IIT Waste Energy Management Project

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Beneficial Use of Waste Heat in Municipal Water Supply

by

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ABSTRACT (SUMMARY)

The relatively low temperature of thermal discharges from steam-electric power plants makes waste-heat utilization difficult without modification of the power cycle and attendant reduction in electrical energy generated. The present report concerns in situ beneficial use of waste heat by direct once-through condenser discharge into a municipal water supply. Computations are presented regarding the matching of flow rates, heat losses in distribution and energy savings. A number of benefits and penalties are also assessed qualitatively including legal and operational aspects and reliability. Especially attractive are improvements in electrical generating efficiency, and savings in water-heater energy. Secondary advantages include alleviation of pipe freeze up in winter and improved efficiency of slightly heated wastewater treatment. Penalties include additional pumping power for distribution in the water supply due to increased back pressure on the steam turbines which employ condensers cooled by the water they pump. Additional chlorine is also required to maintain a residual concentration in the distribution system. There may also be difficulties with public acceptance of water preheated by up to about 24 F, especially in summer.

The water supply of greater Chicago and 4880 MW(e) of colocated fossil-fired load-following generating capacity were analyzed as a hypothetical test case. It was concluded that the net annual energy savings is 23×10^{12} B, equivalent to 4 million bbl of oil, with a net savings in cost of \$12./capita for the population of 4.66 M. While not developed for energy conservation purposes, three actual systems with operating experience are summarized. In order to determine feasibility of application, site-specific systems analysis is required.

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INTRODUCTION

It is well known in power engineering that for every unit of electrical energy generated in a steam-electric power plant, approximately two units of heat energy must be rejected to the environment. Nearly 30% of the total U. S. energy consumption is for generating electricity, and almost all of this in thermal plants [1]. Consequently, about 20% of the total U. S. energy consumption goes into waste heat of electric generating stations. The possibility of recovering even a small portion of this energy, perhaps the largest locally concentrated source of waste heat, is attractive.

Unfortunately, the relatively low temperatures required in conventional steam condensers preclude many utilization schemes. Cooling water is typically heated by only about 25 F in most plants. The present paper concerns the possibility of alleviating these problems, while still deriving benefits, by discharging heated once-through cooling water from condensers directly into a municipal supply. The principal direct beneficial use of waste heat in this scheme is the savings in water-heater energy input. Also important is the energy savings in using once-through cooling of power-plant condensers rather than closed-cycle cooling towers or cooling ponds which result in higher turbine back pressures, reduced thermal efficiency and greater fuel consumption. If the steam-condenser coolant flow rate does not exceed the water-supply flow rate, the capital and operating costs of closed-cycle cooling can be saved as well.

However, the pumps of water-supply systems are often driven with steam turbines also operating in the condensing mode. The condensers

are cooled by the pumped water. Therefore, an increase in water-supply temperature will result in a penalty offsetting in part the gain at the electric generating station*. However, in the hypothetical test case considered in the present report this penalty is only 10% of the savings in cost and 17% of the savings in energy, of that of the electric generating station.

Additional penalties and benefits may occur in the water supply system. For example, chemical requirements will be affected by water temperature, and some will increase while others will decrease. The problem is complicated by the effect of factors such as pH. In the present report, we discuss some previous studies in this area. However, for the evaluation of the hypothetical test case we adopt an empirical approach based on operating experience in Chicago. A byproduct benefit would be the alleviation of pipe freeze-up in winter, as demonstrated in one of the actual case studies cited. On the other hand, the increased temperatures could increase thermal stresses, corrosion and deposits in the piping systems although no such effects have been reported in the several operating water supplies using preheated water.

Multiple use of water resources and the elimination of evaporative consumption in power-plant cooling are attractive in the larger view of conservation. Also significant is the elimination of local environmental effects of heat and humidity discharges to the atmosphere near the plant site.

A basic question to be considered is whether the various benefits and penalties justify possible implementation on the basis of cost and

*The author is indebted to Arthur Horwitz, Engineer of Water Pumping, City of Chicago, for pointing out this problem.

energy savings. For this purpose we have defined a hypothetical test case based on the water-supply system of the City of Chicago which serves a population of 4.66 million in the city and suburbs. It should be understood that this selection was made solely for convenience due to the ready availability of data, and the author is not proposing the present system be employed in Chicago. Indeed, Chicago is not well suited for the system because the existing local urban electric generating stations employ once-through cooling already and are not colocated with the present filtration plants. Further, as discussed below, implementation would be facilitated by municipally owned electric and water utilities which is not the case in Chicago. Nevertheless, the hypothetical test case does illustrate the values of parameters that might be encountered in a metropolitan area as well as the application of heat transfer and thermodynamic principles involved. To a large extent the results would be transferrable to other communities on a per-capita basis of the water supply, assuming similarly matched colocated systems.

In the next sections, potential energy and water savings as well as legal and operational problems are briefly summarized. It should be emphasized, however, that the present investigation was mainly concerned with the principal thermal effects, energy savings and economic advantage if any. These considerations are dealt with in the next chapter, followed by a discussion of the case studies and by the conclusions.

Potential Energy and Water Conservation

About 4% of the U. S. energy consumption is due to residential and commercial water heating [2-4]. Overall efficiencies are currently about 56% [5]. Until recently water heaters have been set at about 140 F. Assuming an intake temperature of 55 F, preheating the water by 25 F

would save 29% of useful water-heater energy. The potential savings is therefore $(0.29)(0.56)(4) = 0.65\%$ of present U. S. energy consumption. Recently, energy conservation practice has resulted in many water heaters being set as low as 100°F. In this case, the potential savings would be 56% of useful energy. The development of more energy-efficient water heaters will minimize storage losses. In newer gas units, the efficiency is about 72% less 1%/hour of storage while for electric it is 98% less 4%/hour [6,7].

An additional savings would occur due to improved electrical generating efficiency. As discussed later, once-through rather than closed-cycle cooling saves about 1.5% of fuel requirements. On the basis of 30% of U. S. energy consumption being due to electricity, the potential savings is $(0.3)(1.5)$ or 0.45% of U. S. consumption. However, as noted below, sufficient water-supply capacity exists to cool only 20% of all electric power plants. The net savings potential is therefore $(0.20)(0.45)$ or 0.09%. The combined potential savings between water heaters and electric power plants is thus $0.65 + 0.09 = 0.74\%$ of present U. S. energy consumption.

An additional factor is water resource management. The average per capita water consumption is 150 gpd [8]. Based on 33% thermal efficiency, 1 kW(e) per-capita electrical consumption, and a 25-F rise in cooling-water temperature, the per-capita condenser flow is 790 gpd which is about 5 times the water-supply rate. In a typical closed-cycle cooling system about 2% of the circulating flow is lost by evaporation. Ordinarily, this would be an amount equivalent to about 10% of the average water-supply rate.

Many regions of the U. S. are short of water of this magnitude.

By discharging into the closed conduit of a municipal supply, consumption by evaporation in the cooling system is essentially eliminated.

The fact that the per-capita condenser flow exceeds the per-capita water-supply flow means that only a few (20%) of the generating stations could be potentially cooled entirely by water supplies. However, even this is a substantial potential. Those generating stations located at or near water supplies could be selected for the application. Thus, in the present test case we assume colocated systems. Of course, some of the economic advantage could be used to justify transmission although this would reduce the benefit in relation to cost.

Considering the increased requirements for zero discharges in the 1985 standards of the Federal Water Pollution Control Act [9], increases in electrical demand, and shortages of water [10,11], multiple use of water is attractive in order to reduce costs and conserve resources. The proposed scheme is particularly attractive in the sense it is essentially passive. No special equipment, technology or large investment is involved in the basic scheme.

Legal and Operational Problems

There appears to be no legal temperature restriction on discharges from power plants into municipal water supplies [12]. However, there are limits on pH, residual chlorine, rust inhibitors, etc. as governed by the Safe Drinking Water Act [13]. Recent developments in anti-surface-tension agents allow the necessary chlorine dosages to be reduced to extremely low levels and still prevent biological fouling of steam condensers [14]. Chlorine is also added during water-supply treatment, and it is necessary to maintain a residual concentration throughout the distribution system for sanitary purposes. In the event of accidents

involving contamination at the power plant, provisions should be made to alert the filtration plant in order to adjust treatment or switch to an alternate supply.

If the electric power plant was placed downstream of the filtration plant, no such warning would be possible before contamination occurs. However, the power plant would benefit from the clean municipal water and the subsequent reduced fouling of the steam-condenser tubes.

In any case, the present political and social implications of nuclear power probably prohibit use of this form of energy in the system under evaluation due to possible radiation leaks in the event of an accident. While cooling water is in either a second or even third loop removed from the reactor, this possibility does exist. However, according to Oliker [15], a nuclear plant in Europe is currently providing district heating, and more such plants are under design and construction. Nevertheless, a fossil-fueled plant will be studied here.

Typical power plants operate at 70-80% capability [16] whereas municipal supplies are seldom out of service. The municipal supply should maintain a conventional source of water in the event of planned and forced outages of the power plant. A stand-by cooling system for the electric power plant should not be required.

The flow in a municipal supply may peak on a daily basis at 150% of the annual average and range on a hourly basis from 25-300% of the daily average [4,17]. It is clear that a basic problem exists in matching a base-load electric generating station, intended to operate at as nearly full power as possible, with the variable water supply. If we utilize a stand-by closed-cycle cooling system for periods of low

municipal flow, we lose some of the economic advantage due to the capital investment in that equipment. Conversely a power plant sized to minimum municipal flow would be relatively small because of the already large ratio of per-capita condenser flow to water-supply flow (5:1).

It follows that the principal advantage would occur with a load-following power plant. Ideally, condenser flow would be modulated simultaneously with electrical demand and the water-supply flow, with a uniform rise in water temperature. In a load-following electric power plant, the ratio of average to peak power is about 50%. Data for the City of Chicago in 1976 [17] also indicate an identical ratio in terms of peak hourly water-supply demand to the annual average value. The hourly, daily and monthly variations show similar variation to mid-western-utility electrical-demand patterns. For the present hypothetical test case, we assume the flow rates are perfectly matched. In reality, small differences in electrical and water-supply demand profiles could be compensated by fixing the condenser flow at the municipal supply rate and allowing the rise in temperature to vary slightly. The matching of water flow rates will be an important criteria in site selection. In a site-specific assessment study, the requirements for any conventional cooling capacity and/or the effect of dilution of preheated water with unheated water from a conventional water source should be accounted for according to the demands of both plants.

Obtaining the necessary cooperation between the power and water utilities would be facilitated in municipalities where they are commonly owned and, ideally, commonly located. If closed-cycle cooling, such as mechanical-draft towers would be otherwise employed, operating costs

would be reduced for a private or public utility. In any case, once-through cooling will increase thermal efficiency and avoid de-ratings under extreme environmental conditions. Therefore, there may be sufficient economic advantage to the electric utility to finance the venture in terms of the interconnection. Because both power plants and water filtration plants currently employ intake structures, and some of these could be shared in a new installation, we have not accounted for the cost of interconnection in the present study. However, a portion of the computed savings could be considered as necessary return on investment for the interconnection and transmission costs that may be required.

As determined in the hypothetical test case, the water-supply system will suffer energy and economic penalties while the electric utility and the water users would generally gain. In the case of municipally owned utilities an offset of the benefits and penalties would be facilitated. Otherwise it would appear necessary for the electric utility to compensate the water supply, perhaps by supplying make-up electric power at no charge. It is felt that the savings in water-heater energy should be left to the consumers to compensate for the inconvenience of preheated water for drinking, etc. Indeed, in the present case we also compute the estimated net savings to the water-supply consumer assuming all net savings are passed on. However, the water-heater energy savings appear to dominate and not much difference would occur if all of the electric power consumers shared the generating savings less water-supply penalty. We estimate the justifiable transmission distance based on this net generating savings constituting an acceptable return on investment by the utility.

A final question is whether the consumer would accept water preheated

by about 24 F. Bottled-water companies indicate that a family of four uses about 10 gallons per month of water for drinking purposes. This water could be refrigerated or simply left to stand in order to cool, if private water service was not desired or could not be afforded. The energy required for refrigeration is shown to be negligible compared with water-heater savings. Other problems include possible odors which tend to increase with temperature over a certain range, as discussed below. Further, a few residential, commercial and industrial water-supply users may cool equipment with municipal water. However, according to Kammerer [4] this practice is unusual. While the use of unmetered municipal water for once-through cooling may be attractive to the individual, this approach is clearly not in the interest of managing national water resources. However, in the event of a site-specific application, consideration should be given the trade-off between cost of metered water and installation of cooling towers or similar equipment. Appropriate compensation may be in order in certain cases. Final acceptance may depend on the economic advantage and to whom the advantage accrues. It is hoped that the present work will illuminate the issues that must be considered prior to any attempt at implementation.

THERMAL and ECONOMIC EFFECTS

In this chapter we consider the effects of discharging heated once-through condenser cooling water into a municipal supply from the point of view of:

1. Power Plant
2. Transmission
3. Water Supply
4. Water Heaters
5. Wastewater Treatment
6. Overall System

While we subsequently assume the power plant and the filtration plant to be colocated, the section on transmission discusses the magnitude of temperature drop that might otherwise be encountered and the section on the overall system estimates the justifiable transmission distance. The section on the water supply includes losses in distribution within that system.

In each case, we discuss the applicable thermodynamic and heat-transfer principles. As an example, these are applied to the hypothetical test case mentioned in the Introduction: the City of Chicago water supply and a fossil-fired electric generating station of a similar load-following characteristic. The principal energy and cost savings are estimated for each of the above system segments, and for the combined overall system. As noted in the Introduction, not all conceivable effects have been analyzed in the present study and additional factors should be considered in an actual site-specific application.

The City of Chicago water supply is under the management of the Department of Water and Sewers. Most of the technical specifications were obtained from an annual report [17] available at the beginning of the study. While additional relevant data is presented in the individual sections, the water supply has the following general characteristics (1976):

population served	4.66 M
average pumpage	1024 Mgp/d
peak hourly pumpage	2025 Mgp/d
installed capacity	2995 Mgp/d
average power, electric	38.8%
average power, steam	61.2%
filtration plants	2
pumping stations	11
miles of distribution	22 Mft

The source of water is Lake Michigan, on which the two filtration plants are located. The system serves the City of Chicago plus a number of suburbs.

Power Plant

For the purpose of the evaluation, two typical modern steam-turbine-generator combinations were initially considered, one nuclear-fueled [18] and one fossil-fueled [19]. These units are available in multiples of about 1000 MW(e) capacity. The data provide the unit heat rate and power output as a function of steam-condenser back pressure. The net heat rate is the ratio of fuel energy to electrical energy output.

The steam condensers were analyzed using the NTU method and the recommended design criteria of the Heat Exchanger Institute [20]. The

sizes were fixed with a 25-F rise in cooling water temperature at the design point and required 0.288 and 0.570 Mgal of water coolant for fossil and nuclear fuel, respectively. Alternative atmospheric-spray systems, evaporative cooling towers and cooling ponds were sized according to simple one-parameter models [21, 22, 23] and meteorological conditions [24,25] not exceeded more than 5% of the time during summer in Chicago. All three systems behaved similarly under off-design conditions when sized to the same design point. Consequently, a single composite closed-cycle cooling-system model was developed which approximated the thermal performance of the individual devices. This approach reduced the number of thermal analyses to be performed. The rise in cooling water temperature was found to be relatively constant at the design value of 25 F. Subsequent economic analysis did allow for differences in costs among the various cooling systems. The above study was reported in Reference 26.

Results in terms of efficiency are summarized in Table 1. The major interest for energy conservation is the advantage in heat rates of once-through cooling over that of closed-cycle systems. The net heat rate is simply the reciprocal of efficiency as a fraction. The percentage savings in heat rate are also shown in the table for once-through cooling. The savings in heat rate can be considered to be the savings in fuel in generating a given amount of electrical energy. These savings range from 0.6-1.5% for fossil fuel and 1.5-2.5% for nuclear with the most advantage in summer. The annual savings is 1% for fossil fuel and 1.9% for nuclear, which is larger due to its lower efficiency. However, fossil fuel is usually far more expensive and the savings in cost would be greater accordingly.

Table 1. Comparison of Seasonal Performance of Typical 1000 MW(e) Generating Units with Alternate Cooling near Chicago [26]

	Fossil Fuel		Nuclear Fuel	
	Once-through	Closed-cycle	Once-through	Closed-cycle
<u>Summer</u>				
Condenser Intake (F)	73.8	85.8	73.8	85.8
Turbine Back Pres. (in Hg)	2.2	3.1	2.2	3.1
Thermal Efficiency (%)	43.4	42.8	31.7	30.9
Savings in Heat Rate (%)	1.5	-	2.5	-
<u>Spring-Fall</u>				
Condenser Intake (F)	55.9	78.3	55.9	78.3
Turbine Back Pres. (in Hg)	1.2	2.5	1.2	2.5
Thermal Efficiency (%)	43.6	43.2	32.1	31.5
Savings in Heat Rate (%)	0.9	-	1.8	-
<u>Winter</u>				
Condenser Intake (F)	34.5	72.5	34.5	72.7
Turbine Back Pres. (in Hg)	1.0	2.1	1.0	2.1
Thermal Efficiency (%)	43.7	43.4	32.2	31.7
Savings in Heat Rate (%)	0.6	-	1.5	-

The literature was reviewed for the costs of capital equipment and operation of the various type cooling systems. Added to the cost was the loss in generated electricity at a replacement charge of \$0.015/kWh(e) to the utility. The charge accounted for both the power needed to operate the equipment and the loss in generating capacity due to elevated turbine back pressure. The incremental "cost of cooling" for plants

with closed-cycle cooling as compared with once-through cooling is given in Table 2 [26].

The present cost of electricity to the consumer in the Chicago area is about \$0.04/kWh(e). If passed along to the consumers, the savings would range up to about 2%, assuming half nuclear-fueled plants and half fossil-fueled plants and based on mechanical-draft wet cooling towers. The annual-average fuel energy savings would be about 1% based on Table 1.

Table 2. Incremental Cost of Cooling for Typical 1000 MW(e) Generating Units near Chicago (1980\$) [26]

Cooling System	Cost (mills/kWh(e))	
	Fossil Fuel	Nuclear Fuel
Cooling Pond	0.30	0.58
Spray Canal	0.57	1.02
Mechanical-Draft Wet Tower	0.61	1.15
Natural-Draft Wet Tower	0.55	1.01

We now consider the hypothetical system of a load-following fossil-fueled power plant discharging into a municipal supply, namely that of the City of Chicago. The condenser flow is 0.288 Mgal/min/1000-MW(e) output based on the design of Reference 26. Thus, for the City supply of average flow 1024 Mgal/day or 0.711 Mgal/min, the average power output of the hypothetical power plant is

$$0.711 \text{ Mgal/min} / (0.288 \text{ Mgal/min} / 1000 \text{ MW(e)}) = 2470 \text{ MW(e)}$$

Assuming a 51% load factor of average output relative to peak output, identical to that of the water supply, the rated power output of the plant may be taken as 4800 MW(e), say 4 1200-MW(e) generating units. Under rated power, the total condenser flow rate would be 1.41 Mgpm as matched to the peak water-supply flow rate. In reality, 4800 MW(e) of generating capacity is rather large for a load-following power plant. However, this could be considered split between the two filtration plants in the hypothetical system.

Assuming mechanical draft cooling towers and 8766 hrs/year of average operation, the savings in cost of cooling is

$$2470 \text{ MW(e)} \times 8766 \text{ hr} \times 0.00061 \$/\text{kWh(e)} = \$13.2 \text{ M}$$

in 1980 dollars. If credited to the water-supply population of 4.66 M, the annual savings is \$2.83/capita. The annual energy savings can be computed by using the typical heat rate of 10,000 B(th)/kWh(e). For a 1% savings

$$0.01 \times 2470 \text{ MW(e)} \times 8766 \text{ hr} \times 10,000 \text{ B/kWh} = 2.11 \times 10^{12} \text{ B}$$

Frequently, savings of this type are translated into equivalent barrels of oil with the same energy content, assuming $0.172 \text{ Mbbbl}/10^{12} \text{ B}$ [1]. The annual energy savings here is equivalent to 0.363 Mbbbl.

The discharge of once-through cooling water is now considered to be transmitted to the municipal water supply, preheated by 25 F over the ambient supply water temperature.

Transmission

If the plants are not colocated, transmission could be by buried pipe or open channel. Heat transfer from buried pipe is complex involving possible mass transfer due to thermal and moisture gradients and capillary action, which are all affected by the type of soil [27]. However, we can estimate the temperature drop of heated water using simple engineering formula.

The heat transfer rate per unit length from a buried pipe of diameter d , depth D to the top of the pipe, temperature T , ground surface temperature T_G and thermal conductivity k_G is

$$dq/dx = -S k_G (T - T_G) \quad (1)$$

where S is the shape factor [28]

$$S = \frac{2\pi}{\cosh^{-1} \frac{D + d/2}{d/2}} \quad (2)$$

While the thermal conductivity for soil ranges from 0.2 B/hr-ft-F to 1.5 B/hr-ft-F [29], a typical value of

$$k_G = 0.5 \text{ B/hr-ft-F}$$

is used here. It is apparent that attention needs to be given this variable in specific applications because it seems to be potentially wide ranging.

Using Eq. (1) an energy balance may be performed on the flowing water of mass flow rate $\dot{m}$. Thus, combining (1) with

$$dq/dx = \dot{m} c_w dT/dx \quad (3)$$

and integrating from T_1 to T_2 over a length L

$$(T_2 - T_G)/(T_1 - T_G) = \exp (-S k_G L/(\dot{m} c_w)) \quad (4)$$

where c_w is specific heat of water (1 B/lbm-F).

In order to estimate the importance of the loss between the power plant and filtration plant we assume annual average conditions. Because Chicago has two filtration plants, each is assumed to receive half the total flow in two separate buried pipelines. The conditions are:

$$\begin{aligned} T_1 &= 80 \text{ F} \\ T_G &= 55 \text{ F} \\ \dot{m} &= 0.51 \times 10^9 \text{ gpd} \\ \left. \begin{aligned} d &= 20 \text{ ft} \\ D &= 10 \text{ ft} \end{aligned} \right\} S &= 3.57 \end{aligned}$$

The resulting temperature drop $T_1 - T_2 = 0.13 \text{ F}$ over a length $L = 100$ miles.

If open channel flow were used, the losses would be much greater. For example if each channel were 80 ft wide and if we assume [23] a surface exchange coefficient of $150 \text{ B/da-ft}^2\text{-F}$ and a natural equilibrium temperature of 55 F, the temperature drop over only 10 miles increases to 3.5 F.

In the present analysis, we assume that the plants are colocated

such that no significant interconnection cost or thermal loss is present in either case. Thus, the full 25-F increment over the ambient water temperature is assumed as being delivered to the filtration plant and distribution system.

In the concluding section of this chapter, the justifiable distance of transmission is estimated based on the various savings.

Water Supply

We analyze the water supply effects in three parts:

1. filtration
2. pumping
3. distribution

Filtration. Renn [30] has summarized the effects of increased temperature on municipal supplies:

1. The rates of organic-matter decomposition, oxygen demand and carbon dioxide generation are increased.
2. Pathogenic organisms survive shorter periods.
3. Activity of disinfectants and demand of chlorine increase.
4. The proportion and odor of blue-green algae are increased.
5. Density and viscosity decrease.
6. Alum flocculation and precipitation are more efficient.

It would appear that Items 1-3 would be favorable and that savings in treatment chemicals may accrue. The cost of all chemicals except alum used for floc, discussed below, was \$3.60 /Mg (\$/million gallons) for

Chicago in 1976 [17] which we use as the example for the present evaluation. The present cost is about \$0.30/year on a per capita basis or \$1,350,000 for the entire Greater Chicago system. However, evaluation of possible savings is complicated by the effect of pH which often simultaneously changes with temperature. Further, in the case of chlorine, chemical dosage needed for disinfectant at the plant may decrease but dosage to maintain a residual concentration throughout the system may increase. This effect is discussed separately below.

In any case, it is felt that no advantage can be gained for the size of facilities because of the need for full capacity in the event of outages of the associated power plant.

In the case of Item No. 4, the optimal temperatures of blue-green algae are 60-80 F while Chicago water is about 35-70 F. Applying a 25-F rise brings the Chicago range to 60-95 F. Based on the seasonal intake water temperatures discussed in the next subsection, the blue-green algae range would be encountered 57% of the time rather than 29% of the time as at present. Odors would be favored in winter rather than summer. To the author's knowledge and experience, odors are not currently a problem in the City even in the summer. Thus, a doubling of the time in which blue-green algae are favored may not be serious.

The effect of temperature on density and viscosity (Item No. 5) is such to favor settling and permit more rapid filtration. However, it is again felt that no advantage can be claimed in design capacity due to the possibility of power outages. While Renn [30] indicated possible savings in alum used as a flocculant (coagulant) to remove fine impurities, a more detailed experimental study by Camp, Root and Bhoota [31] noted that the floc requirement at optimal pH was virtually unchanged with temperature. Thus, no advantage in alum dosage can be claimed at present

The above considerations suggest some savings may occur except for increased chlorine required to maintain residual concentration. Because the savings are probably small and would be difficult to estimate, only a penalty for increased chlorine is included. This penalty is estimated based on present trends in the system under study [17].

An inspection of the monthly records indicates that the present range of chlorine dosage is as given in Table 3. This data suggests a temperature coefficient of 0.16 lbm/Mgal-F based on present low and

Table 3. Chlorine Dosage for City Supply

Condition	$T_1 - F$	Dosage - lbm/Mgal	
		Unheated [17]	Heated
low	32	10.0	14.0
high	72	16.5	20.5
average		13.4	17.4
maximum		16.8	20.8

high monthly values. It is assumed that the present dosage is just adequate to maintain the necessary residual concentration, and that an extrapolation of 62% of the present temperature range is acceptable. Based on these assumptions, the values for heated water are also shown in Table 3.

It is the author's understanding that some water supplies have difficulty in not exceeding allowable chlorine concentrations. Increased

dosages at the filtration plant may not be acceptable for the purpose of maintaining residual concentration throughout the system. In this case, it may be possible to augment the dosage at the pumping stations.

In the present case, we use the above estimates to determine the additional cost of chlorine. Present cost (1976) is \$1.22/Mgal which we adjust to \$1.67/Mgal in 1980 dollars used throughout the present study [26]. The average dosage will be increased by 30%, to \$2.18/Mgal. Resulting cost data are summarized in Table 4.

Table 4. Effect of Increased Chlorine on Annual Cost (1980 \$)

Item	Annual Cost
Present Cost	
375 x 10 ⁹ gal @ \$1.67/Mgal	\$0.626 M
Per capita of 4.66 M	\$0.13
New Cost	
375 x 10 ⁹ gal @ \$2.18/Mgal	\$0.814 M
Per Capita of 4.66 M	\$0.17
Increased Cost	
Total	\$0.188 M
Per Capita	\$0.04

As discussed in the chapter on case studies, no problems are reported in water treatment in the several existing systems. At the same time, documentation of thermal effects on a quantitative basis are apparently not available. In the event of any planned implementation of the

proposed system, it would be highly desirable to include a detailed assessment of this previous experience.

Pumping Power. Present energy requirements are listed in Table 5.

The thermal power provided by steam will be affected because the pumped water is used to cool the steam condensers. Accordingly, there will be a rise in the required heat rate and attendant increases in energy consumption and fuel cost. As discussed in the next section, the losses in distribution are relatively small. Therefore, it will be assumed that the full 25-F rise in temperature of pumped water will occur at the pumping stations. Actually, a small amount of cooling makes this assumption conservative.

Table 5. Present Annual Energy Consumption in Pumping [17]

Fuel	Amount	Energy-MMWh(th)
Coal @ 13.8 kB/lbm	27.6 ktons	0.223
Gas @ 100 kB/therm	22.4 Mtherm	0.656
Oil @ 132 kB/gal	38.7 kgal	<u>0.001</u>
Total Thermal (Steam)	-	0.880 (74%)
Electric @ 10 kB/kWh(e)	107 MkWh(e)	<u>0.313</u> (26%)
Total	-	1.193

The effect of turbine back pressure on energy required is determined by noting that the turbine output per unit mass of steam is given by

$$w_t = \eta_t (h_1 - h_{2s}) \quad (4)$$

where η_t is isentropic efficiency, assumed constant, and h_1 is inlet enthalpy while h_{2s} is isentropic exhaust enthalpy. In the case of the city supply, water pumping turbines operate from 100-400 psi intake pressure.

In the present example we assume a typical value of 300 psia and saturated vapor ($h_1 = 1203$ B/lbm). At 2 in-Hg normal back pressure, $h_{2s} = 876$ B/lbm. However, as a consequence of raising the coolant temperature, the saturation temperature equivalent to the saturation pressure will rise in nearly direct proportion. Thus, the saturation temperature will rise from the present 101 F at 2 in Hg to 126 F at 4.1 in Hg. The resulting $h_{2s} = 914$ B/lbm. The turbine output will be reduced according to Eq. (4), by a fraction

$$(h_{2s'} - h_{2s}) / (h_1 - h_{2s}) = 0.116$$

or about 12%. Thus, about 12% more energy will be required to produce the same pumping, because the heat input is not appreciably increased when a given turbine experiences a change in back pressure of the expected amount.

The additional power could be obtained by increasing the throttle of present turbines or by adding additional pumping units on line. In either case, the present pumping system has 113% capacity above peak flow [17]. While some of this is no doubt necessary to provide the high degree of reliability currently enjoyed, an increase in present requirements by 12% does not seem prohibitive. In the present case, no capital charge is made for the additional pumping because of present excess capacity. Increased cost are determined by the additional fuel

required. Maintenance cost increments are neglected relative to that of the fuel.

Presently, 0.88 MMW(th) energy is required annually for thermal power (Table 5). This would increase by 11.6% or by 0.102 MMW(th). It is interesting to consider this energy to be made up by electric pumps so that we can compare it with the benefit at the power plant. Assuming a boiler-turbine efficiency of 34%, the 0.102 MMW(th) could be made up with only 0.0348 MMW(e). Based on 8766 hr/yr, the result is 4.0 MW(e) of average power. The savings at the power plant was 1% of 2470 MW(e) or 24.7 MW(e) which more than offsets the penalty.

Based on electric pumping, the extra annual fuel energy required at a net heat rate of 10,000 B/kWh(e) is 0.35×10^{12} B, equivalent to 0.06 Mbbl of oil. The cost of electricity for pumping was \$0.0228/kWh(e) in 1976 [17] which we adjust to \$0.0312/kWh(e) in 1980 dollars [26]. Consequently, the additional 0.0348 MMW(e) would cost \$1.09 M or \$0.23/capita on an annual basis. One approach would be for the electric utility to credit the water supply accordingly, perhaps with a further credit for increased chlorine, etc.

Distribution. In the system of interest, ambient water taken into a power plant is heated and discharged into a municipal water supply. The objective of the present analysis is to estimate the amount of temperature drop that may occur in the distribution system. For the present, quasi-steady operation is assumed. In the hypothetical example, seasonal performance is analyzed. Unsteady effects are discussed later.

A schematic diagram of the water distribution system is given in Figure 1. The system is assumed to be made up of M pipe elements, each of which has a diameter d_i , depth D_i and total length L . We consider for

Figure 1. Assumed Distribution-System Schematic for Maximum Heat Loss.

the sake of analysis that the number of pipes in parallel is N_i for each set. Thus the average length of pipe $\bar{L}_i$ and flow rate $\dot{m}_i$ are

$$\bar{L}_i = L_i / N_i \quad (5)$$

$$\dot{m}_i = \dot{m} / N_i \quad (6)$$

It is assumed that flow is equally distributed in the parallel paths.

The application of Eq. (4) to each element i yields the final temperature T_{2_i} in terms of initial temperature T_{1_i}

$$\begin{aligned} (T_{2_i} - T_G) / (T_{1_i} - T_G) &= \exp(-S_i k_G \bar{L}_i / (\dot{m}_i c_w)) \\ &= \exp(-S_i k_G L_i / (\dot{m} c_w)) \end{aligned} \quad (7)$$

which is independent of N_i . Thus more pipes in parallel have proportionately less flow, compensating exactly for reduced length of the parallel path.

The discharge of each section i represents the intake of each section $i + 1$. Overall, to the furthest extent of the system where the temperature is T_O (Figure 1)

$$\begin{aligned} (T_O - T_G) / (T_i + \Delta T_P - T_G) &= \prod_{i=1}^M \exp(-S_i k_G L_i / (\dot{m} c_w)) \\ &= \exp \left(-\sum_{i=1}^M (S_i L_i) k_G / (\dot{m} c_w) \right) \end{aligned} \quad (8)$$

We now consider the hypothetical example. The data for the present

distribution system result in

M

$\sum_{i=1}^M S_i L_i = 42,464 \text{ kft}$ as shown in Table 6. As discussed previously, it is assumed that the power plant elevates the ambient water by 25 F.

Ambient (T_i) and initial heated water ($T_i + \Delta T_p$) temperatures are listed in Table 7. Values for the soil temperature T_G at the depth at which the distribution pipes are buried, about 5-6 ft, were obtained from Soil Taxonomy, Agricultural Handbook No. 436, December, 1975 and are also listed in Table 7 for the Chicago area. Seasonal flow rates are listed based on Reference 17, as a ratio to the annual average of 1024 Mgd. The two filtration plants are analyzed as being in parallel in the present study. Using the seasonal temperature data, the resulting final distribution-system temperature of discharge T_o is given in Table 7. The losses in distribution of heated water for Summer, Spring-Fall and Winter are only 1.3, 1.4 and 1.4 F, respectively. The net increases in temperature above ambient are therefore 23.7, 23.6 and 23.6 F, respectively, in Summer, Spring-Fall and Winter. These data represent the worst case of most distant users. Users nearest the filtration plant would receive essentially the full 25-F rise. In the calculations that follow in the next section, we use one half of the maximum loss described above. Because the loss is very small, this arithmetic average and the true integrated average should not differ greatly.

For reference, the slight amount of heating or cooling of unheated water is also shown in Table 7. We will compare effects, with and without heating throughout the study. The net increases in water temperature T_o over the unheated values are 23.8, 23.5 and 23.4 F, respectively, for Summer, Spring-Fall and Winter and are remarkably constant.

Table 6. Distribution System for Chicago Water Supply (depth D is to top of pipe)

Pipe Diameter d_i (in)	Depth D_i (ft)	Length L_i (kft)	S_i	$S_i L_i$ (kft)
4	5	55	1.523	83
6	"	5,696	1.681	9,575
8	"	9,850	1.813	17,858
10	"	25	1.929	48
12	"	3,253	2.034	6,617
14	"	25	2.131	53
16	"	640	2.220	1,408
20	"	85	2.386	202
24	"	780	2.536	1,978
30	"	271	2.741	743
36	"	858	2.928	2,512
42	6	91	3.102	282
48	"	271	3.045	825
54	"	43	3.184	137
60	"	43	3.316	143
Total	$L =$	21,987 kft	$\sum S_i L_i =$	42,464 kft

Table 7. Hypothetical Thermal Data for the Water Distribution System in Chicago

Quantity	Summer		Spring-Fall		Winter	
	Unheated	Heated	Unheated	Heated	Unheated	Heated
Ambient Water $T_i - F$	70.0	70.0	48.9	48.9	33.1	33.1
Intake Water $T_i + \Delta T_p - F$	70.0	95.0	48.9	73.9	33.1	58.1
Ground $T_G - F$	68.0	68.0	51.1	51.1	36.0	36.0
$\dot{m}/\dot{h}$ (annual)	1.17	1.17	0.956	0.956	0.916	0.916
Discharge (extreme)* $T_o - F$	69.9	93.7	49.1	72.6	33.2	56.6
Distribution (extreme)* $\Delta T - F$	-0.1	-1.3	0.1	-1.4	0.2	-1.4
Overall (extreme)** $\Delta T - F$	-0.1	23.7	0.1	23.6	0.2	23.6
Net (extreme)*** $\Delta T - F$	-	23.8	-	23.5	-	23.4

* Change in temperature across entire distribution system.

** Overall change relative to ambient water.

*** Net change relative to unheated water.

It should be noted that the temperature and flow variables used here are seasonal averages. Hourly flow can vary by a factor of two or more from the average. Unsteady effects may be determined by knowing the hourly flow rates. The above steady-state analysis may be adopted for the unsteady case neglecting the heat capacity of the ground if we use the Lagrangian view point and replace

$$\dot{m}_i \rightarrow M_i/t_i \quad (9)$$

where M_i is mass of water in element i and t_i is element residence time. By knowing the system flow-rate history, the values of t_i can be computed throughout for any system discharge time. The overall system residence time under average flow conditions is 4.2 hrs. Because hourly flow variation involves characteristic times of this order, unsteady effects could be important on this basis. However, because the cooling in the system is very small compared with the temperature rise, the net result will come out essentially the same. That is, the system will behave linearly, and the temperature based on average flow will be practically the same as the mass-average temperature based on unsteady flow. Periods of low ΔT due to high flow will be virtually compensated by periods of high ΔT due to low flow. The storage effect of the ground will be to damp these variations even further.

Inspection of the governing equation (8) indicates that the cooling range scales with $T_i + \Delta T_p - T_G$. Thus, the present results can be modified for other temperatures in direct proportion to this factor, for the same distribution system. Further, correct to first order error of a series expansion, the cooling range is proportional to the exponent of

the Napierian base of Eq. 8. The result is that the cooling range $T_o - T_i - \Delta T_p$ is effectively inversely proportional to flow rate in a given system. This approximation will be valid so long as the cooling range is small compared with $T_i + \Delta T_p - T_G$.

Water Heaters

In this section, we consider an average water user with intake temperature $\bar{T}_o$

$$\bar{T}_o = (T_o + T_i + \Delta T_p)/2 \quad (10)$$

which is averaged between the state near the filtration plant and the end of the system. Values for the hypothetical example are given in Table 8. First we consider the losses between the intake of the user and the water heater, and then the effect of preheated water on energy consumption. Residential, commercial and industrial service water heaters are treated on the same basis. Large users of process heat involving water would require special treatment.

Only a portion of the water taken into the user's facility will be heated in a water heater. Typical residential conditions are assumed. As discussed in the Federal Register, October 4, 1977, the U. S. average hot-water usage is 64.3 gpd for the average family of four, as determined by a survey of 100 utilities. Therefore, on the basis of 150 gpd/capita, about 11% of the water will be heated. For the sake of analysis, it is assumed that a single line carries this flow to the water heater. Actually, a main may serve several devices including the water heater, and the actual temperature drop would be less due to the greater flow rate. Therefore, the present calculation is generally conservative from

Table 8. Hypothetical Thermal Data for Water-Heater Analysis

Quantity	Summer		Spring-Fall		Winter	
	Unheated	Heated	Unheated	Heated	Unheated	Heated
Water Intake						
$\bar{T}_O - F$	70.0	94.4	49.0	73.3	33.1	57.3
Flow Rate						
$\dot{m}_H - \text{gpd}$	75.2	75.2	61.5	61.5	58.9	58.9
Heater Intake						
$T_C - F$	70.0	92.2	51.3	72.9	37.3	58.7
Useful-Energy						
Savings - %	-	30	-	23	-	20
Net-Energy						
Savings - %						
Gas	-	19	-	13	-	11
Electric	-	28	-	21	-	18

the point of view of computing energy savings so long as the water temperature is greater than that of the surrounding space. Because the line is normally in a basement or unheated/uncooled space, the effect of heat transfer on heating and air conditioning will be neglected.

For the purposes of considering the above losses, we assume a 25-ft, 1-in-outside-diameter line carrying the water to be heated in the home. For the horizontal pipes usually employed, the heat-transfer coefficient in natural convection for the expected laminar-flow regime is given by [28]

$$\bar{h} = 0.27(\overline{\Delta T}/d_o)^{1/4} \quad (11)$$

where $\overline{\Delta T}$ is the average temperature difference between the pipe outside-surface temperature and the space air temperature, and d_o is the pipe outside diameter (B-hr-ft units) including insulation. Most present cold-water lines are insulated to avoid condensation. Because, reducing losses is favorable using heater water, the use of insulation is assumed here for both unheated and heated water. The primary thermal resistance is due to the insulation. For typical 1-in thickness of fiberglass, the conductance per unit length of insulation is [28]

$$\begin{aligned} K_i &= 2\pi k_i / \ln(d_o/d_i) \\ &= 2\pi(0.038 \text{ w/m-C}) / \ln 3 \\ &= 0.125 \text{ B/hr-ft-F} \end{aligned} \quad (12)$$

For typical $\overline{\Delta T} = 6 \text{ F}$, as discussed below, the convection conductance per unit length $h \pi d_o = 0.469 \text{ B/hr-ft-F}$ which results in an overall conductance determined by adding resistances in series and then taking the reciprocal. Thus

$$K = (K_i^{-1} + (\bar{h} \pi d_o)^{-1})^{-1} \quad (13)$$

$$= 0.0987 \text{ B/hr-ft-F}$$

The $\overline{\Delta T}$ chosen above corresponds to about 1/3 of the average overall (initial) ΔT between water and space-air temperatures which is consistent with the thermal resistance for convection $(\bar{h} \pi d_o)^{-1}$ being about 1/3 of the overall resistance K^{-1} . Because $\bar{h} \propto \overline{\Delta T}^{1/4}$ and the convection resistance is generally small compared with that of insulation, use of the constant K given above should give adequate results.

Applying Eq. (13) to the energy balance on the water with mass flow rate $\dot{m}_H$

$$\dot{m}_H c_w dT/dx = K (T_a - T) \quad (14)$$

where T_a is the surrounding air temperature, taken here as 70 F. Integrating Eq. (14) from the user inlet ($T = \bar{T}_O$) to the water-heater inlet ($T = T_C$) over a length L

$$(T_C - T_a) / (\bar{T}_O - T_a) = \exp(-K L / (\dot{m}_H c_w)) \quad (15)$$

Computed values of T_C are given in Table 8 based on $\dot{m}_H = 64.3 \text{ gpd}$ adjusted

for the seasonal flow-rate ratios of Table 7.

The savings in useful-energy consumption for elevating water temperature will be directly proportional to the reduction in required ΔT across the water heater. We assume that the final outlet water-heater temperature is 145 F in the hypothetical example. Results are listed in Table 8. It is reasonable to assume that these percentage savings include losses of heating the water up to 145 F, but not holding it there in storage. The ratio of heat input required to elevate water temperature to heat input required to elevate and maintain water temperature is dependent on the residence time t according to

$$Q_{\Delta T}/Q = (\eta_{\Delta T} + 0.5 t \, dn/dt)/\eta_{\Delta T} \quad (16)$$

where $\eta_{\Delta T} = 0.72$ and 0.98 and $dn/dt = -0.04$ and -0.01 hr^{-1} , for gas and electric heaters, respectively [6].

Assuming a standard 40-gal tank and the flow rates of Table 8, the seasonal flow residence times t are 12.8, 15.6 and 16.3 hrs. for Summer, Spring-Fall and Winter, respectively. As a result, the ratio of heat-energy input required to elevate water temperature to total heat-energy input for service requirements, $Q_{\Delta T}/Q$, is found from Eq. (16) to be 0.64, 0.57 and 0.55 for gas in Summer, Spring-Fall and Winter, respectively, and 0.94, 0.92 and 0.92 for electric in Summer, Spring-Fall and Winter, respectively. The difference between gas and electric units is due to electric heaters being nearly 100% efficient in directly heating the water, whereas gas units have stack and other losses. However, heat losses through the water-heater walls are similar. In both cases, the percentage of savings of useful energy discussed above must be reduced

by the fractions just given to obtain actual savings in energy. Results are shown in Table 8 for the hypothetical example. The annual average savings are reduced to 14% and 22%, for gas and electric units, respectively. Assuming equal numbers of each type unit, the overall savings is 18% of total water-heater energy input.

The heat energy required to maintain water temperatures is not conserved by using preheated water. In principle, it would be possible to either eliminate the losses during storage by increasing insulation or to reduce the flow residence time to zero by eliminating storage and then heating the water only when it is needed. In either of these cases, the energy savings using preheated water increases to 24%. Commercial water heaters are likely to be already more efficient due to their larger size with an expected smaller surface area to volume ratio. In addition, it is feasible to turn them off when not in use, at least in certain non-residential cases.

It is interesting to note that the seasonal savings are anticipated to be greater in Summer where water requires less heating range than in Winter (Table 8). Most beneficial uses of waste heat are considered to yield the reverse effect. Thus, the present scheme may be complementary to other concepts of waste heat utilization.

The present energy consumption for hot-water heating may be determined by using the efficiency formula

$$\dot{Q} = \dot{m}_H c_w \Delta T / (\eta_{\Delta T} + 0.5 \pm d\eta/dt) \quad (17)$$

for both gas and electric units. Using the aforementioned efficiency data and the required temperature rise for non-preheated water from

Table 8, gas annual energy consumption is 378 therms and electric annual energy consumption is 6017 kWh(e), each per family of 4. Assuming equal number of units of each type, 14% savings for gas and 22% for electric, and an electric power net heat of 10,000 B/kWh(e), the annual savings for a population of 4.66 M is 21.6×10^{12} B (equivalent to 3.71 Mbbbl of oil) assuming a comparable prorating over the entire system.

Based on gas at \$0.308/therm and electricity at \$0.0474/kWh(e), the savings per family of 4 is \$16.32 for gas and \$62.71 for electric. The average annual savings is therefore \$9.88 per capita and \$46.0 M for the population of 4.66 M, assuming a uniform prorating of savings.

Refrigerated Drinking Water. As noted in the introduction, a family of 4 uses about 10 gal/mo for drinking. Based on 2.5 gal/mo-capita, extraction of 83 B/mo would be required to compensate for preheating water by 25 F. We will not charge for any further cooling. Assuming a coefficient of performance of 4, the required electrical energy is 0.14 W(e), which is negligible. While somewhat more energy may be needed to maintain refrigeration and allow for increased opening of the refrigerator door, it is felt that the required power is still minute. Neglecting, the last two mentioned effects, the required annual energy for the hypothetical example is only 0.006×10^{12} B on the basis of additional power-plant fuel at a heat rate of 10,000 B/kWh(e).

Other Thermal Effects. Much of the water used in residential, commercial and industrial processes is increased in temperature by other direct heating. Examples include cooking in residences and restaurants. Additional energy and economic benefits would accrue. Conversely, cooled water is also required in other cases. These effects tend to offset one

another and are neglected here. Similarly, the presence of heated water for general purposes where otherwise not required would increase air conditioning loads in Summer and reduce heating requirements in Winter. Other uses of water such as for lawns and gardening, fire fighting, etc. do not seem to be sensitive to temperature up to the level of about 95 F anticipated. However, problems with freezing would be alleviated in Winter. Water used in sprays would experience an increased cooling potential difference relative to the wet-bulb temperature, and would cool more than at present thereby compensating for some of the elevated temperature.

Waste Water Treatment

After the water has been distributed to the users, it is used in a wide variety of processes and eventually discharged into the sewer system and delivered to the sewage treatment plant. The average temperature of this water at the sewage treatment plant is affected by several events: first, the energy added to the water by the users, second the mixing of rain or snow run off, and third the heat transfer losses in the sewer system. The present section considers the net effect of using preheated water supplies by considering overall energy balances and estimates of losses to the ground.

Because the energy added by the users is uncertain owing to the complex heat transfer processes occurring in various processes, the temperature of discharge from the users is used as a parameter to be determined from present experience. We assume that the run-off water mixes with the user discharge at the beginning of the sewer system. Thus the conditions at the beginning of the sewer, denoted S , are

$$T_S = (\dot{m}_{WS} T_{WS} + \dot{m}_{RO} T_{RO}) / \dot{m}_S \quad (18)$$

$$\dot{m}_S = \dot{m}_{WS} + \dot{m}_{RO} \quad (19)$$

where WS denotes origination from the water supply and RO denotes run off. The temperature at the wastewater plant T_{WW} is given by the relation for cooling in a buried pipe

$$T_{WW} - T_G = (T_S - T_G) \exp[-k_G (SL)_S / (\dot{m}_S c_w)] \quad (20)$$

For the hypothetical test case, the product $(SL)_S$ was estimated as 40,600 kft based on an analysis of the sewer system similar to that of the water-supply distribution system. Data from the Metropolitan Sanitary District [32] provided present seasonal values of T_{WW} and $\dot{m}_S$. The annual average ratio of run-off to water-supply flow was 0.38. The run-off temperature was taken as the ambient-air value. The above equations were then applied to determine the present average discharge temperature of water-supply users T_{WS} , assuming the full water-supply flow rate. This temperature was found to be 73 F for Summer and Spring-Fall, and 71 F for Winter. It appears that temperature of discharge from the water supply into the sewers is nearly independent of initial water-supply temperature for practical purposes, even though the ambient water temperature varied by about 40 F. This suggests that near equilibrium is achieved in the users' facilities. An increase in water-supply temperature by another 25 F would result in a wastewater temperature increase of less than 2 F based on an interpolation and extrapolation of

present experience. The resulting temperature at the wastewater plant would increase less than 1 F due to subsequent cooling in the sewers and dilution with run-off water. While any such increase in temperature would be beneficial for wastewater treatment due to increased biological and chemical activity, the magnitude of the benefit appears too small and uncertain to include here. Further no benefit for treatment capacity could be claimed because of the possibility of power-plant outages.

A more direct method of using power-plant waste heat beneficially for wastewater treatment is through direct interaction between the two facilities [33].

It is interesting to note that the present analysis indicates that the principal cooling of the power plant occurs in effect at the water-supply users. Because they will be distributed over a relatively large area, thermal pollution is effectively diluted.

Overall System

In the sections on the power plant, water supply, and water heaters, estimates were made of the annual energy and cost savings. The savings are summarized in Tables 9 and 10. While the penalty for the water supply system offsets some of the gain, there is still a clear benefit overall.

The net annual savings in energy was 23.4×10^{12} B, equivalent to 4.01 mbbl of oil. The net annual savings in cost was \$57.9 M or \$12.44 per capita. In the latter case, it is interesting to note that \$9.88 is due to direct water-heater savings. If the electric utility compensated the municipal water-supply department for additional cost, it would still retain savings of \$11.9 M. It should be noted, however, this

Table 9. Annual Energy Savings for Hypothetical System Based on City of Chicago and 25-F Rise in Intake Temperature

Item	10^{12} B	Equivalent Mbbbl oil
Power Plant Fuel	2.11	0.363
Water Supply Pumping	-0.35	-0.060
Water Heaters	<u>21.6</u>	<u>3.71</u>
Net Savings	23.4	4.01

Table 10. Annual Cost Savings for Hypothetical System

Item	System M \$ (1980)	Per Capita \$ (1980)
Power Plant	13.2	2.83
Water Supply		
Chlorine	- 0.2	- 0.04
Pumping	<u>- 1.1</u>	<u>- 0.23</u>
	- 1.3	- 0.27
Water Heaters	<u>46.0</u>	<u>9.88</u>
Net Savings	57.9	12.44

figure is based on saving the capital cost of closed-cycle cooling as well as its operation. If the electric utility currently uses once-through cooling, no savings would accrue to it. In this case, the per capita benefit would reduce to \$9.61 after compensation for additional water-supply costs.

The above figures do not include any cost of transmission in the event the power plant and filtration plant were not colocated. However, the present savings could be considered the return on investment if transmission is required. In an urban area, a buried pipe would probably be required. If we assume the utility would finance the venture based on the aforementioned net savings of up to \$11.9 M, and we assume a 30 year life and a 20% return on investment for a private (regulated) utility, then the present worth of an acceptable transmission system would be up to \$59.2 M in 1980 dollars. Recent experience in Chicago for the Tunnel and Reservoir Plant (TARP) suggests the following costs per mile for the proposed system: \$12.8 M capital investment including pumping, and \$5000 for pumping power on an annual basis. The resultant allowable transmission distance is 4.6 miles. This figure does not include maintenance and other operational costs besides power. Because the acceptable distance is relatively small, the pumps could probably be placed at the electric power station and maintained by existing personnel. The thermal analysis in the section on transmission indicates no significant cooling would occur in a buried pipe of 4.6 miles length.

Because the acceptable transmission distance is small compared with distance in urban areas, and because construction of a transmission system may be difficult or impractical, the present view is toward essentially

colocated systems. However, the above estimates suggest an inter-connection distance up to several miles may be economically justified as an alternative to closed-cycle cooling of the electric power plant.

CASE STUDIES

In this chapter, the operating experiences of several existing systems are briefly summarized. While none of the systems were developed for energy conservation purposes, their experiences are nonetheless useful.

Henderson, Kentucky

In the case of Henderson, Kentucky [34], located on the Ohio River, local conditions made construction of water intakes very expensive for a new filtration plant. Instead, the heated condenser-coolant discharge from an existing municipal power plant on the same site was used. The population of Henderson is about 17,000. The filtration plant employs walking beam flocculators and rake-type sludge collectors. Chemicals added include hydrated lime and dry aluminum sulphate for coagulation and color and turbidity removal. Post lime feeding is used ahead of the filtered water basin for stabilization of finished water. Chlorine for disinfection and taste and odor control, activated carbon for taste and odor control, and sodium silicofluoride for fluoridation are added at one or more points in the system. In addition to distributing water through a fixed pipe system, a coin-operated meter dispenses 500 gallons at a time, primarily to local farmers. Apparently there have been no problems with the system even during the summer.

Edmonton, Alberta (Canada)

At Edmonton, a power-plant discharge at an average temperature of 65 F is blended with 33-F river water in order to produce an intake to the water supply averaging 56 F in temperature all winter [35]. An average flow of 60 Mgd serves a population of 550,000. The use of

heated water has minimized the occurrence of water-main breaks and seems to have virtually eliminated domestic freeze-ups altogether. Studies are in progress to establish the minimum temperature to avoid freezing problems. This particular system is operated with heated water only 6 months of the year. "Noticeable" savings in energy attributed to water-heater power consumption were reported.

New Orleans, Louisiana

Owing to the location of New Orleans, it is necessary to provide substantial pumping power for sewage [36]. Steam turbines operating in the condensing mode are employed for this purpose and are cooled by municipal water after filtration. The water then continues through the water-supply system.

The 550,000 population requires an annual average water-supply flow of 127 Mgal with a range of 90 Mgal in Winter to 170 Mgal in Summer. Monthly average intake water temperatures are given in Table 11. It is interesting to note that the temperatures range up to 86 F in July and August.

Table 11. Monthly Average Water Intake Temperatures in New Orleans [36].

Month	T (F)	Month	T (F)
January	45	July	86
February	45	August	86
March	53	September	83
April	63	October	71
May	72	November	61
June	80	December	47

The steam turbines provide for a base load of 6 MW(e) wherein 60 Mgal of condenser coolant is raised in temperature by 10 F. The peak coolant flow is 140 Mgal. No fouling or corrosion is observed on the condenser tubes because filtration occurs before cooling.

Filtration at the ambient water temperature includes the annual average dosage rates of Table 12.

Table 12. Annual Average Dosage Rates for Water Supply Treatment in New Orleans [36]

Chemical	Dosage (ppm)
Lime	70
Chlorine	5
Ferrous Sulphate	7
Polyelectrolyte	0.6
Potassium Permanganate	0.5
Fluoride	0.45

The use of treated water for coolant of power generation has been accomplished since 1900 in New Orleans.

CONCLUSIONS

The use of heated steam-condenser discharge from a large electric power plant for the source of a municipal water supply offers a number of benefits and penalties. As summarized in Tables 9 and 10 of the chapter on Thermal and Economic Effects, the electric power plant and the users of water heaters both benefit in terms of energy consumption and cost, while the water-supply department would suffer a penalty.

It was suggested that the electric utility compensate the water-supply department in order to offset the penalty to the latter in terms of increased pumping power and chlorine dosage. After this compensation, there would still be an annual savings to the electric utility of 1.76×10^{12} B (0.303 Mbb1 of oil, equivalent) and \$11.9 M (1980\$) for the hypothetical case considered. The hypothetical case involved the City of Chicago water-supply system serving 4.66 M, and a load-following fossil-fueled power plant producing an average of 2470 MW(e). It was estimated that up to 4.6 miles of transmission could be justified on the basis of a 20% return on investment before taxes, by employing the savings to finance the venture.

The saving to the water-supply users amounted to 21.6×10^{12} B (3.71 Mbb1 of oil, equivalent) and \$46.0 M (1980\$), or \$9.88/capita. This savings may be sufficient to compensate for the inconvenience of preheated water in the warmer seasons. A number of specific disadvantages have been identified. However, based on the experience of several existing systems and based on the arguments presented here, these disadvantages do not seem to rule out the proposed system in general.

If it is decided to pursue development of the concept on an active

basis, it is suggested that the work proceed with a two-phase study. In Phase 1 a survey of possible sites for implementation is proposed. Especially important is a matching of flow rates, colocation and, preferably, co-ownership of the utilities. Both new facilities and retrofits may be considered. The present analysis could be used to assess the merit of a number of promising sites. In Phase 2, a detailed design study would account for local prevailing conditions both in terms of savings and operational problems. For this purpose, perhaps one or two sites may be analyzed. Based on the results of Phase 2, a demonstration project might be pursued.

It is suggested that any demonstration project be designed to permit fully independent operation of the two facilities, which would probably incur additional expense not charged for the mature technology. This approach would permit an experimental determination of the characteristics of the system as well as permit conventional operation in the event of unforeseen difficulties.

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