, *CTI Journal, 13*:2, pp. 20-28, 1992.
4. Cooling Tower Institute, Water Chemistry and Treatments, in *CTI Cooling Tower Manual,* Chapter 6, Houston, Texas, 1990.
5. Electric Power Research Institute, *Options for Handling Noncombustion Waste,* Palo Alto, California, 1993.
6. Anonymous, Cooling Tower Institute's Annual Operating Seminar, February 8, 1991, *CTI Journal, 13*:1, pp. 52-73, 1992.
7. J. L. Dennis, An Unnecessary Risk: Legionnaires' Disease, ASTM Special Technical Publication No. 1071, *Biological Contaminants in Indoor Environments,* Boulder, Colorado, pp. 84-98, July 16-19, 1989.
8. N. P. Cheremisinoff and P. N. Cheremisinoff, *Cooling Towers, Selection, Design and Practice,* Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, 1981.
9. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Cooling Towers, in *ASHRAE Handbook, 1992 HVAC Systems and Equipment,* Chapter 37, ASHRAE, Atlanta, Georgia, 1992.
10. S. V. Shelton and E. D. Weber, Modeling and Optimization of Commercial Building Chiller/Cooling Tower Systems, *ASHRAE Transactions, 97,* pt. 2, pp. 1209-1216, 1991.
11. D. Heard, personal communication, Houston, Texas, September 1994.
12. Ecodyne Cooling Products Division, *Weather Data Handbook,* McGraw-Hill Publishing Co., New York, 1980.
13. Roadway of Oklahoma City, personal communication, Oklahoma City, Oklahoma, August 1994.
14. B. Russell, University of Oklahoma, personal communication, Norman, Oklahoma, August 1994.
15. J. Hipskind, K. Hawks, J. Tumilty, and V. Goldschmidt, Natural Cooling Cycle in Cooling Towers—Analysis and Utilisation, *ASHRAE Transactions, 97,* pp. 1197-1208, 1991.
16. Marley Cooling Tower Company, *Cooling Tower Energy and Its Management,* Technical Report No. H-001A, Mission, Kansas, 1982.
17. I. Karassik, W. Krutzsch, W. Fraser, and J. Messina (eds.), *Pump Handbook,* McGraw-Hill Publishing Co., New York, 1986.

18. American Institute for Pollution Prevention and J. R. Aldrich, *A Primer for Financial Analysis of Pollution Prevention Projects,* U.S. Environmental Protection Agency, EPA/600/R-93/059, Washington, D.C., 1993.
19. Council of Economic Advisors, *Economic Indicators,* prepared for the Joint Economic Committee, U.S. Government Printing Office, Washington, D.C., August 1994.
20. L. W. Canter, *Environmental Impact Assessment,* (Rev. Edition), McGraw-Hill Publishing Co., New York, 1996.
21. U.S. Department of Labor, *Title 29 Code of Federal Regulations, Part 1904.8, Reporting of Fatality of Multiple Hospitalization Accidents,* USDOL, Washington, D.C., 1993.
22. U.S. Department of Labor, Occupational Safety and Health Administration, Office of Management Data Systems: Search of All Federal and State Investigations from April, 1984 to July, 1994 for *Cooling Towers,* OSHA, Washington, D.C., 1994.
23. World Bank, *Environmental Assessment Sourcebook,* Washington, D.C., 1991
24. World Bank, *The Environmental, Public Health, and Human Ecology: Consideration for Economic Development,* Washington, D.C., ca. 1982.

Direct reprint requests to:

Deborah I. Nelson
School of Civil Engineering and Environmental Science
University of Oklahoma
202 West Boyd Street
Room 334
Norman, OK 73019-0631