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IIT Waste Energy Management Project

Technical Report TR-78-1

Effect of Alternate Cooling Systems and Beneficial Use
of Waste Heat on Power Plant Performance

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ABSTRACT

This report concerns the performance and costs of alternate closed-cycle cooling systems for steam-electric power plants. Included are cooling ponds, spray canals and mechanical- and natural-draft wet cooling towers. Besides equipment, operational and maintenance costs, loss of generating capacity is determined on a seasonal basis in order to determine life-cycle costs relative to once-through cooling. In addition, two beneficial uses of waste heat are similarly analyzed: once-through discharge of condenser coolant into a municipal water supply and interaction of a conventional cooling system with a wastewater treatment plant. Both typical nuclear- and fossil-fueled power plants are considered throughout. Meteorological and system parameters were taken for the Chicago area as an example. Plant heat rates, availability and unit costs were selected from the literature.

A new unified analysis of closed-cycle-cooling system performance is developed in order to facilitate computation of loss of generating capacity. The order of cooling systems in terms of increasing cost is: once-through, pond, natural-draft wet tower, spray canal and mechanical-draft wet tower. Alternatively, once-through discharge into a municipal water supply would save 1-2% of power-plant fuel and 14-22% of residential water-heater energy. Or, the interactive wastewater plant would save 2-15% of treatment costs, favoring larger facilities.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
LIST OF TABLES	vi
LIST OF FIGURES	viii
NOMENCLATURE	ix
 CHAPTER	
I. INTRODUCTION	1
The Problem	1
Literature Survey	2
Fundamentals of Power Plant Theory	5
II. COOLING SYSTEMS	12
Cooling Pond	14
Spray Canal	14
Cooling Towers	16
Generalized One Parameter Model	18
Conclusions	19
III. STEAM CYCLE ANALYSIS	21
Selection of Cycle Parameters	21
Fossil Plant Performance	21
Nuclear Plant Performance	22
Condenser Performance	22
Conclusions	26
IV. COUPLED ANALYSIS	28
General Method	28
Closed-Cycle System Studies	29
V. BENEFICIAL USES OF WASTE HEAT	39
Possible Beneficial Uses	39
Municipal Water Supply	40
Wastewater Treatment Systems	41
Conclusion	55

CHAPTER	Page
VI. COST ANALYSIS	57
General Methods	57
Compilation of Source Data	58
Alternate Economic Analysis	66
Capital Costs of Alternative Cooling Systems	68
Operating Costs of Cooling Systems	70
Interconnected Wastewater Treatment System Economics	78
Economics of Pre-heated Municipal Water Supply	85
Conclusions	99
VII. CONCLUSIONS	100
Results and Conclusions	100
Recommendations for Further Study	105
BIBLIOGRAPHY	108

LIST OF TABLES

Table	Page
1. Typical Cooling System Performance Parameters	10
2. Representative Weather Conditions	13
3. Cooling System Performance with Constant Range	20
4. Fossil Plant Performance	23
5. Nuclear Plant Performance	24
6. Rankine Cycle Performance	25
7. Power Plant Performance with Closed Cycle Cooling System	30
8. Cooling System Blowdown Standards	35
9. Make-up Water Effects on Power Plant Performance	36
10. Power Plant Performance Incorporating Seasonal Variations in b_f/c_w Values	38
11. Open Cycle Cooling System Performance	42
12. Sludge Gas Production and Possible Sales	46
13. Interconnected Large Power Plant and Large Sewage Treatment Plant Parameters	49
14. Interconnected Medium Power Plant and Medium Sewage Treatment Plant Parameters	52
15. Interconnected Plant Sizes	56
16. Cooling Tower Cost Comparison for 2000 MW(e)	59
17. Cooling Lake and Spray Canal Costs	60
18. Cooling Tower Capital Cost	61
19. Once Through Cooling System Cost	61
20. Comparative Cost Study	62
21. Fuel Costs	64
22. Variation of Plant Capacity with Age	65

Table		Page
23.	Capital Costs of Cooling Systems	70
24.	Plant Availability	72
25.	Overall Plant Capability in Five Year Periods .	72
26.	Operating Cost Parameters	73
27.	Once Through System Performance Parameters . . .	74
28.	Closed-Cycle System Performance	75
29.	Operating Costs of Alternative Cooling Systems .	76
30.	Total Cost of Cooling Methods	79
31.	Capital Costs of Wastewater Treatment Equipment	81
32.	Annual Costs of Primary/Secondary Treatment . .	82
33.	Annual Costs of Sludge Heating	83
34.	Total Cost of Wastewater Systems	86
35.	Parameters of Large Sized Interconnected Plants	87
36.	Parameters of Medium Sized Interconnected Plants	88
37.	Interconnected Power Plant Operating Costs . . .	89
38.	Total Costs of Cooling Methods for Interconnected Power Plant	91
39.	Power Plant Cost and Savings	92
40.	Wastewater Treatment Cost and Savings	94
41.	Power Plant Savings for Water Supply Discharge System	96
42.	Savings in Water Heating Costs	97
43.	Savings in Wastewater Treatment Cost	98

LIST OF FIGURES

Figure		Page
1.	Once-Through Cooling System	6
2.	Closed-Cycle Cooling System	6
3.	Interconnected Wastewater Treatment System . .	44

NOMENCLATURE

Symbol	Explanation
A	Area of heat transfer surface
A_T	Area of cooling tower heat transfer surface
B	Bowen ratio
BL	Blowdown quantity
b_f	Change in total heat content of air with wet-bulb temperature
C_A	Total annual cost
C_{AE}	Annual capital cost equivalent
C_{AL}	Total annual levelized cost
C_B	Annual blowdown treatment cost
C_C	Capital cost
C_F	Annual fuel cost
C_L	Annual cost of purchased power
C_M	Annual make-up water cost
C_{MT}	Annual maintenance cost
C_S	Specific heat of saturated air
C_T	Total cost over economic life of plant
c_w	Specific heat of cooling water
E	Equilibrium lake temperature
EV	Quantity of water evaporated
e	Evaporative fraction of cooling water flow
e_j	Escalation in insurance rates expressed as a decimal fraction
e_o	Escalation in operating costs expressed as a decimal fraction

Symbol	Explanation
e_t	Escalation in taxes expressed as a decimal fraction
F_E	Fuel cost escalation factor
f	Interference factor due to adjacent spray
h	Total heat of air
h_A	Heat transfer coefficient of air
i	Interest rate expressed as a decimal fraction
i_{fg}	Latent heat of vaporization of water
j	Insurance rate expressed as a decimal fraction
K	Surface exchange coefficient
k	Mass transfer coefficient
l	Incremental period designation
m	Concentration of dissolved materials in cooling water
$\dot{m}$	Mass flow rate of water
$\dot{m}_A$	Mass flow rate of air
$\dot{m}_e$	Rate of evaporation of water
N	Number of spray modules in spray canal
NHR	Plant net heat rate
NHR_T	Turbine cycle heat rate
NTU	Number of transfer units
n	Economic life of plant
n_c	Cycles of concentration
n_l	Number of years in l th period
ntu	Empirical NTU for spray canal
O_C	Annual operating cost

Symbol	Explanation
P	Present worth
p	Condenser backpressure
Q	Condenser flow
$\dot{Q}_R$	Heat rejected through condenser
Q_1	Heat supplied at higher temperature
Q_2	Heat supplied at lower temperature
q	Rate of heat transfer from cooling water
R.H.	Relative humidity
r	Ratio of spray flow to total flow
T_A	Ambient water temperature
T_C	Cold water temperature
T_{DB}	Dry-bulb temperature
T_H	Water temperature at cooling system intake
T_{SAT}	Saturation temperature of steam corresponding to turbine backpressure
T_{WB}	Wet-bulb temperature
$\bar{T}$	Mean cooling water temperature
T_f	Mean film temperature
t	Tax rate expressed as a decimal fraction
U	Overall condenser heat transfer coefficient
W	Generator power output
W_P	Present worth of total annual cost
w	Humidity ratio
η_{th}	Thermal efficiency of power plant
$\eta_{S.G.}$	Steam generator efficiency

CHAPTER I

INTRODUCTION

The Problem

The effect of discharging large quantities of heated water on the environment is well known^{1*}, particularly with regard to the lowering of the assimilative capacity of streams. New power plants are therefore required to conform to fairly severe pollution control standards, and it is generally not permitted to discharge heated water directly into natural waterways or lakes. It therefore becomes necessary to consider the use of closed-cycle cooling systems, where water leaving the power plant is cooled and returned to the plant. The average temperature of the cooling water in the power plant steam condenser is increased as a result, and this has a deleterious effect on power plant performance.

There is considerable interest in both reducing such plant de-ratings and utilizing the rejected heat for beneficial purposes such as discharging into a municipal supply or an open-field irrigation system or such as integration with a wastewater treatment plant.

The present work is primarily concerned with the effect of alternate cooling systems on power plant performance. The conventional cooling systems analyzed include

*Superscript numbers refer to numbered references in the bibliography.

mechanical and natural-draft evaporative cooling towers, spray canals and cooling ponds. Also of interest is the possible beneficial use of waste heat. One system, considered in some detail, is an interactive wastewater treatment plant that involves flow recycle and heat exchange. Some consideration is also given to discharge of once-through cooling water directly into a municipal water supply. In both instances, the economic impacts on the power plant and the beneficial use of waste heat are presented.

In the next section we present a brief literature survey of related work. This is followed by a discussion of the fundamentals of power plant theory central to our study. In Chapter II, the performance of alternate conventional cooling systems are analyzed. Then, in Chapter III, the steam cycle is considered in detail for typical fossil and nuclear-fuel systems. In Chapter IV, the method of analyzing the coupled cooling system and steam cycle is presented. This permits the direct comparison of alternate conventional cooling systems. The beneficial use of waste heat is discussed in Chapter V. Chapter VI presents economic analyses of the alternate approaches. The work closes with Chapter VII on conclusions including recommendation for further study.

Literature Survey

Several excellent sources exist for reference material in waste heat management including power plant

performance, cooling systems and beneficial use of waste heat. Parker and Krenkel² survey almost all aspects of the field through 1969 providing 423 references. On the other hand, Rimberg¹ presents a "technology review" wherein a few of the then recent (1974) technical reports are analyzed in great detail. Excellent chapters are presented in the areas of power plant performance and beneficial uses of waste heat including wastewater treatment and agriculture.

Two recent symposiums provide a large number of papers on various aspects of the problem^{3, 4}. In particular, the so called "Miami Conference" is published in three extensive volumes⁴, although much of the work was preliminary in nature.

One of the most useful source materials in the general area of power engineering is published by Babcock and Wilcox Company in a form combining that of a handbook and that of a text book⁵. Almost all aspects of power generation other than cooling systems are dealt with in considerable detail.

While there is no single reference covering all aspects of conventional cooling systems in depth, Kolflat⁶ discusses many aspects of thermal discharges in general. Cooling towers are covered in detail by Fraas and Ozisik in their text⁷ on heat exchangers. The basic reference for cooling ponds remains the Edison Electric Institute

report of Edinger and Geyer⁸. Lorenzi and Porter⁹ of IIT provide a recent update of the approach introduced by Edinger and Geyer, but with a more concise and accurate formulation. Porter and Chaturvedi¹⁰ present both basic theory and experimental data on atmospheric spray cooling. The above references on cooling systems provide basic thermal performance information. This information can be used both to size a device to meet the required cooling duty under specified design conditions and to predict off-design performance throughout the year.

The beneficial use of waste heat has an extensive bibliography as discussed previously. However, a recent IIT paper¹¹ dealing with condenser discharging into municipal water supplies is the only reference known to the Author in that area. Rimberg's book¹ deals with two integrated wastewater-treatment systems in considerable detail. Covered are both chemical treatment and the more conventional biological treatment. The present investigation is concerned with the latter, and information was also provided from an IIT analysis in progress.

The objective of the current study was to combine aspects of power plant performance, cooling systems and beneficial uses of waste heat in a systems analysis that could be used for evaluation purposes on an economic basis. To Author's knowledge no single previous study has accomplished this task in a unified and consistent manner for either conventional cooling systems or beneficial

uses of waste heat, much less the two together. The present work seeks to achieve this goal.

Fundamentals of Power Plant Theory¹²

The basic central-station power cycle has evolved from the Rankine cycle, which involves two isobaric and two isentropic processes. Heat is supplied at the higher pressure to the working fluid (water) by burning fossil fuel (coal, oil or gas) or by nuclear fission to produce steam at typical pressures of 16 MPa-24 MPa (2400 psig-3600 psig) and temperatures of 550 C - 800 C (1000 F - 1500 F). The steam is expanded in a turbine to produce shaft work which drives an electric generator. Consistent with the Second Law of Thermodynamics, this "heat engine" rejects heat to the cooling water flowing through tubes in a surface condenser. The steam pressure in the condenser is in the range of 1.3 kPa to 3.3 kPa (0.5 psia to 2.0 psia). The heat taken by the cooling water is ultimately transferred to the environment (Figs. 1 and 2).

To assist in the evaluation of power plant performance, certain figures of merit are used. From a thermodynamic standpoint¹³, the thermal efficiency is given by the relation

$$\eta_{th} = \frac{Q_1 - Q_2}{Q_1} = \frac{\text{Net Work Output}}{\text{Heat Supplied}} \quad (1.1)$$

However, in the electric power industry, the quantity most used is the net heat rate, defined by the reciprocal

Figure 1. Once-Through Cooling System

Figure 2. Closed-Cycle Cooling System

of Eq. (1.1).

$$\text{NHR} = \text{Net Heat Rate} = \frac{\text{Heat Supplied}}{\text{Net Work Output}} = \eta_{th}^{-1} \quad (1.2)$$

This corresponds to the fuel energy required by the plant per unit output of power. Knowing the cost and calorific value of a fuel, it is directly possible to evaluate the cost of electric power generation for a plant with a particular heat rate. The net heat rate for the plant is usually specified by turbine and steam-generator manufacturers¹⁴ for a particular configuration as a function of condenser pressure.

The imperfect transfer of heat from the fuel to the water in the steam generator requires the knowledge of a steam-generator efficiency $\eta_{S.G.}$. The net heat rate of the turbine cycle is given by

$$\text{NHR}_T = (\text{NHR}) \eta_{S.G.} \quad (1.3)$$

The rate of heat rejected by the steam for net power output $\dot{W}$ is given by

$$\dot{Q}_R = \dot{W} (\text{NHR}_T - 1) \quad (1.4)$$

Note that the factor 1 should be replaced with 1 = 3413 B/kw-hr if heat rejection rates in B/hr are utilized, which is often the case in practice. An energy balance on the condenser yields¹⁵

$$\dot{Q}_R = \dot{m} c_w (T_H - T_C) = \frac{UA(T_H - T_C)}{\ln \left(\frac{T_{SAT} - T_C}{T_{SAT} - T_H} \right)} \quad (1.5)$$

where

- $\dot{m}$ = liquid water coolant flow rate
- c_w = liquid water specific heat
- T = temperature
- H = denotes initial hot water
- C = denotes final cold water
- T_{SAT} = denotes saturated liquid water at the condenser back pressure

Eqs. 1.3-1.5 may be combined to yield two equations with four unknowns NHR , T_{SAT} , T_C and T_H . These equations are solved together with the equation for the cooling system which relates T_C and T_H (Chapter II) and the tabulated heat rate data which relate NHR and T_{SAT} (Chapter III). An alternate relationship between T_C and T_H is used for the beneficial use of waste heat. The above relationships are predicated upon the parameters, U , A , etc. being known and the operating point of the system then being determined. The system is first "designed" by defining the operating point and solving for the parameters. In the present investigation, this is done through combinations of parameters in so far as possible. That is, the final detailed design was not considered. The various systems were costed using published data from the literature, taking advantage of previous detailed-design and construction experience but adjusting for appropriate inflation rates.

For preliminary purposes of evaluating predictive models, a fixed $T_H - T_C$ was first assumed as discussed in the cooling system study of the next Chapter. Physically, this corresponds to neglecting the plant derating (or improvement) under off-design conditions. This procedure uncouples the power cycle and cooling system and allowed a convenient comparison of the relative performance of the alternative cooling systems under comparable conditions. The alternate systems were shown to behave similarly under the same off-design conditions when sized to the same design point. As a result of this study, a representative hypothetical cooling system was devised and considered to be operative as coupled with the power plant with variable $T_H - T_C$ as discussed above.

A typical range of operating conditions of actual power plants is given in Table 1. These conditions were used as guidelines in sizing the steam condenser that interfaces the power-cycle and cooling system elements. Ambient weather conditions were selected representative of the Chicago area to be consistent with other studies in progress at IIT. For the purposes of the study two 2000 MW(e) generating stations were assumed, one nuclear and one fossil fueled. However, certain discussion is also presented for smaller municipal units assuming that they scale down linearly. As shown in Table 1, most modern plants utilize about a 14 C (25 F) range in cooling water temperature. Based on typical

Table 1. Typical Cooling System Performance Parameters

Owner and Plant Name	T_{WB} C (F)	$T_H - T_C$ C (F)	$T_C - T_{WB}$ C (F)	Coolant Flow m^3/s (Mgpm)
Detroit Edison: Greenwood 1 ¹⁶	24.4 (76.0)	15.9 (28.7)	10.0 (18.0)	16.40 (0.26)
AEP: Big Sandy 1 ¹⁷	22.2 (72.0)	12.6 (22.7)	8.3 (15.0)	7.57 (0.12)
Keystone: Keystone Station	22.2 (72.0)	15.6 (28.0)	10.0 (18.0)	8.83 (0.14)
Allegheny Power: Ft. Martin	22.2 (72.0)	13.3 (24.0)	10.0 (18.0)	15.78 (0.25)
NYSG&E: Homer City	22.2 (72.0)	15.6 (28.0)	11.1 (20.0)	13.25 (0.21)
AEP: Muskingum 5	21.1 (70.0)	13.3 (24.0)	10.0 (18.0)	13.88 (0.22)
TVA: Paradise 3	22.6 (72.6)	15.3 (27.5)	12.6 (22.6)	16.40 (0.26)
AEP: Big Sandy 2	21.1 (70.0)	15.9 (28.7)	8.9 (16.0)	15.78 (0.25)
AEP: J.E. Amos 1-2	21.1 (70.0)	15.9 (28.7)	8.9 (16.0)	15.78 (0.25)
GA Power: Etowah 1-2	24.4 (76.0)	14.2 (25.6)	10.6 (19.0)	16.40 (0.26)
GPU: 3 Mile Island 1	22.2 (72.0)	15.6 (28.0)	8.9 (16.0)	13.25 (0.21)
Cincinnati G&E: Miami Ft. 7	24.4 (76.0)	14.4 (26.0)	11.1 (20.0)	11.99 (0.19)

heat-exchanger NTU(number of transfer units), a specification of this range essentially fixes the system design. The 14 C (25 F) range choice was employed here at the design point. While the two plants analyzed are somewhat larger than those of Table 1, they are representative of even newer plants currently under construction or being planned. It is likely that in a few years, still larger generating units will be encountered. However, because the present study has implications for the retrofit of existing stations, it was felt that the chosen designs would be more relevant on an overall basis.

CHAPTER II

COOLING SYSTEMS

Among the closed-cycle systems in common use are cooling ponds, spray canals and evaporative cooling towers. Because local conditions and manufacturers' designs vary, simple one-parameter models were used here to analyze each type. The relevant parameters are determined under design conditions and then held constant in order to predict off-design operation. Weather conditions are listed in Table 2. Because evaporation is the primary mode of cooling for each of the present systems, it follows that each system behaves somewhat similarly. Based on an assumed constant 14 C (25 F) range, this is demonstrated in the current chapter. Further, a combined simplified model is developed that represents a hypothetical device which approximates any one of the actual systems. This model is used later for coupling with the power cycle through the steam condenser, thereby considerably reducing the number of computations needed. However, the subsequent economic analysis will be based on separate cost figures for each type of system.

Table 2. Representative Weather Conditions

Season	Wet-Bulb T_{WB} C (F)	Dry-Bulb T_{DB} C (F)	Ambient Water T_A C (F)	100% Sunshine $\frac{W}{m^2} \frac{B}{hft^2}$	Wind Speed $\frac{m}{s} \frac{mi}{h}$	Cloud Cover %	R.H. %
Design	23.9 (75.0)	31.1 (88.0)	28.8 (83.8)	460 (146)	2.0 (4.4)	0.0	55.0
Summer	18.1 (64.6)	22.7 (72.8)	23.2 (73.8)	587 (186)	4.0 (8.9)	58.0	64.5
Spring/Fall	7.8 (46.1)	11.0 (51.8)	13.3 (56.0)	467 (148)	5.0 (11.1)	63.0	64.8
Winter	-3.6 (25.5)	-2.0 (28.4)	1.4 (34.5)	314 (100)	5.0 (11.1)	71.0	69.0

Cooling Pond

A cooling pond loses heat to the atmosphere by back radiation, conduction and evaporation while receiving heat through shortwave solar radiation, and long-wave atmospheric radiation⁸. It is possible to determine an equilibrium or driving temperature E of the pond and a net heat transfer coefficient, K . For steady mass flow rate through the pond and pond surface area A , an energy balance yields

$$\frac{T_C - E}{T_H - E} = \exp(-KA/(\dot{m} c_w)) \quad (2.1)$$

The equilibrium temperature E and transfer coefficient K depend on the season and may be evaluated by the procedure developed by Lorenzi and Porter⁹. The cooling pond facilitates heat transfer by virtue of its large area exposed to the atmosphere. For present design purposes the single quantity $A/(\dot{m} c_w)$ is to be determined in order to size the pond. It is then held constant in order to analyze the seasonal off-design performance.

Spray Canal

The contact area in this case is increased by pumping a part of cooling water flow from a canal containing the entire flow through spray modules or nozzles arranged in rows. The sprays are usually 12 m - 15 m (40 ft - 50 ft) in diameter and 3 m - 6 m (10 ft - 20 ft) high¹⁶. The pumps employed are typically 56 kW (75 HP) motor-driven

propeller type. The equation governing spray canal performance¹⁰ is given by

$$\frac{T_C - T_{WB}}{T_H - T_{WB}} = \exp(-N(1 - f)r (1 - \exp(\text{ntu } b_f/c_w))) \quad (2.2)$$

$$\approx \exp(-N(1 - f)r \text{ntu } b_f/c_w), \quad \text{ntu} \ll 1$$

where WB denotes wet-bulb temperature, N is number of modules or nozzles, f is an interference allowance to correct for local wet-bulb elevation and r is ratio of module or nozzle flow rate to condenser flow rate. The quantity $N(1 - f)r$ is to be evaluated at the design point and presumably does not vary over the year. The value of $\text{ntu} = 0.15$ was used here for one type of module, as has been empirically obtained¹⁰. However, for small ntu , we may regard the product $N(1 - f)r \text{ntu}$ as being held constant. Thus we are not necessarily restricting the analysis to a particular manufacturer's equipment. The quantity b_f/c_w is the ratio of rate of change in total heat content with wet-bulb temperature to the specific heat of water¹⁰, a function of a mean film temperature, T_f , given by

$$T_f = \frac{T_H + T_{WB}}{2} \quad (2.3)$$

and is tabulated^{9,10}. It is however a weak function of T_H and T_{WB} for a given season and as a first approximation may be assumed intraseasonally invariant¹⁸.

Cooling Towers

While spray canals are an improvement over cooling lakes from the standpoint of land use, the evaporative cooling tower is even more economical in terms of land use². The scope of the present study involves the wet cooling tower which enables cooling by direct evaporation of the cooling water. Water is allowed to fall from the top of a stack of fill which may be seasoned wood or concrete arranged in staggered horizontal rows to increase contact area. A counter current of air passes through the tower and, in carrying off some of the water as vapor, cools the falling drops. Drift loss is reduced by enclosing the fill with slats.

Air is drawn over the falling drops in an induced-draft tower or forced over them in a forced-draft tower. The types described above are ascribed the generic name of mechanical-draft cooling towers. Towers which depend on the difference in air density between the top and the base of the tower to provide air flow through the fill are known as natural-draft cooling towers. While natural and mechanical-draft towers are basically independent of ambient wind, natural-draft type are affected by the ambient atmospheric density profile.

The forced-draft mechanical type enables a potentially greater air flow and consumes less power than the induced-draft type, but tends to cause recirculation of

humid air in the tower by sucking in the exhaust plume. Neighboring towers may also generate similar interference. Usually a number of mechanical-draft units are used in parallel. The natural draft type provides an effect similar to the mechanical draft towers without the consumption of fan power. It is not possible to control the cold water temperature by varying the draft, however. Furthermore, the fill must not have dense packing which would severely restrict air flow⁷.

The dismayingly large number of parameters involved in cooling tower design has resulted in the development of various correction curves and nomographs in order to simplify design procedures¹⁹. However, attempts have also been made²⁰ to present a uniform simplified method of analysis. For the present analysis, the relation used was developed based on the premise that the driving force for evaporation is the difference in total heat, h , between that of the air at the temperature of the water at a given stage in the tower and that evaluated at the wet-bulb temperature of air surrounding the water at that stage. The total heat is the enthalpy of air and vapor per unit mass of air, but subtracts the contribution of moisture present taken as saturated liquid.

An energy balance on the cooling tower, with air mass flow rate $\dot{m}_A$, contact area A_T , and mass transfer coefficient k , yields

$$\begin{aligned} \dot{Q}_R &= \dot{m} c_w (T_H - T_C) = \dot{m}_A (h(T_{WB_{out}}) - h(T_{WB_{in}})) \quad (2.4) \\ &= \frac{kA_T [(h(T_H) - h(T_{WB_{out}})) - (h(T_C) - h(T_{WB_{in}}))]}{\ln \left[\frac{h(T_H) - h(T_{WB_{out}})}{h(T_C) - h(T_{WB_{in}})} \right]} \end{aligned}$$

It is typical⁷ to have the ratio $\dot{m}/\dot{m}_A$ approximately equal to 1.5, which is nearly constant over the year for mechanical-draft towers. For simplicity, we also assume it constant for natural-draft systems. Consistent with the one-parameter model assumed, this parameter has been kept fixed at 1.5. The ratio $kA_T/\dot{m}$ is determined at the design conditions and can be evaluated from Equation 2.4 after rearrangement. Tables of total heat of air as a function of the known wet-bulb temperature are available²¹. In order to obtain seasonal water temperatures in the tower, it is necessary to guess values of T_H or T_C and evaluate the quantity $kA_T/\dot{m}$. The guessed value is then modified until the latest value of $kA_T/\dot{m}$ meets a specified tolerance with respect to the actual value. Unlike K in a cooling pond, quantity k is essentially constant in a cooling tower with fixed $\dot{m}/\dot{m}_A$.

Generalized One Parameter Model

From the foregoing considerations, it appears that

it may be possible to represent the evaporative cooling systems by a single equation. The representation proposed is

$$\frac{T_C - T_{WB}}{T_H - T_{WB}} = \exp\left(-\frac{b_f}{c_w} NTU\right) \quad (2.5)$$

Similar to the actual cooling systems, the quantity NTU is evaluated at the design point and then held constant at off-design conditions to predict seasonal performance.

Conclusions

A comparison of the thermal performance of each of the above mentioned systems is presented in Table 3. It appears that the spray canal, cooling tower and the generalized cooling system are quite similar in their behavior. The cooling pond shows some deviation from the trends indicated by the other systems, and it appears that a separate cooling pond model may have to be used for more accurate work. For the purposes of preliminary design, the use of a generalized cooling system would probably provide an adequate description of cooling-system behavior. Also, cooling ponds are expected to be used less in the future due to the high cost of the large land area required. Even so, the generalized model approximates the stringent summer conditions well and exhibits correct qualitative behavior under off-design conditions.

Table 3. Cooling System Performance with Constant Range

Design Conditions: $T_H = 48.9 \text{ C (120 F)}$ $T_C = 35.0 \text{ C (95 F)}$ $T_{WB} = 23.9 \text{ C (75 F)}$ $E = 28.9 \text{ C (84 F)}$

		Summer	Spring/Fall	Winter
Cooling Pond [*] :				
T_H	C (F)	42.8 (109.2)	35.6 (96.1)	27.8 (82.0)
T_C	C (F)	28.9 (84.2)	21.7 (71.1)	13.9 (47.0)
E	C (F)	23.3 (73.9)	13.3 (55.9)	1.7 (35.0)
$K \text{ W/m}^2\text{-C (B/hr-ft}^2\text{-F)}$				
		64.8 (11.4)	52.3 (9.2)	39.8 (7.0)
Spray Canal ^{**} :				
T_H	C (F)	45.0 (113.0)	41.1 (106.0)	38.3 (100.9)
T_C	C (F)	31.1 (88.0)	27.2 (81.0)	24.4 (75.9)
Cooling Tower [*] :				
T_H	C (F)	46.7 (116.1)	42.8 (109.0)	39.4 (102.9)
T_C	C (F)	32.8 (91.1)	28.9 (84.0)	25.6 (77.9)
Generalized System ^{**} :				
T_H	C (F)	47.2 (117.0)	42.8 (109.0)	40.0 (104.0)
T_C	C (F)	33.3 (92.0)	28.9 (84.0)	26.1 (79.0)

* $KA/(\dot{m} c_w) = 1.173$ (design) for $K = 62.4 \text{ W/m}^2\text{-C}$ (11.0 B/hr-ft²-F)** $r(1-f)N = 3.45$ for $ntu = 0.15$ * $KA_T/\dot{m} = 0.852$ for $\dot{m}/\dot{m}_A = 1.5$

** NTU = 0.518

CHAPTER III

STEAM CYCLE ANALYSIS

Selection of Cycle Parameters

Modern steam power plants typically utilize operating pressures of 16 MPa (2400 psig), and temperatures of 550 C (1000 F) at the turbine inlet^{13,22}. Reheat is not generally employed in nuclear plants. A detailed study of turbine-steam-generator performance was not performed here. Instead, tabulations of heat rate as a function of steam condensation temperature were employed. A comparative table of heat rates for a simple Rankine cycle was derived using the same turbine inlet condition as in the case of fossil-fuel and nuclear-fuel plants. It was initially hoped that the simple Rankine cycle could be used to approximate actual power cycles in a manner similar to the representation of a hypothetical cooling system as previously discussed. However, results did not substantiate this approach. The condenser parameters were evaluated for the design point and maintained constant for other seasonal conditions. The fossil-fuel steam generator was assumed to have an efficiency of 0.89 and the nuclear-fuel steam generator to have an efficiency of 0.97⁵, the lower efficiency of the fossil-fuel steam generator being due to stack losses.

Fossil Plant Performance

Tables are available¹⁴ which document heat rate of

the plant as a function of condenser backpressure.

The power output $\dot{W}$ of the plant may be calculated at a given turbine backpressure, (BP), from the relation

$$\dot{W}_{BP} = \dot{W}_{1.5''} \frac{NHR_{1.5''}}{NHR_{BP}} \quad (3.1)$$

where the heat rates refer to the valves-wide-open, (VWO), condition at the turbine inlet. Table 4 summarizes the results of the calculation using the theory of Chapter I.

Nuclear Plant Performance

As in the case of fossil plant heat rates, nuclear plant heat rates as a function of condenser back pressure are available in the literature²². The corresponding data appear in Table 5. Rankine cycle data appear in Table 6.

Condenser Performance

The parameter $UA/(\dot{m} c_w)$ was calculated at the design point corresponding to a turbine backpressure of 13.5 kPa (4.0"Hg). The Heat Exchanger Institute recommends a temperature rise in the condenser in the range of 11 C - 14 C (20 F - 25 F). Furthermore, power condensers use a water velocity of 1.85 m/s (6 ft/s) in 22 mm (7/8") tubes. The value of U ranges from 377.8 W/m²-C (665.6 B/hr-ft²-F) at design to 290.6 W/m²-C (512 B/hr-ft²-F) at winter conditions, as defined by correction curves²³. A mean value of 340.5 W/m²-C (600 B/hr-ft²-F) was selected. Rearrangement of Equation 1.5 yields values

Table 4. Fossil Plant Performance^{*}

Condenser Backpressure kPa (in. Hg)	T _{SAT} C (F)	Plant NHR (VWO) 1 ($\frac{B}{kWh}$)	$\dot{W}$ MW(e)	Plant NHR (100%) 1 ($\frac{B}{kWh}$)	$\dot{Q}_R$ GW ($10^9 \frac{B}{hr}$)
3.4 (1.0)	26.13 (79.03)	2.293 (7826.0)	1000.767	2.289 (7812.0)	1.037 (3.542)
5.1 (1.5)	33.18 (91.72)	2.295 (7832.0)	1000.000	2.291 (7819.0)	1.038 (3.546)
6.8 (2.0)	38.41 (101.14)	2.299 (7849.0)	997.834	2.297 (7841.0)	1.042 (3.598)
8.5 (2.5)	42.62 (108.71)	2.313 (7893.0)	992.271	2.312 (7890.0)	1.049 (3.581)
10.2 (3.0)	46.14 (115.06)	2.331 (7955.0)	984.538	2.231 (7955.0)	1.057 (3.610)
11.9 (3.5)	49.44 (121.00)	2.354 (8033.0)	974.978	2.354 (8035.0)	1.067 (3.645)
13.5 (4.0)	51.91 (125.43)	2.380 (8124.0)	964.176	2.380 (8124.0)	1.078 (3.681)

* Single nominal 1000 MW(e) unit with steam flow 3.13×10^6 kg/hr (6.89×10^6 lb/hr) at 100% throttle.

Table 5. Nuclear Plant Performance**

Condenser Backpressure kPa (in. Hg)	T _{SAT} C (F)	Plant NHR (100%) 1 ($\frac{B}{kWh}$)	$\dot{W}$ MW(e)	$\dot{Q}_R$ GW($10^9 \frac{B}{hr}$)
3.4 (1.0)	26.13 (79.03)	3.106 (10600.0*)	1028.0*	2.061 (7.038*)
5.1 (1.5)	33.18 (91.72)	3.114 (10628.0)	1022.0	2.064 (7.048)
6.8 (2.0)	38.41 (101.14)	3.141 (10720.0*)	1016.0*	2.070 (7.070*)
8.5 (2.5)	42.62 (108.71)	3.168 (10813.0)	1004.0	2.080 (7.104)
10.2 (3.0)	46.14 (115.06)	3.217 (10980.0*)	987.0*	2.093 (7.148*)
11.9 (3.5)	49.44 (121.00)	3.278 (11189.0)	970.0	2.113 (7.217)
13.5 (4.0)	51.91 (125.43)	3.340 (11400.0*)	948.0*	2.135 (7.290*)

* Calculated Values

** Single nominal 1000 MW(e) unit with steam flow of 3.13×10^6 kg/hr (6.89×10^6 lb/hr) at 100% throttle.

Table 6. Rankine Cycle Performance

Condenser Backpressure kPa (in. Hg)	T _{SAT} C (F)	Plant NHR (100%) [*] 1 ($\frac{B}{kWh}$)	$\dot{W}$ MW(e)	$\dot{Q}_R$ GW ($10^9 \frac{B}{hr}$)
3.4 (1.0)	26.13 (79.03)	2.225 (7593.0)	1286	1.569 (5.358)
5.1 (1.5)	33.18 (91.72)	2.266 (7732.0)	1249	1.580 (5.397)
6.8 (2.0)	38.41 (101.14)	2.298 (7843.0)	1223	1.587 (5.419)
8.5 (2.5)	42.62 (108.71)	2.329 (7948.0)	1201	1.595 (5.445)
10.2 (3.0)	46.14 (115.06)	2.350 (8020.0)	1184	1.598 (5.457)
11.9 (3.5)	49.44 (121.00)	2.374 (8102.0)	1168	1.604 (5.477)
13.5 (4.0)	51.91 (125.43)	2.393 (8167.0)	1154	1.607 (5.488)

* Based on steam flow of 3.13×10^6 kg/hr (6.89×10^6 lb/hr) at throttle¹⁴.

of mass flow rate of water in the tubes as well as the design value $UA/(\dot{m} c_w)$, both of which are maintained constant. The heat transfer area can also be calculated in order to obtain an idea of condenser size. Corresponding to a temperature rise of 14 C (25 F), the following values were obtained for each 1000 MW(e) unit:

(a) Fossil Plant:

Flow Rate: $18.6 \text{ m}^3/\text{s}$ (0.288 Mgal/min)
 Condenser Area: $3.75 \times 10^4 \text{ m}^2$ ($0.3963 \times 10^6 \text{ ft}^2$)
 $UA/(\dot{m} c_w)$: 1.615

(b) Nuclear Plant:

Flow Rate: $36.8 \text{ m}^3/\text{s}$ (0.570 Mgal/min)
 Condenser Area: $7.43 \times 10^4 \text{ m}^2$ ($0.7849 \times 10^6 \text{ ft}^2$)
 $UA/(\dot{m} c_w)$: 1.615

Conclusions

It appears that $UA/(\dot{m} c_w)$ is essentially insensitive to variation in ambient conditions. This was separately verified by taking corrected values of U corresponding to inlet temperatures for each season and back calculating inlet temperatures for the revised value of U obtained from the previous iteration. The values of flow rates obtained are in agreement with those documented in the literature²⁴. As evidenced by Table 6, the Rankine cycle heat rejection rate at a given back pressure is between that for a fossil and nuclear plant. However, the differences appear too large to be neglected. The net heat rate is plant

specific and data similar to that used here would have to be available for the particular plant configuration considered. The next step involves coupling the power cycle with the cooling system in order to observe their mutual interaction.

CHAPTER IV

COUPLED ANALYSIS

General Method

The present chapter involves the development of interactive system models to various stages of approximation. The simplified one-parameter model was coupled with the steam cycle described in Chapter III. Reference to Equations 1.3 through 1.5 indicates that it would be necessary to utilize trial values of the cooling water temperature and employ iteration. In order to facilitate coupling with wastewater treatment systems in subsequent analyses, the hot water temperature, T_H , was selected as the independent variable and the other parameters were consequently evaluated. The values of the independent variable were improved using the Newton-Raphson method as follows.

Two initial trial values of hot water temperature with a specified interval were selected, and the corresponding heat rejection rates were calculated from the cooling system performance equation of Chapter II. The steam condensation temperatures were calculated from the condenser characteristic equation (Eq. 1.5), and the corresponding steam cycle heat rejection rates were found. The errors in the two values of heat rejection rate were calculated for each value of T_H . The equation of the line through the first and second points so

obtained was used to evaluate the third value of T_H at the point of intersection of the line and the abscissa. Based on this new value of T_H , the corresponding error was calculated and a fourth value of T_H obtained using the two preceding points to obtain the equation of a new line. This procedure was repeated until the error obtained was within a prescribed tolerance. The computer program developed for this purpose incorporates suitable checks in the event of lack of convergence and provides methods of varying the selected interval if this should happen.

Closed-Cycle System Studies

The simplest coupled model involved the direct connection of the steam cycle and the cooling system. A 1000 MW(e) unit was analyzed for the cases of fossil-fueled and nuclear-fueled steam generators. In each case the design point parameters were $T_H = 48.9$ C (120.0 F), $T_C = 35.0$ C (95.0 F), and $T_{WB} = 23.9$ C (75.0 F). The change in total heat of water with film temperature was assumed constant for each season and no make-up water addition was incorporated into the program developed. The thermal performance and resulting power plant behavior are documented in Table 7.

The next degree of refinement involved the incorporation of blowdown and evaporation losses. Prior to the presentation of results, a brief discussion of the equations governing evaporative heat transfer is presented.

Table 7. Power Plant Performance with Closed Cycle Cooling System

Plant and Season	T_H C (F)	T_C C (F)	Range C (F)	T_{SAT} C (F)	P kPa (in. Hg)	b_f/c_w^*	NHR 1 (B/kWh)	$\dot{W}$ MW(e)
Fossil								
Design	48.9 (120.0)	35.0 (95.0)	13.9 (25.0)	52.3 (126.2)	13.54 (4.00)	1.57	2.38 (8124)	962
Summer	46.6 (115.9)	32.0 (91.1)	13.8 (24.8)	50.1 (122.1)	12.19 (3.60)	1.34	2.36 (8053)	973
Spring-Fall	42.4 (108.3)	28.8 (83.8)	13.6 (24.5)	45.8 (114.4)	9.99 (2.95)	0.97	2.33 (7949)	985
Winter	39.6 (103.2)	26.0 (78.8)	13.6 (24.4)	42.9 (109.2)	8.63 (2.55)	0.73	2.31 (7899)	992
Nuclear								
Design	48.9 (120.0)	35.0 (95.0)	13.9 (25.0)	52.3 (126.2)	13.54 (4.00)	1.57	3.34 (11400)	948
Summer	46.6 (115.9)	32.0 (91.1)	13.8 (24.8)	50.1 (122.1)	12.19 (3.60)	1.34	3.29 (11225)	955
Spring-Fall	42.4 (108.3)	28.8 (83.8)	13.6 (24.5)	45.8 (114.4)	9.99 (2.95)	0.97	3.22 (10975)	988
Winter	39.6 (103.2)	26.1 (78.9)	13.6 (24.4)	42.9 (109.2)	8.63 (2.35)	0.73	3.18 (10825)	999

* Estimated seasonal values.

The study of fundamental mass transfer concepts is beyond the scope of the discussion, and only simple laws relating to air-water interaction are considered^{25,26}.

In evaporative cooling systems, water evaporates into air, obtaining the latent heat of vaporization from the bulk water flow. The water consequently decreases in temperature until an equilibrium temperature is reached, when the heat transferred to the water is equal to the heat removed by vaporization. This equilibrium temperature is the wet-bulb temperature of air.

An energy balance yields

$$q = i_{fg} \dot{m}_e \quad (4.1)$$

where i_{fg} , the latent heat of vaporization is essentially constant at 490.9 kJ/kg (1025.0 B/lb) for normal ambient temperature ranges. The air is at the dry-bulb temperature (T_{DB}), and sensible heat transfer to the water can be expressed by the relation

$$q = h_A A (\bar{T} - T_{DB}) \quad (4.2)$$

where $\bar{T}$ is the mean cooling water temperature. The rate of mass transfer is given by

$$\dot{m}_e = kA (w(\bar{T}) - w_a) \quad (4.3)$$

where $w(\bar{T})$ represents the humidity ratio of saturated air at the air-water interface at temperature $\bar{T}$.

Combining equations 4.1 and 4.3, the quantity of evaporative heat transfer can be found from

$$q = kA i_{fg} (w(\bar{T}) - w_\infty) \quad (4.4)$$

The ratio of sensible heat transfer to evaporative heat transfer is called the Bowen Ratio (B), and is found from the relation

$$B = \frac{h_A (\bar{T} - T_{DB})}{k i_{fg} (w(\bar{T}) - w_\infty)} \quad (4.5)$$

The ratio $h_A/(C_s k)$, called the Lewis Number, is a measure of the relative rates of propagation of energy and mass in the system for unit driving potentials. For air-water mixtures at low diffusion rates, the ratio is approximately unity. The evaporative fraction, e , defined as the ratio of evaporative flow to total system flow, is given by the equation

$$e = \frac{c_w (T_H - T_C)}{i_{fg} (1 + B)} \quad (4.6)$$

The loss of water due to evaporation is made up by the addition of fresh water from a water source such as a lake, river, or in some cases, a city water supply. Furthermore, evaporation of pure water increases the concentration of solids in the cooling water. In order to control their level of concentration, recourse is

taken to discharging a quantity of water known as blowdown. This should be done at the cold water end of the cooling system in order to protect the environment and cause minimal thermal pollution. Water at ambient temperature, which is usually lower than the cooling water temperature, should then be added at the entry to the condenser for maximum thermal benefit and to obtain the required condenser flow. The quality of water discharged as blowdown is subject to stringent pollution standards and depends on plant location. The Environmental Protection Agency has defined limits on permissible levels of certain potentially harmful dissolved and suspended compounds such as chromates, chlorine, metals and their compounds²⁷. Data for new plants are summarized in Table 8.

In certain cases, no discharge is permitted without prior treatment, and discharged water is required to have ambient water characteristics²⁸. Various treatment methods are used depending on the specific pollutants present²⁹. It appears that blowdown quantity depends on plant location. For the present analysis, the blowdown quantity was taken as equal to the evaporated quantity. This would cause a concentration of dissolved materials equal to twice that in ambient water, as can

be shown by the following simple mass balance.

Using the following notation:

Q = Incoming flow from condenser

EV = Evaporation

BL = Blowdown

m_1 = Concentration of make up

m_2 = Concentration in system

the mass balance yields

$$Qm_2 - BLm_2 + (BL + EV) m_1 = Qm_2 \quad (4.7)$$

or

$$n_c = m_2/m_1 = 1 + EV/BL \quad (4.8)$$

where n_c is called cycles of concentration. The quantity of make-up water required is the sum of the evaporation and blowdown amounts.

In analyzing the system with make-up and blowdown streams, the energy balance was modified to include these components at the interface between the cooling system outlet and condenser inlet. While the introduction of relatively cool make-up water and the discharge of relatively hot blowdown improves thermal performance, it may be preferable to allow for the absence of these streams and design the system for full capacity without make-up and blowdown. Further, performance acceptance tests are often specified to exclude "extraneous streams" that may make thermal performance evaluation uncertain.

Table 8. Cooling System Blowdown Standards

Pollutants in Blowdown	Limits for New Plants	Remarks
	$\frac{\text{kg}}{\text{m}^3}$ ($\frac{\text{mg}}{\text{l}}$)	
Free or Residual Chlorine	$\frac{0.0005}{0.0002}$ (0.5) (max) (0.2) (avg)	Discharge not more than 2 hours daily.
Chromium	-	Should be undetect- able.
Phosphorous	-	Should be undetect- able.

Thus, in the present analysis, the size of the system was based on full capacity without make-up and blowdown. However, the effect on operation was determined incorporating the influence of it, assuming two cycles of concentration. Results are shown in Table 9, including an adjusted design point with blowdown and make-up exactly equivalent to the design point neglecting these flows (Table 7). The influence of blowdown and makeup is to increase power output from 0.2-2%.

Further refinement in predicted performance was obtained by including intraseasonally variable values of the quantity b_f/c_w which were evaluated at the mean

Table 9. Make-up Water Effects on Power Plant Performance

Plant and Season	T_H	Condenser T_C C (F)	Condenser $T_H - T_C$ C (F)	Cool. Sys. T_C C (F)	Cool. Sys. $T_H - T_C$ C (F)	T_{SAR} C (F)	P kPa (in. Hg)	b_f/c_p	ϕ^*	δ	Quantity _{evap} Evaporated m^3/s (10^3 gpm)	MMH 1 (H/1000)	$\dot{m}$ 10 ⁶ (a)
Fossil													
Design	48.4 (119.1)	34.3 (93.7)	14.1 (25.4)	34.8 (94.1)	13.7 (25.0)	51.8 (125.4)	13.54 (4.00)	1.57	0.021	0.121	0.39 (6.1)	2.36 (8124)	944
Summer	45.9 (114.6)	32.0 (89.6)	13.9 (25.0)	32.2 (89.9)	13.4 (24.8)	49.3 (120.7)	11.68 (3.45)	1.34	0.019	0.210	0.35 (5.6)	2.36 (8027)	976
Spring-Fall	41.2 (106.1)	27.1 (80.8)	14.1 (25.3)	27.6 (81.7)	13.1 (24.4)	44.6 (112.2)	9.31 (2.75)	0.97	0.017	0.340	0.31 (4.9)	2.32 (7923)	988
Winter	37.4 (99.4)	23.4 (74.1)	14.1 (25.3)	24.0 (75.2)	12.8 (24.3)	40.8 (105.5)	6.77 (2.00)	0.73	0.014	0.544	0.26 (4.2)	2.31 (7878)	995
Nuclear													
Design	48.4 (119.1)	34.5 (94.1)	13.9 (25.0)	34.8 (94.6)	13.6 (24.5)	51.8 (125.4)	13.54 (4.00)	1.57	0.021	0.121	0.77 (12.1)	3.14 (11400)	948
Summer	45.9 (114.6)	32.1 (89.8)	13.8 (24.8)	32.5 (90.5)	13.4 (24.1)	49.3 (120.7)	11.68 (3.45)	1.34	0.019	0.210	0.69 (11.0)	3.10 (11169)	972
Spring-Fall	41.2 (106.1)	27.6 (81.7)	13.6 (24.4)	28.1 (82.6)	13.1 (23.5)	44.6 (112.2)	9.31 (2.75)	0.97	0.017	0.340	0.62 (9.8)	3.19 (10999)	995
Winter	37.4 (99.6)	24.0 (75.2)	13.5 (24.3)	24.7 (76.5)	12.8 (23.1)	40.9 (105.6)	7.79 (2.30)	0.73	0.015	0.545	0.53 (8.3)	3.16 (10970)	1009

* Blowdown quantity=Evaporation quantity

** Make-up=Blowdown+quantity+Evaporation quantity

† Estimated seasonal values.

film temperature obtained in each subsequent iteration. Table 10 summarizes the results. The effect is generally negligible.

It is evident that incorporation of blowdown and evaporation effects has a small but perhaps still significant effect on power output and temperature values. The use of variable b_f/c_w is also recommended because temperature levels are variable over potentially a wide range. Indeed, it turns out that interaction with a wastewater plant involves a substantial variation in temperature level because of the greater "make-up" and "blowdown" involved in that process.

Table 10. Power Plant Performance Incorporating Seasonal Variations in b_f/c_w Values

Plant and Season	T_H	Condenser T_C	Condenser $T_H - T_C$	Cool. Sys. T_C	Cool. Sys. $T_H - T_C$	T_{SAT}	P	b_f/c_w	ϕ^*	η	Quantity ** Evaporated m^3/m (10^3 gpm)	NER	$\dot{W}$
		C (F)	C (F)	C (F)	C (F)	C (F)	kPa (In. Hg)					1 (B/kWh)	MW(m)
Fossil													
Design	48.6 (119.4)	34.7 (94.4)	13.9 (25.0)	34.9 (94.8)	13.6 (24.5)	52.0 (125.6)	13.9 (4.1)	1.55	0.021	0.117	0.33 (5.3)	2.39 (8137)	964
Summer	46.1 (114.9)	32.3 (90.2)	13.7 (24.7)	32.7 (90.8)	13.4 (24.1)	49.5 (121.1)	11.9 (3.5)	1.32	0.019	0.221	0.30 (4.8)	2.35 (8091)	975
Spring-Fall	41.5 (106.7)	27.9 (82.2)	13.6 (24.4)	28.4 (83.2)	13.1 (23.5)	44.9 (112.8)	9.6 (2.9)	0.95	0.017	0.358	0.28 (4.4)	2.32 (7899)	987
Winter	38.1 (100.6)	24.6 (76.3)	13.5 (24.3)	25.3 (77.6)	12.8 (23.0)	41.4 (106.6)	8.1 (2.4)	0.70	0.015	0.564	0.24 (3.8)	2.31 (7865)	994
Nuclear													
Design	48.6 (119.4)	34.7 (94.4)	13.9 (25.0)	34.9 (94.8)	13.6 (24.5)	52.0 (125.6)	13.6 (4.0)	1.55	0.021	0.117	0.66 (10.5)	3.34 (11408)	947
Summer	46.1 (114.9)	32.3 (90.2)	13.7 (24.7)	32.7 (90.8)	13.4 (24.1)	49.5 (121.1)	11.9 (3.5)	1.32	0.019	0.216	0.61 (9.6)	3.28 (11189)	970
Spring-Fall	41.5 (106.7)	27.9 (82.2)	13.6 (24.4)	28.4 (83.2)	13.1 (23.5)	44.9 (112.8)	9.6 (2.8)	0.95	0.017	0.343	0.55 (8.7)	3.24 (10924)	992
Winter	38.2 (100.7)	24.7 (76.4)	13.5 (24.3)	25.3 (77.6)	12.8 (23.1)	41.5 (106.7)	8.1 (2.4)	0.71	0.015	0.552	0.48 (7.6)	3.16 (10786)	1007

* Blowdown quantity=Evaporation quantity

** Make-up=Blowdown+quantity=Evaporation quantity

CHAPTER V

BENEFICIAL USES OF WASTE HEAT

Possible Beneficial Uses

The models developed in the preceding chapters represent operating conditions for power plants equipped with conventional closed-cycle cooling systems. The temperature of hot water leaving the plant is 24 C (44 F) above ambient water temperature in summer and 36 C (65 F) in winter. The large quantity of heat rejected annually from a typical 2000 MW(e) plant, 82 PJ (77×10^{12} B) from a fossil plant and 137 PJ (130×10^{12} B) from a nuclear plant could find use in other processes.

Heating of a municipal water supply may be considered as a possible beneficial use¹¹, and this is discussed in greater detail in the following section. The possibility of interconnected wastewater plants was also considered, as described in a subsequent section of this chapter. There is interest in studying effects of warm water for agricultural purposes³⁰. It is anticipated that only cooling system blowdown would be utilized for the purpose because of the large land areas involved. This application and others such as greenhouses, aquaculture, district heating, cogeneration etc. are not considered here.

Municipal Water Supply

Wynn and Porter¹¹ point out that the electrical and water supply demand curves have some similarity. Alternatively, the power plant could supply the minimum municipal requirement which is about 25% of the daily average. This approach would be most suitable for a base-load power plant such as considered in the present study. Unfortunately, the municipality would have to obtain 75% of its flow on the average from another source and there would be considerable dilution of the benefit of savings of hot water heating energy. There is also a problem of matching per capita demands with this strategy. Daily per capita consumption is $0.568 \text{ m}^3/\text{day}$ (150 gal/day). A large fossil plant flow would be able to serve 22 million people and a large nuclear plant would serve 44 million people. Populations of such size are not likely to be found in a reasonable area. It does appear that a medium sized fossil plant of 200 MW(e) capacity could serve a 2 million population adequately, and a single 100 MW(e) nuclear unit could also serve a population of the same size, based on supplying 25% of the daily average water supply. For perfectly matched flows, 2000 MW(e) plants could serve populations of 5.5 million (fossil) and 11 million (nuclear).

The employment of pre-heated municipal water supply has two major advantages. First, the effect on the power plant is an increase in thermal efficiency equivalent to once-through cooling. However, a standby

cooling facility might be necessary in order to match the systems during low municipal flows and, in emergencies, to uncouple the water supply system. Second, the use of a pre-heated municipal supply would reduce the heating requirement of domestic and industrial water heaters. The economic implication of such benefits is presented in the following chapter.

The effect of once-through cooling on power plant performance is shown in Table 11 in a manner similar to that of the closed cycle system (Table 10). It is assumed that the full flow is in the once-through mode as described above. However, it becomes necessary to reduce the condenser flow in winter in order to maintain a minimum cooling water temperature. This points out yet another problem in matching the systems. Because the details of such matching are quite site specific, they were not considered by Wynn and Porter¹¹ in their preliminary study. In the present investigation we also assume the systems are perfectly matched and determine the maximum benefit for the water supply.

Wastewater Treatment Systems

A number of alternative treatment plant configurations to meet various effluent quality standards have been studied³¹. It appears that waste heat supplied by the power plant would be useful at two stages. First, in the secondary treatment of wastewater, hot water from the condenser would be mixed with sewage in order to

Table 11. Open Cycle Cooling System Performance

Plant and Season	T_H C (F)	T_C C (F)	$T_H - T_C$ C (F)	T_{SAT} C (F)	p kPa (in. Hg)	NHR l (B/kWh)	$\dot{W}^*$ MW(e)
Fossil							
Design	42.4 (108.3)	28.8 (83.8)	13.7 (24.5)	45.8 (114.4)	9.99 (2.95)	2.33 (7950)	986
Summer	36.7 (98.0)	23.2 (73.8)	13.8 (24.2)	40.0 (104.0)	7.62 (2.25)	2.30 (7855)	997
Spring-Fall	26.7 (80.1)	13.3 (56.0)	13.4 (24.1)	30.1 (86.1)	4.23 (1.25)	2.29 (7818)	1000
Winter*	14.8 (58.6)	1.4 (34.5)	13.4 (24.1)	26.1 (79.0)	3.39 (1.00)	2.29 (7812)	1001
Nuclear							
Design	42.4 (108.3)	28.8 (83.8)	13.7 (24.5)	45.8 (114.4)	9.99 (2.95)	3.20 (10920)	988
Summer	36.7 (98.1)	23.2 (73.8)	13.5 (24.3)	40.1 (104.1)	7.62 (2.25)	3.15 (10750)	1012
Spring-Fall	26.8 (80.2)	13.3 (56.0)	13.4 (24.2)	30.1 (86.1)	4.23 (1.25)	3.12 (10620)	1026
Winter**	14.8 (58.6)	1.4 (34.5)	13.4 (24.1)	26.1 (79.0)	3.39 (1.00)	3.11 (10600)	1028

* Condenser flow reduced by 32.5%

** Condenser flow reduced by 32.4%

* For nominal 1000 MW(e) unit. Proportional output for other size units.

expedite reaction. Second, in sludge digestion, a temperature of 35 C (95 F) is required for anaerobic reaction to occur. The computerized mathematical model developed for this purpose (based on Fig. 3) incorporates the use of heat exchangers to raise and maintain sludge temperature with provision for burning fuel oil in winter when required. Current practice involves the use of fuel oil or gas to heat the sludge throughout the year. Thus, waste heat would supplant precious oil or gas.

The model employed considers two separate streams from the cooling system, one each to the sludge digester and the secondary-treatment facility. The hottest water in the system is used in both cases. The digester heat exchanger is of the indirect-contact type with a typical $NTU = 0.262$. The range on the cooling-water side was designed for 22 C (40 F) for heating the sludge plus 3 C (5 F) for maintaining it at 35 C (95 F). Discharges from the secondary treatment facility and the digester heat exchanger are considered mixed, and a portion is returned to the cooling system as make-up. The excess water is designated "water product" in Figure 3. Blowdown, as such, is not required where recycle flow is appreciable, as in the present case, and where the secondary treated effluent is of sufficiently low concentration. For example, if the secondary treated effluent were of ambient concentration and recycle

Figure 3. Interconnected Wastewater Treatment System

exceeded isolated-plant blowdown then concentration in the system will be below that of an isolated plant. In the present case, blowdown was assumed at normal rates of an isolated plant in order to compensate for above-ambient concentration in the secondary treated effluent.

The sludge digestion process results in evolution of gas which is 65% methane and 35% carbon dioxide. This gas is of low grade with a lower heating value of 22.4 MJ/m^3 (600 B/ft^3)³². A number of possible uses for this gas may be considered. A fossil plant could use this gas as a supplement to regular fossil fuel. The sludge digester could also use sludge gas in winter when hot water from the power plant would not be able to deliver heat at the required temperature. The gas could possibly be used for sludge incineration. Sludge gas quality could be improved by removal of carbon dioxide and used for domestic or industrial purposes. Reduction of the carbon dioxide to carbon monoxide would undoubtedly render sludge gas unsuitable for domestic use but might find use in industrial processes.

Additional equipment would be required in each of the cases considered. In the present analysis, the benefits of using sludge gas were credited to the wastewater plant in terms of potential sale of gas (Table 12). It must be reiterated that the quantity of

sludge gas evolved is independent of plant interconnection and depends only on sludge quantity. The data of Table 12 were based on a 2 million population being served by a large plant, corresponding populations for medium and small sized plants being 200,000 and 33,000 respectively.

Table 12. Sludge Gas Production and Possible Sales³³

Treatment Plant Size	Gas Production $\frac{\text{m}^3}{\text{s}}$ ($\frac{\text{ft}^3}{\text{day}}$)	Available Heat $\text{kw}(\frac{10^6 \text{ B}}{\text{day}})$	Possible Annual Sales* (10^6 \$/yr.)
Small	0.019 (59440)	436.3 (35.7)	0.03
Medium	0.123 (375760)	2756.1 (225.5)	0.18
Large	1.311 (3999200)	29327.2 (2399.5)	1.94

* Based on cost of \$2.20/ 10^6 B, (1980 \$)

Make-up water for the cooling facility is obtained from treated wastewater. It is expected that the treatment plant would provide such water with pollutants maintained at levels acceptable for power plant use. The plants should probably be designed for independent operation in the event of a partial or total shut down of either plant. In the case of the wastewater

plant, there may be enough safety factor to include normal expected unavailability of power capacity. Therefore, in the economic analysis, results are later presented with and without the attendant savings in capital cost.

The specific process reported here is the activated sludge process with ammonia removal, designed to meet so called Group II standards projected for inland rivers and streams. Waste heat is particularly beneficial to ammonia removal which is quite temperature dependent. Less effective processes without ammonia removal appear limited by settling time and do not benefit accordingly.

The amount of recycle flow taken from the condenser to the secondary treatment facility was varied in increments, and the corresponding temperatures and flow rates of diluted wastewater were determined. An economic optimal point exists because increased temperatures are accompanied with increased flow rates of the mixture. The data reported here correspond to the near optimum operation of the wastewater plant. While this condition may not be that of the overall system optimum, it would encourage participation by the wastewater treatment plant. Further, there is still substantial benefit for the power plant. Normally, cold water make-up is only about 4% of condenser flow whereas in the interactive system it is 10 - 20%. The optimal temperature of the diluted wastewater is about 20 C (68 F) as compared

with the normal 10 C (50 F) for stringent winter conditions of undiluted flow.

Details of the analysis of the wastewater plant for the present and additional processes are to be described in a forthcoming report by the IIT environmental engineering group. The present study was intended only to illustrate the basic approach in determining the effect on power plant performance and overall system economics.

Several combinations of interlinked plants were considered. Consideration was given to a large sized power plant connected with a large sized sewage plant and an equivalent medium sized power plant connected with a medium sized sewage plant (Tables 13 and 14). It may be assumed that interconnection of smaller sized sewage and power plants would result in thermal performance according to a linear extrapolation. Smaller plants may be found in towns where municipalities often have co-located utilities. In all of the cases mentioned above, flow rates are matched on per capita basis. However, large power stations are often located in rural areas, and adjacent towns may have small sewage treatment plants. It is expected that such a combination would not alter power plant performance but that benefits would accrue to the wastewater plant.

Table 13a. Interconnected Large Power Plant and Large Sewage Treatment Plant,
Power Plant Parameters

Plant and Season	T_H	T_C	Condenser		T_{SAT}	P		NHR		W
	C (F)	C (F)	$T_H - T_C$	C (F)	C (F)	kPa (in. Hg)		l (B/kWh)	MW(e)	
Fossil										
Design	45.9 (114.7)	32.2 (90.0)	13.7 (24.7)		48.9 (120.0)	11.51 (3.40)	2.35	(8025)	975	
Summer	43.9 (111.0)	30.2 (86.4)	13.7 (24.6)		46.8 (116.3)	10.50 (3.10)	2.21	(7955)	987	
Spring-Fall	39.9 (103.8)	26.3 (79.3)	13.6 (24.5)		42.6 (108.7)	8.47 (2.50)	2.31	(7890)	992	
Winter	36.6 (97.9)	23.2 (73.7)	13.4 (24.2)		39.6 (103.3)	7.45 (2.20)	2.30	(7850)	998	
Nuclear										
Design	46.0 (114.8)	32.8 (90.1)	13.7 (24.7)		48.9 (120.0)	11.51 (3.40)	3.27	(11150)	972	
Summer	43.9 (111.0)	30.2 (86.4)	13.7 (24.7)		46.8 (116.3)	10.33 (3.05)	3.23	(11025)	985	
Spring-Fall	39.9 (103.8)	26.3 (79.4)	13.6 (24.4)		42.9 (109.2)	8.80 (2.60)	3.18	(10825)	1002	
Winter	36.8 (98.3)	23.3 (74.0)	13.5 (24.3)		39.9 (103.8)	7.45 (2.20)	3.15	(10750)	1013	

Table 13b. Interconnected Large Power Plant and Sewage Treatment Plant, Cooling System Parameters

Plant and Season	C. S. [*] C (F)	P. P. ^{**} C (F)	$T_H - T_C$ (C. S.) C (F)	C. S. Flow m^3/s (10^6 gpm)	Bypass m^3/s	Evap. Prec.	Bowen Ratio	Evap. Qty? m^3/s (10^3 gpm)
Fossil								
Design	34.2 (93.6)	34.2 (93.6)	11.7 (21.1)	29.0 (0.46)	0.0	0.018	0.117	0.53 (6.45)
Summer	31.9 (89.5)	31.9 (89.5)	11.9 (21.4)	29.0 (0.46)	0.0	0.017	0.215	0.50 (7.87)
Spring-Fall	27.6 (81.7)	27.6 (81.7)	12.0 (22.1)	29.0 (0.46)	0.0	0.016	0.340	0.45 (7.13)
Winter	24.5 (76.1)	24.5 (76.1)	12.1 (21.8)	29.0 (0.46)	0.0	0.014	0.553	0.40 (6.29)
Nuclear								
Design	34.2 (93.6)	34.2 (93.6)	11.0 (21.2)	64.4 (1.02)	0.0	0.019	0.118	1.19 (18.69)
Summer	31.9 (89.5)	31.9 (89.5)	11.9 (21.5)	64.4 (1.02)	0.0	0.017	0.215	1.11 (17.58)
Spring-Fall	27.7 (81.9)	27.7 (81.9)	12.2 (21.9)	64.4 (1.02)	0.0	0.016	0.347	1.02 (16.13)
Winter	24.6 (76.3)	24.6 (76.3)	12.2 (22.0)	64.4 (1.02)	0.0	0.014	0.530	0.89 (14.16)

* Flow leaving cooling system

** Flow entering power plant, fossil: 37.2 m^3/s (0.576 gpm), nuclear: 73.6 m^3/s (1.14 gpm).

?Blowdown quantity=Evaporation quantity. Columns 2 & 3 will be identical unless the bypass flow is zero or fresh make-up is used.

Table 13a. Interconnected Large Power Plant and Sewage Treatment Plant, Sewage Plant Parameters

Plant and Season	Raw Sewage Flow	Sewage Temp.	Sludge Flow	Sludge Temp.	Heat Req'd. for Sludge		Hot Water for Digester	Hot Treated Discharge	Discharge Temp.
	m ³ /s (10 ⁶ gpm)	C (F)	m ³ /s (10 ³ gpm)	C (F)	MM (10 ³ B/hr)	MM (10 ⁶ B/hr)	m ³ /s (10 ³ gpm)	m ³ /s (10 ⁶ gpm)	C (F)
Fossil									
Design	14.5 (0.23)	24.4 (76.0)	0.13 (2.07)	31.6 (88.9)	1.97 (6.71)	0.08 (0.29)	0.11 (1.76)	13.3 (0.21)	21.9 (81.5)
Summer	13.9 (0.22)	22.4 (72.4)	0.13 (2.02)	29.7 (85.5)	4.52 (15.43)	0.26 (0.90)	0.19 (2.93)	12.6 (0.20)	20.1 (66.2)
Spring-Fall	13.3 (0.21)	18.8 (65.8)	0.12 (1.92)	26.2 (79.2)	5.70 (19.45)	0.52 (1.76)	0.23 (3.64)	12.0 (0.19)	26.6 (79.9)
Winter	12.3 (0.21)	14.2 (57.5)	0.12 (1.94)	22.1 (71.8)	7.27 (24.82)	0.90 (3.06)	Fuel Req'd. ^a	12.8 (0.19)	22.4 (72.3)
Nuclear									
Design	14.5 (0.23)	24.4 (76.0)	0.13 (2.07)	31.6 (88.9)	1.97 (6.71)	0.08 (0.29)	0.11 (1.76)	11.9 (0.19)	21.9 (81.5)
Summer	13.9 (0.22)	22.4 (72.4)	0.13 (2.02)	29.7 (85.5)	4.52 (15.43)	0.26 (0.90)	0.19 (2.93)	12.9 (0.19)	20.1 (66.2)
Spring-Fall	13.3 (0.21)	18.8 (65.8)	0.12 (1.92)	26.2 (79.2)	5.70 (19.45)	0.52 (1.76)	0.23 (3.64)	10.7 (0.17)	26.7 (80.0)
Winter	12.3 (0.21)	14.2 (57.5)	0.12 (1.94)	22.1 (71.8)	7.27 (24.82)	0.90 (3.06)	Fuel Req'd. ^a	22.4 (0.18)	22.4 (72.4)

^a No hot water used in digester; reverse heat transfer would occur.

Table 14a. Interconnected Medium Power Plant and Medium Sewage Treatment Plant,
Power Plant Parameters

Plant and Season	T_H	T_C	Condenser $T_H - T_C$	T_{SAT}	P		MHR		W
	C (F)	C (F)	C (F)	C (F)	kPa	(in. Hg)	l (B/kWh)		MW(a)
Possil									
Design	45.6 (114.1)	31.9 (89.4)	13.7 (24.7)	48.5 (119.3)	11.34 (3.35)		2.35	(8015)	979
Summer	43.5 (110.3)	29.8 (85.7)	13.6 (24.5)	46.4 (115.5)	10.26 (3.03)		2.34	(7962)	987
Spring-Fall	39.3 (102.8)	25.8 (78.5)	13.5 (24.3)	42.3 (108.1)	8.47 (2.50)		2.31	(7890)	992
Winter	36.3 (97.3)	22.8 (73.1)	13.4 (24.2)	39.2 (102.6)	7.28 (2.15)		2.30	(7850)	998
Nuclear									
Design	45.8 (114.5)	32.1 (89.8)	13.7 (24.7)	48.7 (119.7)	11.51 (3.40)		3.27	(11150)	972
Summer	43.7 (110.6)	30.1 (86.1)	13.6 (24.5)	46.6 (115.9)	10.33 (3.05)		3.23	(11020)	985
Spring-Fall	39.6 (103.3)	26.1 (78.9)	13.6 (24.4)	42.6 (108.6)	8.63 (2.55)		3.17	(10810)	1003
Winter	36.7 (98.0)	23.2 (73.7)	13.5 (24.3)	39.7 (103.4)	7.45 (2.20)		3.15	(10750)	1018

Table 14b. Interconnected Medium Power Plant and Sewage Treatment Plant, Cooling System Parameters

Plant and Season	C. S. [*] C (F)	P. P. ^{**} C (F)	T _H -T _C (C. S.) C (F)	C. S. Flow m ³ /s (10 ⁶ gpm)	Bypass m ³ /s	Evap. Prac.	Bowen Ratio	Evap. Qty [‡] m ³ /s (10 ³ gpm)
Fossil								
Design	34.1 (93.4)	34.1 (93.4)	11.5 (20.7)	3.15 (0.05)	0.0	0.018	0.117	0.06 (0.96)
Summer	31.8 (89.3)	31.8 (89.3)	11.7 (21.0)	3.15 (0.05)	0.0	0.017	0.216	0.06 (0.89)
Spring-Fall	27.5 (81.5)	27.5 (81.5)	11.8 (21.3)	3.15 (0.05)	0.0	0.017	0.351	0.05 (0.81)
Winter	24.3 (75.8)	24.3 (75.8)	11.9 (21.5)	3.15 (0.05)	0.0	0.013	0.558	0.04 (0.71)
Nuclear								
Design	34.2 (93.5)	34.2 (93.5)	11.7 (21.0)	6.94 (0.11)	0.0	0.018	0.117	0.13 (2.00)
Summer	31.9 (89.4)	31.9 (89.4)	11.8 (21.2)	6.94 (0.11)	0.0	0.017	0.215	0.12 (1.86)
Spring-Fall	27.6 (81.7)	27.6 (81.7)	11.9 (21.5)	6.94 (0.11)	0.0	0.016	0.349	0.11 (1.70)
Winter	24.6 (76.2)	24.6 (76.2)	12.2 (21.9)	6.94 (0.11)	0.0	0.014	0.553	0.09 (1.50)

* Flow leaving cooling system

** Flow entering power plant, fossil: 3.7 m³/s (0.058 gpm), nuclear: 7.4 m³/s (0.114 gpm).

‡ Blowdown quantity=Evaporation quantity. Columns 2 & 3 will be identical unless the bypass flow is zero or fresh make-up is used.

Table 14c. Interconnected Medium Power Plant and Sewage Treatment Plant, Sewage Plant Parameters

Plant and Season	Raw Sewage Flow m^3/s (10^6 gpm)	Sewage Temp. C (F)	Sludge Flow m^3/s (gpm)	Sludge Temp. C (F)	Heat Req'd. for Sludge To Raise Temp.	Heat Req'd. for Sludge To Maintain Temp.	Hot Water for Digester m^3/s (10^3 gpm)	Hot Treated Discharge m^3/s (10^6 gpm)	Discharge Temp. C (F)
					HR (10^6 Btu/hr)	HR (10^6 Btu/hr)			
Poncell									
Design	1.5 (0.02)	24.4 (76.0)	0.01 (165)	27.9 (82.2)	0.21 (0.72)	0.01 (0.04)	0.01 (0.09)	1.26 (0.02)	28.2 (82.8)
Summer	1.4 (0.02)	22.4 (72.4)	0.01 (160)	26.0 (78.8)	0.29 (0.99)	0.03 (0.11)	0.01 (0.19)	1.26 (0.02)	26.4 (79.4)
Spring-Fall	1.3 (0.02)	18.0 (65.0)	0.01 (150)	22.5 (72.5)	0.40 (1.38)	0.07 (0.25)	0.02 (0.32)	1.26 (0.02)	22.0 (72.2)
Winter	1.3 (0.02)	14.3 (57.5)	0.01 (152)	18.1 (64.6)	0.65 (2.21)	0.11 (0.36)	Fuel Req'd. ^a	1.26 (0.02)	18.3 (65.0)
Nuclear									
Design	1.5 (0.02)	24.4 (76.0)	0.01 (165)	27.9 (82.2)	0.21 (0.72)	0.01 (0.04)	0.01 (0.09)	1.26 (0.02)	28.2 (82.8)
Summer	1.4 (0.02)	22.4 (72.4)	0.01 (160)	26.0 (78.8)	0.29 (0.99)	0.03 (0.11)	0.01 (0.19)	1.26 (0.02)	26.4 (79.4)
Spring-Fall	1.3 (0.02)	18.0 (65.0)	0.01 (150)	22.5 (72.5)	0.40 (1.38)	0.07 (0.25)	0.02 (0.32)	1.26 (0.02)	22.0 (72.2)
Winter	1.3 (0.02)	14.3 (57.5)	0.01 (152)	18.1 (64.6)	0.65 (2.21)	0.11 (0.36)	Fuel Req'd. ^a	1.26 (0.02)	18.3 (65.0)

^a No hot water used in digester; reverse heat transfer would occur.

Further, interconnected plants of the same relative size are expected to exhibit similar performance. A separate analysis was not performed for medium and small sized interconnected plants. The method of analyzing such plants would be identical with methods of analyzing large plants. Table 15 summarizes the types of configurations.

Conclusion

The investigation for interconnected plants indicates that power plant condenser pressure decreases, resulting in improved power plant performance. In addition, heating for the sludge digestion process could be achieved without using other fuel for most of the year. Operating cost for secondary treatment would be decreased due to increased reaction efficiency. Heated water supply would reduce costs of water heater operation. The anticipated savings are estimated in the following chapter.

Table 15. Interconnected Plant Sizes

Population Served (Sewage)	Power Plant Flow		Treatment Plant Flow		Plant Size		Flow Ratios				
	m ³ /s (mgd)		m ³ /s (mgd)				Sewage/Cond.		R/S*		
	Fossil	Nuclear	Sewage	Recycle	Power	Sewage	Fossil	Nuclear			
2,000,000	36.3 (829)	71.9 (1642)	13.1 (300)	7.2 (165)	Large	Large	0.362	0.182	0.550		
33,000	36.3 (829)	71.9 (1642)	0.2 (5)	**	Large	Small	0.006	0.003	**		
200,000	3.6 (83)	7.2 (164)	1.3 (30)	0.3 (7)	Medium	Medium	0.362	0.182	0.217		
33,000	0.6 (14)	1.2 (28)	0.2 (5)	**	Small	Small	0.362	0.182	**		

* Recycle/Sewage

** Small quantity required for sludge digester. No recycle flow required for primary/secondary treatment.

CHAPTER VI

COST ANALYSIS

General Methods

In analyzing the economic viability of alternative power plant cooling devices, it is necessary to consider two aspects when assessing the merits of a given type of system. These include the initial cost involved in construction of the system (referred to as the capital cost) and the operating cost of the system. The system with lowest overall cost over its expected life which would meet performance requirements would then be the best choice. It is not intended here to obtain these cost parameters on an itemized basis. The costs involved are governed primarily by plant type, location and layout, as well as by labor and material availability. Instead, the results of a review of current literature in the area are presented.

Cooling system costing can readily be performed with reference to a "typical unit" conforming to design standards in "current practice"²². In existing power plants the practice previously had been, by far, the once-through cooling system. Being associated with a proposed beneficial use, this method is still of interest. When an isolated power plant is to be considered, however, alternative schemes are necessary. In considering such schemes, the difference in cost between each proposed

type and the base case is evaluated. Only the factors differing from the base case or from the alternatives need be considered in such an analysis. The method with the lowest cost difference is the best one.

To allow for cost variations with time, it becomes necessary to standardize costs by referring them to costs in a particular year. Such cost projections are possible by referring to cost indexes³⁴. In the present analysis, cost data were referred to 1980 construction and startup. It must be stressed that costs are subject to fluctuation which cannot always be accounted for in cost projections.

In the first part of the following discussion, source cost data is presented with explanatory notes as considered necessary. For the sake of completeness, general equations of cost analyses methods are presented. This should also provide an opportunity for further detailed study where desired. Subsequent sections present costs referred to the base year for alternative systems over the expected economic life.

Compilation of Source Data

Cooling towers as a cooling system type have been gaining in interest due to their compactness and minimal environmental effect, both in terms of land use and thermal effects³⁵. Methods for estimating operating costs and total costs are available³⁶⁻³⁹. From Table 16, it is evident that costs vary depending on the

manufacturer and also vary with time.

Table 16. Cooling Tower Cost Comparison for 2000 MW(e)

Source	Year	Cost per Transfer Unit* in \$ ³⁶	Cost in 10 ⁶ \$	
			Fossil **	Nuclear [†]
Marley Co.	1970	4.75	2.43	4.82
Dynatech	1971	6.75	3.46	6.85
Burns & Roe	1973	8.11	4.15	8.23
Marley Co.	1973	7.50	3.84	7.61

* Transfer Unit = (GPM) (RF) where RF = 0.89 for

$T_{WB} = 24^{\circ}C$ (75 F), Range = $14^{\circ}C$ (25 F),

Approach = $8^{\circ}C$ (15 F)¹⁴.

** GPM = 5.75×10^5

[†] GPM = 11.40×10^5

Capital cost data for cooling lakes and spray canals suitable for 2000 MW(e) nuclear plants³⁸ are presented in Table 17. Cooling tower costs for a 1000 MW(e) nuclear unit³⁹ are presented in Table 18. Table 19 may be formulated from Table 17 in order to estimate once-through cooling costs. A case study¹⁶ is presented in Table 20 for two types of cooling towers and a spray canal suitable for an 800 MW(e) fossil plant.

Table 17. Cooling Lake and Spray Canal Costs³⁸ (2000 MW(e))

Item	Cooling Lake 10 ⁶ \$ (1975)	Spray Canal 10 ⁶ \$ (1975)
Plant Area	0.56	1.27
Cooling System Area	5.82	0.61
Total Land Cost	7.38	1.88
Water Intake Line	2.16	2.16
Water Intake	0.17	0.17
Make Up Line	3.20	5.72
Pumps	0.76	0.46
Total Water Supply Cost	5.29	8.57
Clearing of Area	0.29	0.10
Dike Construction	7.32	1.59
Slope Protection	1.68	1.56
Spray Units	-	15.88
Total Cooling System Cost	9.29	19.03
Blowdown Ditch	0.40	0.09
Blowdown Pipe	0.90	1.68
Diffuser	0.63	0.63
Total Blowdown Cost	1.93	2.30
Total Cost	23.89	31.78

Table 18. Cooling Tower Capital Cost (1000 MW(e))³⁹

Item	Cost 10^6 \$ (1974)	$\frac{\$}{\text{KW}}$ (1974)
Circulating Pump Structure	0.811	0.76
Circulating Pumps and Motors	1.447	1.35
Circulating Pipe	1.832	1.71
Electrical Equipment	1.125	1.05
Tower and Basin	9.410	8.78
Total Cost	14.625	13.65

Table 19. Once Through Cooling System Cost (2000 MW(e))

Item	Cost in 10^6 \$ (1975)
Canal Area	0.61
Water Supply	8.51
Dike Construction	3.15
Total	12.27

Table 20. Comparative Cost Study¹⁶ (800 MW(a), Costs in 1971 \$/kW)

Item	Spray Canal	Natural Draft Tower	Mech. Draft Tower
Intake/Discharge	0.92	0.64	0.70
Earthwork	2.08	0.58	0.97
Circulating Water Pipe	1.94	1.15	2.54
Pumps and Motors	0.58	0.83	0.83
Cooling Equipment & Erection	2.98	6.76	3.28
Electrical	1.64	0.32	0.54
Total	10.14	10.28	8.86

Annual operating costs can be defined by the equation

$$O_C = C_M + C_B + C_F + C_{MT} + C_L \quad (6.1)$$

where

C_F = Fuel cost (\$0.30/million Btu - \$0.98/million Btu^{*})

C_{MT} = Maintenance cost (\$200/yr - tower cell. A cell handles, typically, 20,000 gpm³⁷.)

C_L = Cost of purchasing power from other utilities (\$0.008/kWh)^{*}

^{*}1974 figure. Escalation rates are discussed later.

C_M = Make up water cost, including treatment if necessary ($\$0.03/\text{m}^3$ - $\$0.40/\text{m}^3$)

C_B = Blowdown treatment cost ($\$0.00/\text{m}^3$ - $\$0.40/\text{m}^3$)

Operating cost is to be obtained in dollars per year. Annual Capital Cost Equivalent, C_{AE} , which includes effects of tax, insurance, inflation, amortization and salvage may be taken as 14.7% of initial capital investment for a twenty year economic life³⁶. Thus for a \$1000 investment, \$147 would have to be set aside each year over the life of the plant to pay for the various factors stated above. The above rate incorporates the effect of inflation through cost of capital, projected taxes, etc.

The total annual cost would therefore be the sum of operating costs and the capital cost equivalent. Details of cost calculations are presented in subsequent sections.

Table 21 lists fuel costs and anticipated escalation factors⁴⁰. The high cost of oil may preclude its wide use in new stations. Low sulphur coal was taken as a representative fossil fuel. Operating costs consist mainly of fuel cost and must be carefully calculated. In addition, fan and pumping costs for cooling towers and pumping costs for canals can be estimated as follows⁴¹.

Pumping Power: 0.89% of rated electrical output

Fan Power: 0.46% of rated electrical output

In order to estimate fuel cost it is necessary to evaluate the fuel requirement over the plant life.

Table 21. Fuel Costs⁴⁰

Fuel Type	Cost (1975 $\frac{\$}{10^6 \text{ B}}$)	Proposed Value ($\frac{\$}{10^6 \text{ B}}$)	Escalation Factors P_E			
			1975- 84	1985- 89	1990- 94	1995- 2005
Nuclear	0.45	0.45	1.79	6.00	6.00	8.00
Residual Oil	2.00 - 2.25	2.08	1.92	6.95	4.00	8.00
Distillate Oil	2.25 - 2.50	2.33	1.90	5.90	4.00	8.00
Low Sulphur Coal	1.25 - 1.35	1.25	1.54	4.00	4.00	8.00
High Sulphur Coal	1.00 - 1.10	1.03	1.54	4.00	4.00	4.00
Lignite Coal	0.80 - 1.30	1.26	1.52	4.00	4.00	4.00

Due to deterioration in material capacity, plant output decreases with age even though fuel requirements may remain the same. Although the change in efficiency is complicated, the following hypothetical rating was adopted for the purpose of this analysis (Table 22). The overall plant capability, calculated later in this chapter, agrees with data available in the literature¹⁸.

Table 22. Variation of Plant Capacity with Age

Year	Output Capacity as Percentage of Rated Output
0- 5	100
6-10	95
11-15	90
16-20	80

Because fuel cost is the principal operating cost, escalation was applied only to it and to the cost of purchased power. Escalation of water treatment and consumption costs, maintenance, etc., is very uncertain but fortunately has a small influence on the result.

The resulting total cost is

$$C_T = (C_{AE} + C_M + C_B + C_{MT}) n + \sum_l n_l (C_F + C_L) F_{E_l} \quad (6.2)$$

where

n = Number of years of economic life

i = Incremental period designation

F_E = Fuel cost escalation factor

n_i = Number of years in i th period

Alternate Economic Analysis

In this section, a review of equations relevant to cost estimation is presented¹⁸. Although these relations were not used in the present analysis, they have been included for completeness and should serve as guidelines for detailed work in the analysis of a specific plant.

Annual Capital Carrying Cost is given by

$$C_C = P \left[i + \frac{i}{(1+i)^n - 1} \right] + P(t+j) \quad (6.3)$$

where

C_C - Annual capital carrying cost

P - Present worth

i - Interest rate, expressed as a decimal fraction

n - Economic life of the plant

t - Tax rate per year, expressed as a decimal fraction

j - Insurance rate per year, expressed as a decimal fraction

The first term is called the Capital Recovery Factor.

The total annual cost becomes, therefore

$$C_A = C_C + O_C \quad (6.4)$$

Cost escalation for the various components can be accounted for in the following manner: If taxes increase by fraction e_t , insurance by fraction e_j and operating costs by e_o , then the present value of the total cost is given by

$$\begin{aligned}
 W_p = & P + Pt \left(\frac{1 + e_t}{1 + i} \right) + Pj \left(\frac{1 + e_j}{1 + i} \right) + O_c \left(\frac{1 + e_o}{1 + i} \right) \\
 & + Pt \left(\frac{1 + e_t}{1 + i} \right)^2 + Pj \left(\frac{1 + e_j}{1 + i} \right)^2 + O_c \left(\frac{1 + e_o}{1 + i} \right)^2 + \dots \\
 & \dots + Pt \left(\frac{1 + e_t}{1 + i} \right)^n + Pj \left(\frac{1 + e_j}{1 + i} \right)^n \\
 & + O_c \left(\frac{1 + e_o}{1 + i} \right)^n
 \end{aligned} \quad (6.5)$$

or, for $n \gg 1$ and $i > e_t, e_j, e_o$

$$W_p = P + Pt \left(\frac{1 + e_t}{1 - e_t} \right) + Pj \left(\frac{1 + e_j}{1 - e_j} \right) + O_c \left(\frac{1 + e_o}{1 - e_o} \right) \quad (6.6)$$

The total cost, levelized and taken for each year is given by

$$C_{AL} = W_p \left[i + \frac{i}{(1 + i)^n - 1} \right] \quad (6.7)$$

where the factor in square brackets reduces W_p to annual cost.

The cost of energy generation in \$/kWh can then be found from

$$\frac{\$}{\text{kWh}} = \frac{C_{AL}}{\frac{\text{kWh}}{\text{year}}} \quad (6.8)$$

The approach of using levelized annual costs can

incorporate the effect of spending money at different times during the life of the system, including escalation rates. In a period of high inflation relative to interest rates it is preferred to expend early in the period. On the other hand, if interest rates are high relative to inflation, it is preferable to delay payments. Because different systems can have varying payment rates in general, and the life of the system may vary as well, it may be important to base economic analysis on levelized annual costs. However, in the present case the difference in spending patterns is negligible because of the similarity of the equipment. Therefore, the simpler total cost analysis was performed without levelization. Total cost per unit energy (\$/kWh) was based on total cost over the life of the system including loss of capacity, in the numerator, and total energy output based on rated capacity over the life of the system, in the denominator.

Capital Costs of Alternative Cooling Systems

Fundamental to the comparison of capital costs of alternative systems is data reduction to the base year. Using cost index data ³⁴, capital costs for construction in 1980 were obtained.

The following illustrates the escalation rate employed here:

1980	\$1.00	1974	0.61
1978	0.84	1972	0.52
1976	0.73		

In practice, expenses accrue over a period of time and it is necessary to estimate costs of various stages. Nevertheless, the method used enables a comparative study of the alternatives. Reference to Table 23 indicates almost invariant values of cost per unit power rating, for closed-cycle systems, notwithstanding the fact that the data is for fossil and nuclear plants at different locations. While such an observation may not be universally applicable, it was assumed that capital cost of cooling for both fossil and nuclear plants are the same. Ordinarily, the lower thermal efficiency and the absence of stack losses would suggest greater cooling costs for nuclear systems than fossil plants. Since, the amortization cost is only approximately 1% of total cost, this discrepancy was not considered serious.

It should be noted that cooling system capital cost would be a small percentage of total power plant capital cost. This is especially so for the case of the nuclear power plant where the steam generator is designed with protective back-up systems and various accident prevention devices. The capital carrying cost for the entire plant would therefore be a greater percentage of the total annual cost. Since the present work is concerned with the estimation of incremental cost and cost comparison studies, only cost data pertaining to alternate cooling systems was considered.

Table 23. Capital Costs of Cooling Systems

System Type	Capital Cost (1980 \$ kW)	Proposed Cost (1980 \$ kW)
Once Through Cooling**	9.13	9.13
Cooling Lake ^{38**}	17.77	17.77
Spray Canal ^{38 **}	23.60	22.44
Spray Canal ^{16*}	21.27	
Mech. Draft Cooling Tower ^{39**}	22.15	20.37
Mech. Draft Cooling Tower ^{16*}	18.59	
Natural Draft Cooling Tower ^{16*}	21.57	21.57

* Fossil ** Nuclear.

Operating Costs of Cooling Systems

Annual operating costs of a cooling system may be estimated using Equation 6.1. Only the components not common to all systems need be studied since it is sought only to compare costs of alternatives. It is necessary to select a value representing the economic life of the plant, often taken as 20 years.

Operating costs over a 20-year period were evaluated accordingly. Plant age was assumed to reflect in increased power shortfall which would be offset by purchase of energy from another central station. The fuel requirement was assumed to be constant over the life, thus resulting in lower efficiency with increasing

age. It must be stressed that such a convenient assumption may not represent actual operating conditions. Furthermore, the cost of purchased energy could depend on the purchase quantity and plant location. Price variation of such energy would be difficult to predict accurately. It was assumed that the energy shortfall would be offset by purchasing power from a fossil fueled plant. Since fuel cost contributes the most to energy cost, the cost of purchased power was assumed to escalate at the same rate as fuel cost. The factors⁴⁰ listed in Table 21 were used to estimate power costs. Escalation in make-up water and water treatment costs were not evaluated as their proportion of total cost does not exceed 0.7%.

Cost penalties incurred due to plant outage were estimated based on outage patterns⁴⁰ presented in Table 24. Table 25 lists the total energy capability of the plant over its life. These values agree with data available in the literature¹⁸. Representative operating cost parameters³⁶ are summarized in Table 26. Tables 27 and 28 list computed parameters required for cost analysis over the economic life of the plant. Operating costs are listed in Table 29. Annual costs of fuel and purchased power are listed for five year periods, taking into account the cost escalation for each period.

The system which will meet the standards with the

Table 24. Plant Availability⁴⁰

Type	Planned Outage (% of year)	Forced Outage (% of operating period)	Availability (% of year)
Nuclear	15	15	72
Low Sulphur Coal	10	15	77
Oil (Residual/Distillate)	10	7	84
High Sulphur Coal	10	8	73

Table 25. Overall Plant Capability in Five Year Periods¹⁸

Annual Energy Capability				(10 ⁹ kWh)	
				Total Capability	Output*
0 - 5	6 - 10	11 - 15	16 - 20		
Fossil Plant					
13.49	12.82	12.14	10.79	246.20	350.40
Nuclear Plant					
12.61	11.98	11.35	10.09	230.15	350.40

*2000 MW for 20 years

Table 26. Operating Cost Parameters³⁶

Nature of Cost	Symbol	Cost in Dollars	Unit Quantity	Remarks
Make up Water	C_M	0.03 (0.11)	m^3 (10^3 gal)	Includes treatment cost per unit of condenser flow.
Blowdown Treatment	C_B	0.01 (0.04)	m^3 (10^3 gal)	
Maintenance	C_{MT}	5.03 (0.02)	$10^6 m^3$ (10^6 gal)	
Energy Cost	C_L		GJ (kWh)	Purchased
0 - 5 years		3.42 (0.012)		from
6 - 10 years		8.65 (0.031)		other
11 - 15 years		8.65 (0.031)		stations
16 - 20 years		17.30 (0.062)		

Table 27. Once Through System Performance Parameters

Plant and Season	Heat Req'd. PJ (10 ¹² B)	Seasonal Energy Output				Seasonal Energy Shortfall**			
		for Five Year Periods 10 ⁹ kWh				for Five Year Periods 10 ⁹ kWh			
		0 - 5	6 - 10	11 - 15	16 - 20	0 - 5	6 - 10	11 - 15	16 - 20
<u>Fossil</u>									
Summer	36.5 (34.6)	4.4	4.2	4.0	3.5	0.01	0.2	0.5	0.9
Spring/Fall*	72.5 (68.7)	8.8	8.3	7.9	7.0	0.0	0.4	0.9	1.8
Winter	35.7 (33.8)	4.3	4.1	3.9	3.5	-0.004	0.2	0.4	0.9
Annual Total†	111.4 (105.6)	13.5	12.8	12.1	10.8	4.0	4.7	5.4	6.7
<u>Nuclear</u>									
Summer	50.7 (48.0)	4.5	4.3	4.0	3.6	-0.03	0.2	0.4	0.9
Spring/Fall*	101.1 (95.8)	9.0	8.6	8.1	7.2	-0.2	0.2	0.7	1.5
Winter	49.7 (47.1)	4.4	4.2	4.0	3.5	-0.1	0.1	0.3	0.8
Annual Total†	145.1 (137.5)	12.9	12.3	11.6	10.3	4.6	5.3	5.9	7.2

* Total for both seasons ** Excludes auxiliary power requirements and outage effects
† Includes outage effects

Table 28. Closed-Cycle System Performance

Plant and Season	Blowdown 10 ⁶ m ³ (10 ⁹ gal)	Heat Required PJ (10 ¹² B)	Seasonal Energy Output				Seasonal Energy Shortfall**			
			for Five Year Periods				for Five Year Periods			
			10 ⁹ kWh				10 ⁹ kWh			
			0 - 5	6 - 10	11 - 15	16 - 20	0 - 5	6 - 10	11 - 15	16 - 20
<u>Fossil</u>										
Summer	2.4 (0.7)	36.5 (34.6)	4.3	4.1	3.9	3.5	0.1	0.3	0.5	0.9
Spring/Fall*	4.4 (1.3)	72.6 (68.8)	8.7	8.3	7.9	7.0	0.1	0.5	0.9	1.8
Winter	1.9 (0.6)	35.6 (33.8)	4.3	4.1	3.9	3.4	0.02	0.2	0.4	0.9
Annual Total†	6.7 (1.9)	144.7 (139.2)	17.3	16.5	15.7	13.9	0.2	1.0	1.8	3.6
<u>Nuclear</u>										
Summer	4.8 (1.4)	50.6 (47.9)	4.3	4.1	3.9	3.5	0.1	0.3	0.5	0.9
Spring/Fall*	8.7 (2.6)	100.7 (95.4)	8.8	8.4	7.9	7.1	-0.04	0.4	0.9	1.7
Winter	3.7 (1.1)	49.7 (47.1)	4.4	4.2	3.9	3.5	-0.05	0.2	0.4	0.8
Annual Total†	17.2 (5.1)	201.0 (190.4)	17.5	16.7	15.7	14.1	0.01	0.9	1.8	3.4

*Total for both seasons. **Excludes auxiliary power requirements and outage effects
[†]Includes outage effects

Table 29a. Operating Costs of Alternative Cooling Systems (in 10^6 \$, 1980 start-up, Large Sized Plant of 3000 MW(e))

Plant and System	Total Over Plant Life				C_L (Annual)				C_L Total	C_F (Annual)				C_F Total	O_C Total
	C_M	C_E	C_{WT}	Ann. Power	for Five Year Periods					for Five Year Periods					
					0 - 5	6 - 10	11 - 15	16 - 20		0 - 5	6 - 10	11 - 15	16 - 20		
Fossil															
Once Through	-	-	-	-	48.44	150.74	172.38	430.93	4012.00	203.20	520.00	520.00	1056.00	11576.40	15500.00
Cooling Lake	-	-	-	-	49.70	154.13	175.52	432.20	4050.15	203.20	520.00	520.00	1056.00	11576.40	15634.55
Spray Canal	0.04	1.34	0.12	54.56	49.70	154.13	175.52	432.20	4050.15	203.20	520.00	520.00	1056.00	11576.40	15690.61
Wet. Dr. Tower	0.04	1.34	0.12	52.70	49.70	154.13	175.52	432.20	4050.15	203.20	520.00	520.00	1056.00	11576.40	15726.03
Wet. Dr. Tower	0.04	1.34	0.12	54.56	49.70	154.13	175.52	432.20	4050.15	203.20	520.00	520.00	1056.00	11576.40	15690.61
Nuclear															
Once Through	-	-	-	-	55.39	168.36	189.81	460.60	4346.00	110.43	370.17	370.17	493.50	6721.65	11140.10
Cooling Lake	-	-	-	-	50.77	176.90	197.10	474.90	4530.75	110.43	370.17	370.17	493.50	6721.65	11260.40
Spray Canal	14.00	2.40	0.20	109.12	50.77	176.90	197.10	474.90	4530.75	110.43	370.17	370.17	493.50	6721.65	11387.12
Wet. Dr. Tower	14.00	2.40	0.20	105.56	50.77	176.90	197.10	474.90	4530.75	110.43	370.17	370.17	493.50	6721.65	11443.54
Wet. Dr. Tower	14.00	2.40	0.20	109.12	50.77	176.90	197.10	474.90	4530.75	110.43	370.17	370.17	493.50	6721.65	11387.12

Table 29b. Operating Cost of Alternative Cooling System (in 10^6 \$, 1980 start-up, Medium Sized Plant of 200 MW(e))

Plant and System	Total Over Plant Life				C_L (Annual)				C_L Total	C_p (Annual)				C_p Total	O_C Total
	C_N	C_D	C_{WT}	Aux.	for Five Year Periods					for Five Year Periods					
					Power	0 - 5	6 - 10	11 - 15		16 - 20	0 - 5	6 - 10	11 - 15		
<u>Fossil</u>															
Once Through	-	-	-	-	4.84	15.07	17.23	43.09	401.15	20.40	53.00	53.00	106.00	1162.00	1563.15
Cooling Lake	-	-	-	-	4.90	15.41	17.55	43.22	405.00	20.40	53.00	53.00	106.00	1162.00	1567.80
Spray Canal	0.80	0.13	0.01	5.47	4.90	15.41	17.55	43.22	405.00	20.40	53.00	53.00	106.00	1162.00	1574.21
Mech. Dr. Tower	0.80	0.13	0.01	5.27	4.90	15.41	17.55	43.22	405.00	20.40	53.00	53.00	106.00	1162.00	1577.01
Wat. Dr. Tower	0.80	0.13	0.01	5.47	4.90	15.41	17.55	43.22	405.00	20.40	53.00	53.00	106.00	1162.00	1574.21
<u>Nuclear</u>															
Once Through	-	-	-	-	5.56	16.04	18.90	46.06	436.70	11.00	37.13	37.13	49.50	674.20	1110.90
Cooling Lake	-	-	-	-	5.80	17.65	19.71	47.50	453.90	11.04	37.00	37.00	49.32	671.00	1125.70
Spray Canal	1.49	0.25	0.02	10.90	5.80	17.65	19.71	47.50	453.90	11.04	37.00	37.00	49.32	671.00	1130.36
Mech. Dr. Tower	1.49	0.25	0.02	10.34	5.80	17.65	19.71	47.50	453.90	11.04	37.00	37.00	49.32	671.00	1144.00
Wat. Dr. Tower	1.49	0.25	0.02	10.90	5.80	17.65	19.71	47.50	453.90	11.04	37.00	37.00	49.32	671.00	1130.36

lowest total cost would be the best choice. Table 30 presents these data. The once-through system was selected as the base case, and incremental costs were evaluated. It appears that the natural draft cooling tower would be the best choice. Being compact in terms of land use, and requiring lesser maintenance than the mechanical-draft type tower, this method would be well suited for the purpose.

The following sections estimate possible economic benefits obtainable from interconnected plants. The employment of a lower average cooling water temperature enables savings in cost for both plants, as is evident from the calculations presented.

Interconnected Wastewater Treatment System Economics

Savings in cost occur for both the power plant and the wastewater treatment plant. The decrease in turbine exhaust pressure serves to improve thermal efficiency. In the proposed scheme, the cooling system handles only a part of the total cooling water flow, the rest being diverted to the treatment plant (Fig. 3). The savings realized in terms of pumping power is offset by the increased pumping power required by the treatment plant. However, greater benefits accrue to the treatment plant where sludge heating is provided by hot water instead of by fuel oil or gas for most of the year. The use of elevated temperatures enables employment of less

Table 30a. Total Cost of Cooling Methods (Large Sized Plant, 10^6 \$, 1980 start-up)

Plant and System	Cap. Cost Equiv. of Cooling System	Operating Cost	Total Cost	Cost Diff.	Cost Diff. mills/kWh*	Incremental Cost \$
Fossil						
Once-Through	53.68	15588.40	15632.08	Base	-	-
Cooling Lake	104.49	15634.55	15739.04	106.96	0.30	0.68
Spray Canal	131.95	15698.61	15830.56	198.48	0.57	1.27
Mech. Dr. Tower	119.78	15726.83	15846.61	214.53	0.61	1.37
Nat. Dr. Tower	126.83	15698.61	15825.44	193.36	0.55	1.24
Nuclear						
Once-Through	53.68	11108.10	11161.78	Base	-	-
Cooling Lake	104.49	11260.40	11364.89	203.11	0.58	1.30
Spray Canal	131.95	11387.12	11519.07	357.29	1.02	2.29
Mech. Dr. Tower	119.78	11443.56	11563.34	401.56	1.15	2.57
Nat. Dr. Tower	126.83	11387.12	11513.95	352.17	1.01	2.25

*Total kWh required from plant.

Table 30b. Total Cost of Cooling Methods (Medium Sized Plant, 10^6 \$, 1980 start-up)

Plant and System	Cap. Cost Equiv. of Cooling System	Operating Cost	Total Cost	Cost Diff.	Cost. Diff. mills/kWh	Incremental Cost ¢
Fossil						
Once-Through	5.37	1563.15	1568.52	Base	-	-
Cooling Lake	10.45	1567.80	1578.25	9.73	0.28	0.62
Spray Canal	13.20	1574.21	1587.41	18.89	0.54	1.20
Mech. Dr. Tower	11.98	1577.01	1588.99	20.47	0.58	1.31
Nat. Dr. Tower	12.68	1574.21	1586.89	18.37	0.52	1.17
Nuclear						
Once-Through	5.37	1110.90	1116.27	Base	-	-
Cooling Lake	10.45	1125.70	1136.15	19.88	0.57	1.27
Spray Canal	13.20	1138.36	1151.56	35.29	1.01	2.25
Mech. Dr. Tower	11.98	1144.00	1155.98	39.71	1.13	2.53
Nat. Dr. Tower	12.68	1138.36	1151.04	34.77	0.99	2.22

extensive equipment for secondary treatment. The question of standby capability is discussed below.

It was assumed that the two plants would be co-located and no account of cost for laying pipes between the plants was taken. Table 31 lists capital costs of wastewater treatment equipment⁴². Tables 32 and 33 list annual cost of operating the equipment. Cost escalation of fuel oil was considered.

Table 31. Capital Costs of Wastewater Treatment Equipment
(10⁶ \$ (1980))⁴²

Equipment Type	Plant Size		
	Small	Medium	Large
	0.5 m ³ /s	2.7 m ³ /s	27.3 m ³ /s
	(5 Mgd)	(30 Mgd)	(300 Mgd)
Primary/Secondary Treatment:			
a) With Recycle*	3.22	13.23	92.02
b) Without Recycle	3.22	13.53	106.99
Sludge Digester:			
Equipment and Installation			
	0.18	0.36	2.61

* No hot water required for small plant.

Table 32. Annual Costs of Primary/Secondary Treatment⁴²
(10⁶ \$ (1980))

Case & Cost	Wastewater Plant Size		
	Small	Medium	Large
<u>1. Reduced Size Using Recycled Hot Water</u>			
Amortization Cost	0.25	1.04	7.20
Operating Cost	0.16	0.62	4.39
Total Cost	0.41	1.66	11.59
<u>2. Full Size Without Recycled Hot Water</u>			
Amortization Cost	0.25	1.06	8.37
Operating Cost	0.16	0.61	4.80
Total Cost	0.41	1.67	13.17
<u>3. Full Size Using Recycled Hot Water</u>			
Amortization Cost	0.25	1.06	8.37
Operating Cost	0.16	0.62	4.39
Total Cost	0.41	1.68	12.76

Temperature rise for each size of plant: Small 10 C (18 F)
Medium 15 C (27 F)
Large 20 C (36 F)

Table 33. Annual Costs of Sludge Heating (10^6 \$, 1980 start-up)

System Size	Heat Exchanger Amortization Cost ⁴²	Fuel Cost for Five-Year Periods							
		With Recycle				Without Recycle			
		0 - 5	6 - 10	11 - 15	16 - 20	0 - 5	6 - 10	11 - 15	16 - 20
Small	0.010	0.003	0.010	0.007	0.090	0.010	0.030	0.020	0.040
Medium	0.020	0.030	0.080	0.050	0.100	0.070	0.210	0.140	0.280
Large	0.160	0.270	0.830	0.560	1.120	0.840	2.600	1.770	3.530

The cooling system was sized to provide full capacity without recycle. Thus, the power plant benefits during coupling due to reduced operating costs due to improved thermal efficiency. This procedure facilitates the matching of flow rates, and the data to which we refer may be regarded as average values. Further, in the event of wastewater plant outages, the power plant may continue to operate. While this is unlikely, it does provide for meeting full cooling demand at all times.

For the treatment plant, savings were calculated with respect to an isolated treatment plant using fuel oil for sludge heating. In order to evaluate possible real system behavior three cases were evaluated. The first case is sized for heating throughout the year. The base case represents independent operation and is denoted Case 2. Case 3 represents the situation when a treatment plant capable of independent operation uses hot water heating.

The need for full capacity of the wastewater plant for independent operation is uncertain. Because typically only 20% of cooling water for a fossil plant and 10% for a nuclear plant is involved in the coupling, the power plant could be derated to about 10% - 20% of capacity and still provide adequate recycle hot water (by turning off or bypassing part of the cooling system). Outages

of one of two generating units would be fully acceptable. In effect, only unplanned outages are of concern. Because the wastewater plants have an appreciable capacitance of several hours or more, and because they are built with substantial safety factors, the Case 1 of coupled designs with reduced wastewater plant size is felt meaningful. Nevertheless, the more conservative approach is to design for full capacity independent operation (Case 3).

Total cost data for the three sizes of wastewater plants are given in Table 34. The data for small wastewater plants are obtainable essentially independent of the size of the power plant because only a small amount of hot water is needed to heat the sludge digesters. Power plant costs for large-large (power-wastewater) and medium-medium interconnected plants are given in Tables 35-38. As noted previously, the case of small-small plant interconnection can be obtained by linear extrapolation. Incremental savings in power plant costs and in wastewater plant costs are given in Tables 39 and 40.

Economics of Pre-heated Municipal Water Supply

Discharging water into the municipal water supply system would result in improved power plant performance as the effect would be equivalent to once-through cooling. It is anticipated that a back up cooling system would

Table 34. Total Cost of Wastewater Systems (10⁶ \$, 1980 start-up)

Cases and Cost	Small**	Medium*	Large*
1. Reduced Size Using Recycled Hot Water.			
Primary/Secondary Treatment	8.2	33.2	231.8
Sludge Heating*	0.4	1.7	17.1
Total Cost	8.6	34.9	248.9
2. Full Size Without Recycled Hot Water.			
Primary/Secondary Treatment	8.2	33.4	263.4
Sludge Heating	0.7	3.9	46.9
Total Cost	8.9	37.3	310.3
3. Full Size With Recycled Hot Water.			
Primary/Secondary Treatment	8.2	33.6	255.2
Sludge Heating*	0.4	1.7	17.1
Total Cost	8.6	35.3	272.3

*Using fuel oil in winter.

**Linked to small, medium or large power plants.

*Linked to corresponding size power plants.

Table 35. Parameters of Large Sized Interconnected Plants

Plant and Season	Heat Required		Digester Heat from fuel TJ (10^{12} B)	Seasonal Energy Output for Five-Year Periods				Seasonal Energy Shortfall for Five-Year Periods*			
	PJ (10^{12} B)			10^9 kWh				10^9 kWh			
	PJ	(10^{12} B)		0-5	6-10	11-15	16-20	0-5	6-10	11-15	16-20
Fossil											
Summer	36.6	(34.7)	-	4.4	4.1	3.9	3.5	0.1	0.3	0.5	0.9
Spring-Fall**	72.2	(68.4)	-	8.7	8.3	7.8	7.0	0.1	0.5	0.9	1.8
Winter	35.7	(33.8)	63.6 (0.1)	4.3	4.1	3.9	3.5	0.01	0.2	0.5	0.9
Annual Total†	111.3	(105.4)	63.6 (0.1)	13.9	12.7	12.1	10.7	3.6	4.8	5.5	6.8
Nuclear											
Summer	50.6	(48.0)	-	4.4	4.1	3.9	3.5	0.1	0.3	0.5	0.9
Spring-Fall**	100.6	(95.3)	-	8.8	8.4	7.9	7.0	-0.02	0.4	0.9	1.7
Winter	49.7	(47.0)	63.6 (0.1)	4.4	4.2	3.9	3.5	-0.1	0.2	0.4	0.8
Annual Total†	144.7	(137.0)	63.6 (0.1)	12.6	12.0	11.4	10.1	4.9	5.5	6.2	7.4

* Total for both seasons.

** Excludes auxiliary power requirements and outage effects.

† Includes outage effects.

Table 36. Parameters of Medium Sized Interconnected Plants

Plant and Season	Heat Required		Digester Heat from fuel TJ (10^{12} B)	Seasonal Energy Output for Five-Year Periods				Seasonal Energy Shortfall for Five-Year Periods*			
	PJ (10^{12} B)			10^9 kWh				10^9 kWh			
				0-5	6-10	11-15	16-20	0-5	6-10	11-15	16-20
Fossil											
Summer	3.7	(3.5)	-	0.4	0.4	0.4	0.4	0.01	0.03	0.1	0.1
Spring-Fall**	7.2	(6.8)	-	0.9	0.8	0.8	0.7	0.01	0.1	0.1	0.2
Winter	3.6	(3.4)	6.4 (0.01)	0.4	0.4	0.4	0.4	0.001	0.02	0.1	0.1
Annual Total†	11.1	(10.5)	6.4 (0.01)	1.4	1.3	1.2	1.1	0.4	0.5	0.6	0.7
Nuclear											
Summer	5.1	(4.8)	-	0.4	0.4	0.4	0.4	0.01	0.03	0.1	0.1
Spring-Fall**	10.1	(9.5)	-	0.9	0.8	0.8	0.7	-0.002	0.04	0.1	0.1
Winter	5.0	(4.7)	6.4 (0.01)	0.4	0.4	0.4	0.4	-0.01	0.02	0.04	0.1
Annual Total†	14.7	(13.7)	6.4 (0.01)	1.3	1.2	1.1	1.0	0.5	0.6	0.6	0.7

* Total for both seasons.

** Excludes auxiliary power requirements and outage effects.

† Includes outage effects.

Table 37a. Interconnected Power Plant Operating Costs (Large Sized Plants, 10^6 \$, 1980 start-up)

Plant and System	Total Over Plant Life		C_L (Annual) for Five-Year Periods				C_L Total	C_P (Annual) for Five-Year Periods				O_C Total
	C_{MT}	Aux. Pwr.										
			0-5	6-10	11-15	16-20		0-5	6-10	11-15	16-20	
Fossil												
Cooling Lake	0.00	0.00	43.61	153.72	175.15	435.94	4042.1	202.90	527.00	527.00	1054.00	15596.60
Spray Canal	0.12	54.56	43.61	153.72	175.15	435.94	4042.1	202.90	527.00	527.00	1054.00	15651.20
Mech. Dr. Tower	0.12	77.18	43.61	153.72	175.15	435.94	4042.1	202.90	527.00	527.00	1054.00	15673.90
Nat. Dr. Tower	0.12	54.56	43.61	153.72	175.15	435.94	4042.1	202.90	527.00	527.00	1054.00	15651.20
Nuclear												
Cooling Lake	0.00	0.00	58.80	176.99	197.19	475.15	4540.65	110.35	369.90	369.90	493.20	11257.40
Spray Canal	0.24	109.11	58.80	176.99	197.19	475.15	4540.65	110.35	369.90	369.90	493.20	11366.75
Mech. Dr. Tower	0.24	159.86	58.80	176.99	197.19	475.15	4540.65	110.35	369.90	369.90	493.20	11417.50
Nat. Dr. Tower	0.24	109.11	58.80	176.99	197.19	475.15	4540.65	110.35	369.90	369.90	493.20	11366.75

Table 37b. Interconnected Power Plant Operating Costs (Medium Sized Plants, 10^6 \$, 1980 start-up)

Plant and System	Total Over Plant Life		C_L (Annual) for Five-Year Periods				C_L Total	C_P (Annual) for Five-Year Periods				O_C Total
	C_{MT}	Aux. Pwr.										
			0-5	6-10	11-15	16-20		0-5	6-10	11-15	16-20	
Fossil												
Cooling Lake	0.00	0.00	4.36	15.37	17.52	43.59	404.20	20.21	52.50	52.50	105.00	1555.25
Spray Canal	0.01	5.43	4.36	15.37	17.52	43.59	404.20	20.21	52.50	52.50	105.00	1560.68
Mech. Dr. Tower	0.01	7.70	4.36	15.37	17.52	43.59	404.20	20.21	52.50	52.50	105.00	1562.95
Nat. Dr. Tower	0.01	5.43	4.36	15.37	17.52	43.59	404.20	20.21	52.50	52.50	105.00	1560.68
Nuclear												
Cooling Lake	0.00	0.00	5.88	17.70	19.72	47.52	454.10	11.04	36.99	36.99	49.32	1125.80
Spray Canal	0.02	10.89	5.88	17.70	19.72	47.52	454.10	11.04	36.99	36.99	49.32	1136.69
Mech. Dr. Tower	0.02	15.97	5.88	17.70	19.72	47.52	454.10	11.04	36.99	36.99	49.32	1141.77
Nat. Dr. Tower	0.02	10.89	5.88	17.70	19.72	47.52	454.10	11.04	36.99	36.99	49.32	1136.69

Table 38a. Total Cost of Cooling Methods for Interconnected Power Plant (Large Sized Plants, 10^6 \$, 1980 start-up)

Plant and System	Cooling System Cap. Cost Equiv.	Operating Cost	Total Cost
Fossil			
Cooling Lake	104.49	15596.60	15701.09
Spray Canal	131.95	15651.28	15783.23
Mech. Dr. Tower	119.78	15673.90	15793.68
Nat. Dr. Tower	126.83	15651.28	15778.11
Nuclear			
Cooling Lake	104.49	11257.40	11361.89
Spray Canal	131.95	11366.75	11498.70
Mech. Dr. Tower	119.78	11417.50	11537.28
Nat. Dr. Tower	126.83	11366.75	11493.58

Table 38b. Total Cost of Cooling Methods for Interconnected Power Plant (Medium Sized Plants, 10^6 \$, 1980 start-up)

Plant and System	Cooling System Cap. Cost Equiv.	Operating Cost	Total Cost
Fossil			
Cooling Lake	10.45	1555.25	1565.70
Spray Canal	13.20	1560.68	1573.88
Mech. Dr. Tower	11.98	1562.95	1574.93
Nat. Dr. Tower	12.68	1560.68	1573.36
Nuclear			
Cooling Lake	10.45	1125.80	1136.25
Spray Canal	13.20	1136.69	1149.89
Mech. Dr. Tower	11.98	1141.77	1153.75
Nat. Dr. Tower	12.68	1136.69	1149.37

Table 39a. Power Plant Cost and Savings (Large Sized Plants, 10^6 \$, 1980 start-up)

Plant and System	Total Cost		Savings	Unit Savings mills/kWh	Incremental Savings %
	Isolated Plant	Combined Plant			
Fossil					
Cooling Lake	15739.04	15701.09	37.95	0.11	0.24
Spray Canal	15830.56	15783.23	47.33	0.14	0.30
Mech. Dr. Tower	15846.61	15793.68	52.93	0.15	0.33
Nat. Dr. Tower	15825.44	15778.11	47.33	0.14	0.30
Nuclear					
Cooling Lake	11364.89	11361.89	3.00	0.01	0.03
Spray Canal	11519.07	11498.70	20.37	0.06	0.18
Mech. Dr. Tower	11563.34	11537.28	26.06	0.07	0.23
Nat. Dr. Tower	11513.95	11493.58	20.37	0.06	0.18

Table 39b. Power Plant Cost and Savings (Medium Sized Plants, 10^6 \$, 1980 start-up)

Plant and System	Total Cost		Savings	Unit Savings mills/kWh	Incremental Savings %
	Isolated Plant	Combined Plant			
Fossil					
Cooling Lake	1578.25	1565.70	12.55	0.36	0.80
Spray Canal	1587.41	1573.88	13.53	0.39	0.85
Mech. Dr. Tower	1588.99	1574.93	14.06	0.40	0.88
Nat. Dr. Tower	1586.89	1573.36	13.53	0.39	0.85
Nuclear					
Cooling Lake*	1136.15	1136.25	-0.10	-0.003	-0.01
Spray Canal	1151.56	1149.89	1.67	0.05	0.15
Mech. Dr. Tower	1155.98	1153.75	2.23	0.06	0.19
Nat. Dr. Tower	1151.04	1149.37	1.67	0.05	0.15

* Not expected to be used.

Table 40. Wastewater Treatment Cost and Savings (10^6 \$, 1980 start-up)

Plant Size	Plant Interconnection % of Year			Savings		Incremental Savings	
	0	100	77/72*	100	77/72*	100	77/72*
Small**	8.90	8.60	8.67/ 8.68	0.30	0.23/ 0.22	3.37	2.58/ 2.47
Medium*	37.30	34.90	35.45/ 35.57	2.40	1.95/ 1.73	6.43	5.23/ 4.64
Large*	310.30	248.90	263.02/266.09	61.40	47.28/44.21	19.79	15.24/14.25

* 77% for fossil plant, 72% for nuclear plant. Based on assumed power plant availability.

** Connected to small, medium or large power plants.

* Connected to corresponding size power plants.

be required for the plant with suitable facilities for allowing water supply flow to bypass the plant. Such a facility would be necessary in the event of contamination of water flowing through the plant. The bypass would also be required if the power plant were to be shut down for cooling system maintenance. Table 41 lists the savings by employing such a system for the medium sized power plant. As noted in the last chapter, large sized power plants would serve too large a population to be realistic. However, the percentage savings would be the same for any size of power plant in terms of thermal performance.

The user of heated water would benefit from this system due to decreased water heating costs. Maximum savings are expected to be 14% for gas fired heaters and 22% for electric heaters, the annual heat requirements for such heaters being 39.92 GJ (378 therms) for gas heaters and 21.66 GJ (6017 kWh) for electric heaters¹¹.

Based on representative cost data for gas and electric supply* (gas: \$0.308/therm, electricity \$0.0474/kWh), data presented in Table 42 was obtained. It is expected that the utility would have alternative consumers for gas. The available electric energy could be sold to other consumers at the same price. Even if

* Residential rates for non-electric heated homes, Chicago, Illinois, 1978

Table 41. Power Plant Savings for Water Supply Discharge System (10^6 \$, 1980 start-up)*

Plant and Backup System	Total Base Cost	Cost with Water Supply	Savings	Unit Savings mills/kWh	Incremental Savings %
Fossil					
Cooling Lake	1578.25	1573.60	4.65	0.13	0.29
Spray Canal	1587.41	1576.35	11.06	0.32	0.70
Mech. Dr. Tower	1588.99	1575.13	13.86	0.40	0.87
Nat. Dr. Tower	1586.89	1575.83	11.06	0.32	0.70
Nuclear					
Cooling Lake	1136.15	1121.35	14.80	0.42	1.30
Spray Canal	1151.56	1124.10	27.46	0.78	2.39
Mech. Dr. Tower	1155.98	1122.88	33.10	0.95	2.86
Nat. Dr. Tower	1151.04	1123.58	27.46	0.78	2.39

* Medium sized plant of 200 MW(e).
For 2000 MW(e), multiply absolute costs and savings by ten.

there were no commercial buyers, the utility may be able to decrease any energy shortfall or sell the energy to another utility. A typical value of energy sold to another utility would be \$0.012/kWh resulting in an average annual offset of \$2.6 million (1980 dollars) to the utility. Savings for subsequent years may be found by multiplying 1980 savings by the appropriate escalation factors listed in Table 21, it being assumed that additional power would be purchased from a fossil plant using low-sulphur coal.

Table 42. Savings in Water Heating Costs*

Heater Type	Annual Energy Required GJ	Energy Savings GJ	Cost Reduction [†] per Home \$/yr	Gas/ Electricity Revenue Lost 10 ⁶ \$/yr
Gas	39.92 (378 therms)	5.59 (53 therms)	16.32	8.16
Electric	21.66 (6017 kWh)	4.77 (1323 kWh)	62.71	31.36

* Based on 1978 rates for Chicago, Illinois

[†] Family of four

The discharge of warmer water into sewage pipes

would raise wastewater temperature thus enabling the use of less expensive water treatment equipment. The increase in sewage temperature would be about 0.6 C (1.0 F) to 1.1 C (2.0 F)¹¹. Table 43 documents possible savings to the wastewater treatment plant⁴². Significant savings are realizable in the primary/secondary treatment process. Savings are also realizable in sludge heating costs for medium and large sized plants. The elevation in water temperature increases the sludge quantity in small wastewater plants and, as a consequence, indicates slightly increased sludge heating cost. There is net savings in water treatment cost in all the three cases. Sludge heating costs are based on anticipated costs of distillate oil as calculated from data in Table 21 and would vary depending on oil price fluctuation.

Table 43. Savings in Wastewater Treatment Cost (1980 Start-up)

Plant Size	Primary/Secondary Treatment \$/yr	Savings %	Average Annual Savings for Sludge Heating in \$/yr	Sludge Heating Savings %
Small	8938	2.18	-68.62	-0.22
Medium	44255	2.65	781.86	0.43
Large	516264	3.92	7477.92	0.41

The foregoing analysis indicates that savings for the power plant as well as for the wastewater treatment plant may be realized by using a pre-heated water supply. The flow of warm water could also prevent freezing of water pipes in severe winters. However, the cost savings are difficult to assess. Other benefits and penalties are discussed by Wynn and Porter¹¹.

Conclusions

It appears that savings may be realized for the power plant as well as for the water supply user and wastewater treatment plant when water supply systems are to be used instead of closed cycle cooling systems even when the latter are in standby status. There would be significant savings for the power plant and the wastewater treatment plant when the two systems are interconnected.

Although the preliminary cost analysis is based upon numerous simplifying assumptions, it does nevertheless represent a rational approach to cost analysis methods. Dependent as most costs are on local conditions, it would be necessary to study individual cases if more accurate results are sought.

CHAPTER VII

CONCLUSIONS

Results and Conclusions

The present work was intended primarily as an attempt to develop a rational method of selection of cooling system alternatives. Increasingly stringent environmental regulations, coupled with a decrease in conventional energy source reserves has necessitated a more intensive search for efficient energy utilization methods. Methods involving minimal cost alone are no longer acceptable unless they simultaneously meet environmental standards.

The employment of nuclear plants has heightened the thermal pollution problem in recent years. The lower thermal efficiency of nuclear plants results in heat rejection rates which are twice that of a fossil plant with the same electric power rating. The simultaneous trend towards larger sized central stations has intensified the severity of environmental impact. While the specified discharge standards can be met by appropriately sizing the cooling system, an inevitable consequence is increased cost. The restrictions on discharging heated water directly into natural waterways and reservoirs therefore, has to be accounted for when designing new plants and exploring the possibility of mitigating environmental damage due to existing plants. It is therefore necessary

to consider the use of closed cycle cooling systems even though this could result in plant output being reduced by as much as 2.8% with respect to the corresponding open cycle cooling system.

In considering the possible choice of closed cycle cooling systems, which generally exhibit almost identical thermal performance when properly sized, the primary selection criterion would be cost. Of course, site specific environmental constraints, land availability, etc. are also factors. For example, although the data presented in the foregoing discussion suggests that the cooling lake would be the best choice, it should be noted that efficient land utilization is a factor which cannot always be estimated in terms of cost alone. Furthermore, land costs vary widely with location. Thus, it is generally advantageous to consider the use of more compact cooling systems. In terms of land use alone, the cooling tower would be the logical choice.

Even though the initial cost is higher for the natural draft cooling tower, a lower operating cost results in lower total cost when compared with the mechanical draft device, the incremental costs for fossil plants being 0.55 mills/kWh (natural-draft) and 0.61 mills/kWh (mechanical-draft) and for nuclear plants being 1.01 mills/kWh (natural-draft) and 1.15 mills/kWh (mechanical-draft), respectively. Spray canal costs are 0.57 mills/kWh

(fossil) and 1.02 mills/kWh (nuclear), intermediate to mechanical and natural draft towers. Therefore, they may be the best choice if natural draft towers are unacceptable due to visual impact on the surroundings, interference with aircraft flight paths, etc., or if it is desired to modularize the system into smaller units in order to facilitate shipment, erection and construction, and operation under part load. The modular concept of spray modules, or mechanical-draft cells in cooling towers, lends itself to plant expansion as well.

On the other hand, it appears desirable that the available waste heat be utilized gainfully rather than simply disposed. The preliminary investigation performed indicates that an overall annual savings between 2.5% for a small plant and 15% for a large plant could be realizable for wastewater treatment plants. (Savings in the primary/secondary treatment stages alone could be up to 2.5% by simply diluting wastewater with hot water and using some of the effluent as make-up.) The effect on the power plant is somewhat equivalent to using larger make-up and blowdown quantities caused by discharging 10% - 20% of the heated condenser water to the sewage plant and returning this flow to the plant at a temperature lower than that of cooled water from the cooling facility.

Savings of up to 0.14 mills/kWh for spray canals and natural-draft towers and up to 0.15 mills/kWh for mechanical-draft towers are possible for a large sized fossil plant. The corresponding figures for a large nuclear plant are 0.06 mills/kWh and 0.07 mills/kWh. While the net cost to the consumer for electric power is typically 45 mills/kWh, it should be realized that the cost of production is a very small portion of the total. Indeed, the potential savings is of the order of the difference in costs between typical competing cooling systems.

Beyond the savings in costs, the savings in fuel is a principal benefit. Most important, the use of waste heat instead of oil for heating sludge would have a potential savings of 21688 barrels per year based on the assumption of 150 gallons/day of wastewater per capita for a city with two million population. Further, power-plant fuel consumption would be reduced by about 0.1% (fossil) and 0.03% (nuclear). In effect, coal would be made a more attractive fuel, air pollution and size of scrubber reduced, etc. Alternatively oil and gas reserves would be extended. Even nuclear fuel reductions would have significant additional benefits such as reducing wastes to be disposed.

Savings obtained by using a heated water supply would primarily reflect in improved thermal efficiency, the effect being equivalent once-through cooling. In spite of having to build up a back-up cooling system, annual savings up to 2.9% could be realized with respect to the corresponding closed cycle operation. Maximum savings would be realizable from a mechanical-draft tower, namely 0.40 mills/kWh (fossil) and 0.95 mills/kWh (nuclear). Corresponding figures for a spray canal and a natural-draft tower are 0.32 mills/kWh (fossil) and 0.78 mills/kWh (nuclear). Furthermore, the users of hot water would be able to save 14% of the energy for gas heaters and 22% for electric heaters. Annual cost reduction per home would be \$16.32 for gas heaters and \$62.71 for electric heaters. Although these savings would reflect in decreased revenue to the utility, it is expected that other consumers would purchase the available energy at least in the case of gas which is being rapidly depleted. The discharge of warmer water into the sewage system would result in slightly increased wastewater temperatures enabling overall wastewater treatment savings ranging from 2% for a small plant to 3.5% for a large plant.

It is important to note that most hot water heater energy is derived from natural gas. Thus, saving 14% of natural gas consumption of water heaters could extend precious gas reserves appreciably.

Recommendations for Further Study

Certain modifications and extensions should yield more accurate estimates. While it was not attempted to compile an exhaustive list, certain salient points are discussed below.

Ambient parameters may be standardized for monthly, or even daily periods, improving evaluation of performance data. Knowledge of more precise load patterns and anticipated outage schedules would enable the estimation of operating costs with greater accuracy. Detailed data regarding seasonal thermal performance of heat exchangers would further facilitate accurate evaluation of annual performance and cost. The need for accurate cost data, which is site specific and subject to variation, cannot be overstressed. It must be reiterated that the present work is only an attempt to indicate a method of selection. Individual cases would have to be analyzed in detail before judging the economic viability of a particular system.

It appears that the evaporative cooling system, by virtue of its large air-water interface could also be used for wastewater aeration. Currently, aeration is achieved by blowing air through the wastewater. While standby aeration units would be necessary, operating costs would be reduced.

In the present study, equipment, operational and maintenance costs were based on rated capacity according to recent experience documented in the literature. However, while these figures are hopefully realistic, they may not be optimum. Instead, it is proposed that the aforementioned costs be determined as a function of NTU, the parameter of the unified analysis of cooling systems. The expressions for NTU based on the equations and notation of Chapter II are, by inspection

$$\begin{aligned}
 \text{NTU} &\cong \dot{K}A / (\dot{m} b_f) && , \text{ cooling pond,} \\
 & && T_{WB} \cong E \\
 &\cong N(1-f)r \text{ ntu} && , \text{ spray canal,} \\
 & && \text{ntu} \ll 1 \\
 &\cong \dot{K}A_T / \dot{m} && , \text{ wet tower,} \\
 & && L/G \ll 1
 \end{aligned}$$

It should be noted that improvements can be made in cooling-pond analysis by using E instead of T_{WB} (Eq. 2.1). Similarly, by increasing the T_{WB} of a cooling tower, one may account for non-infinitesimal L/G which results in heating and humidification of the air stream. However, these modifications defeat the purpose of the unified model represented by the hypothetical system. And, as shown in Table 3, this model and system give reasonable results. Thus, it is proposed that a single design NTU still be determined to represent all alternative cooling

systems. However, the cost of achieving this NTU would be determined individually for each type system based on previous experience in terms of cost and observed performance. In this way, it should be possible to determine costs of alternate systems as a function of NTU. Present experience could then be used to interpolate and extrapolate with due caution, to new designs on a more rigorous thermodynamic and economic basis.

This approach would also facilitate a statistical study including the uncertainty of meeting specific design conditions. That is, in the current work it was implied that if the particular cooling system were built, it would exactly meet design conditions. In reality, this may not be the case. The proposed technique would make it feasible to incorporate the consequence of exceeding or of falling short of design performance, over the life of the system. Either case is not optimal. In one instance, capital costs are excessive; while in the other instance, loss of capacity costs are high. This information would also be useful in determining the most cost-effective performance acceptance test, because even its cost will increase with test accuracy.⁴² The optimal test could best account for the possible effect of a hidden short fall (or excess) of performance due to test instrumentation error, over the life of the system. After such a test, adjustments could be made in the equipment in order to achieve apparent design conditions. These adjustments might be made under the terms of performance guarantees which in turn will influence the cost of the equipment depending on cooling-system technology.

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