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**BENEFICIAL UTILIZATION OF WASTE HEAT FROM POWER
PLANTS IN WASTEWATER TREATMENT SYSTEMS**

By
Sun-Nain Ni
Alan W. Obayashi

June 1979

Work Performed Under Contract No. EC-77-S-02-4531

Illinois Institute of Technology
Chicago, Illinois

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**Division of Conservation Research
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Beneficial Utilization of Waste Heat from Power Plants
in Wastewater Treatment Systems

by

Sun-Nain Ni

Research Assistant

Alan W. Obayashi

Assistant Professor of Environmental Engineering

Illinois Institute of Technology

Chicago, Illinois 60616

June 1979

ABSTRACT

A number of wastewater treatment processes have been analyzed for possible benefit in using waste heat from co-located steam-electric power plants. Three levels of treatment standards were considered, ranging from secondary treatment to stricter tertiary requirements which involve nutrient removal. Three sizes of plants were also analyzed, ranging from those serving 33,000 to 2,000,000 population. The electric power plants were assumed of corresponding size. The processes analyzed included activated sludge, trickling filter, rotating biological contactors and the Bardenpho process. In the study, a fraction of the condenser discharge was considered mixed with primary-treated wastewater, thereby accelerating the biological secondary-treatment processes at the expense of dilution. In each case, the most cost-effective fraction of condenser flow to be utilized was determined. After treatment, a portion of the mixture would be returned to the power plant in order to "recycle" the corresponding condenser discharge and provide the necessary evaporative makeup for the cooling system. The balance of the mixture would constitute the water product of the treatment plant. The benefit of waste heat used to replace fuel oil in sludge digesters was also analyzed. A standardized EPA computer program was used for the design of all major systems. Thermal performance effects on the power plant were analyzed in a previous report.

In the case of the lowest effluent standards (Group I), the most cost-effective secondary treatment process was activated sludge without "waste-heat recycle" because it is dominated by non-thermal

considerations. Group 2 standards were favored by rotating biological contactors with waste-heat recycle. The most advanced Group 3 standards were optimally met by the Bardenpho process, also with waste-heat recycle. In all cases, anaerobic sludge digestion with waste heat in place of fuel oil was most economical. In general, the use of waste heat favors large plants. The overall savings in levelized annual costs ranged from 1.5% for the smallest plants to 9.9% for the largest plants, by using waste heat optimally as compared with optimal systems without waste heat. During power-plant shut downs in the critical winter period, treatment could be augmented chemically while fuel oil could fire the digesters. At other times of the year, operation and maintenance costs would be increased during power-plant outages but standards could be met conventionally.

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CHAPTER I

INTRODUCTION

Significance of the Study

In the Water Pollution Control Act and Amendments of 1972 (PL 92-500)^{(1)*}, there were two basic goals: First, "that the discharge of pollutants into the navigable water be eliminated by 1985," and secondly, "that wherever attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983."

Since the passage of this act, the increased volume of construction work, combined with the recent inflationary economic trends, has caused a sharp rise in the cost of wastewater treatment facilities. In addition, the costs necessary to operate and maintain (O+M) the wastewater treatment facilities has also increased significantly and in proportion to the construction costs. For example⁽¹⁾ since the passage of PL 92-500 in 1972, over 18 billion dollars have been obligated to date (1977) in funding over 11,000 new and expanded waste treatment facilities. This amount of funding is about 300% greater than the government had allocated for waste treatment facilities during the

*Superscript numbers in parenthesis refer to numbered references in the bibliography.

period from 1961 to 1972. Furthermore, recent proposals to commit an additional 45 billion dollars in federal funds to the clean-up effort have been received. Due to the rising costs and the tremendous amounts of money required to satisfy the mandates of PL 92-500, every effort should be made to reduce the capital and operation and maintenance costs of the wastewater treatment facilities. One possible way of reducing costs is to raise the temperature of the wastewater through interaction with the cooling facility of an electric power plant.

The costs (both capital and operation and maintenance costs) of various wastewater treatment processes depend primarily on size of reactors, some of which may be temperature dependent. The typical municipal wastewater treatment process is the biological treatment process which is widely used in the United States and in most parts of the world. In biological treatment processes (for example, trickling filters) the reactor size required is a function of the biological activity, which can double for each 10°C rise in temperature⁽²⁾ (in the range of about 5°C to 25°C or higher). Consequently, if the processes were temperature dependent and sewage temperature could be raised economically, the reactor size could be smaller for the same treatment efficiency and result in a lower treatment cost.

Sources of Waste Heat

In a power generation system, heat is supplied at a high pressure to the working fluid (water) by burning fossil fuel (coal, oil or gas) or by nuclear fission to produce steam at typical 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 cooling water flowing through tubes in a surface condenser. The heat transferred to the cooling water is ultimately transferred to the environment.⁽³⁾ Examples of two types of cooling systems, a once-through and a closed-cycle are shown schematically in Figure 1.

Approximately 13% of the total U.S. national energy consumption becomes waste heat as a consequence of rejection from the thermal cycles of steam-electric power plants⁽⁴⁾. In 1976, about 6.38×10^{16} BTU (25% of the total U.S. national energy consumption) of energy consumption was used by thermal electric power generation plants, and approximately 4.15×10^{16} BTU resulted in waste heat⁽⁵⁾. Even if only a small portion of this waste heat could be beneficially utilized, a significant amount of energy would be conserved.

Beneficial Utilization of Waste Heat

Due to the enormous amounts of waste heat generated and the recent concern for our energy resources, the bene-

A. Once-Through Cooling System

B. Closed-Cycle Cooling System

Figure 1. The Cooling System of Power Plant

ficial uses of waste heat has attracted considerable interest in recent years. Many studies were reported using waste heat and included agriculture, aquaculture, industrial process steam, desalination, and sewage treatment. A number of agricultural uses of thermal power plant waste heat have been proposed⁽⁶⁾ and include: heating greenhouses, piping heated water underground to agricultural fields to increase crop yields and/or increase the growing season, sprinkling heated water on crops as a frost protection measure, and heating animal shelters. Aquacultural applications utilizing power plant waste heat have received as much attention as agricultural applications. The Tennessee Valley Authority (TVA)⁽⁶⁾ has conducted research using warm water to increase the production of catfish, oysters, and other types of animals. The use of industrial process steam to reduce thermal power plant waste heat has been reviewed by Mandell (7). The possible uses include a high temperature gas cooled reactor to provide electrical energy for either coal gasification, hydrogen production, or steel making. In addition the high temperature gas cooled reactor with a gas turbine could be combined with a multistage flash desalination plant to provide both electrical energy and fresh water.

In the area of sewage treatment, the feasibility of purifying wastewater by using condenser cooling water has been investigated⁽⁷⁾. The study involved using condenser cooling water from a nuclear plant to purify the waste-

water for a city of one million people, with the distillation process being used. Hammerschlag and Rose⁽⁸⁾ reported that the use of steam produced from nuclear power plant condensers has been incorporated for the following purposes: to accelerate the removal of floatable and settleable solids in primary treatment; to accelerate the anaerobic digestion process in secondary treatment by utilizing thermophilic bacteria; and to kill enteric bacteria and remove chemical impurities in tertiary treatment. Rimberg⁽⁹⁾ has detailed a comprehensive summary of the studies concerning the uses of waste heat from power plants for wastewater treatment processes up through 1974. The proposed method for increasing the sewage temperature was an indirect method and involved the use of a heat exchanger with the heat being supplied by the cooling water of the power plant. The possible wastewater treatment processes which could benefit included typical primary-secondary treatment processes such as primary sedimentation, the activated sludge process, nitrification, and chemical precipitation. Rimberg⁽⁹⁾ estimated that due to 10°C rise in sewage temperature up to 30% savings could be achieved in primary sedimentation, 28% savings for activated sludge process and 47% for nitrification. The Tennessee Valley Authority⁽¹⁰⁾ has analyzed the feasibility of utilizing waste heat from a power plant for sludge digestion. Twelve sludge anaerobic digestion alternatives were investigated for a 50 MGD treatment plant.

It was concluded that major benefits could be realized for a treatment plant located next to a power plant using waste heat to maintain the sludge digesters at 35°C and recovering and selling the methane gas. It was estimated that a 44% savings in operational and maintenance costs could be achieved with waste heat utilization. A theoretical study developed by Collins et al⁽¹¹⁾ concluded that increases in temperature for temperature smaller than 20°C will actually cause an increase in the quantity of sludge to be disposed of, whereas increasing the temperature from 20°C will decrease the quantity of sludge.

Benefits for the Power Plant

Condenser cooling water from electric generating plants is the greatest source of man-made waste heat⁽¹²⁾. An analysis of steam electric cooling discharges indicates an average 14°C rise after passing through condensers. The flow of water withdrawn for cooling power plants is roughly equivalent to 10% of the total flow of waters in the U.S. rivers and streams per year. Thermal pollution and shortage of cooling water are two serious problems facing an electric generating power plant. The effective utilization of waste heat of the electric generating power plant by wastewater treatment plants could decrease the degree of pollution by simple dilution, supply a portion of make-up water of the cooling system, and help reduce the scale formation in a

cooling system. It will be mutually beneficial, if the waste heat produced by a power generating facility is utilized by a wastewater treatment plant.

Objectives of the Study

In general, the objective of this study was to assess the benefits of the possible interaction of the power plant with a municipal wastewater treatment facility. This could possibly lead to the conservation of energy through the utilization of waste heat from a power generating plant and reducing its environmental impact. Hopefully the integration of a power plant with the waste treatment system would reduce overall capital and operation and maintenance costs. In Figure 2, a detailed schematic flow diagram is presented and illustrates the possible scheme for a power plant and wastewater treatment plant interaction. The co-location of a power generating plant and the wastewater treatment plant may provide a means by which more efficient uses could be made.

More specifically the objective in this study was to evaluate and indentify the potential wastewater treatment systems which could beneficially use the waste heat of power plants. These treatment systems could be secondary treatment, tertiary treatment, or sludge disposal processes. Different sizes of treatment facilities were also analyzed in order to evaluate a range of community sizes. A 5 MGD treatment plant would typically service a small town of about 30,000

Figure 2. Interaction of Power Plant and Wastewater Treatment Plant

people, while a 30 MGD treatment plant might serve a 200,000 population city. A 300 MGD treatment plant represents a plant which would service a large city of approximately two million people. The potential of an evaporative cooling facility (ECF) as a treatment system is also a significant consideration which could benefit both wastewater treatment plants and electric power generating plants.

CHAPTER II

METHODS OF ANALYSIS

General Approach

As indicated earlier, the major objective of the study was to identify temperature dependent wastewater treatment systems which could possibly benefit from co-located power plants. In order to do this, effluent standards were first established with alternative treatment systems then being selected to meet the standards. In establishing any cost savings from recycling waste heat to a wastewater treatment system, design criteria for each unit process was developed for recycle systems and non-recycle systems. It should be pointed out the major benefits would result in a new treatment plant being co-located at an existing power plant.

In all instances the design wastewater temperature used was 10°C which is the low average sewage temperature in the northern states during the winter. Sewage temperatures were raised by directly recycling cooling water from the power plant with the sewage. In most instances lower reactor sizes at increased temperatures were offset by increased hydraulic requirements caused by the recycling of the cooling water. Thus, in some cases, no benefits were realized by recycling waste heat (cooling water) from the power plant.

Effluent Standards

During the first phase of the study, all possible wastewater treatment processes which could be benefited by the waste heat generated from a power plant were identified. However, before the assessment could be made, the possible process configurations were grouped according to effluent discharge requirements which must be met. Since the standards vary from state to state, the treatment objectives were grouped into three broad categories and range from secondary treatment to more stricter tertiary requirements which would require nutrient removal. The three groups are the following:

- 1) Removal of 5-day biochemical oxygen demand (BOD_5) and suspended solids (SS).
 - 2) Removal of BOD_5 , SS and ammonium nitrogen (NH_4-N).
 - 3) Removal of BOD_5 , SS, total nitrogen (TN including NH_4-N , nitrite nitrogen NO_2^-N , nitrate nitrogen NO_3^-N and organic nitrogen) and total phosphorus (TP).
- Thus the degree of wastewater treatment depends greatly on the discharge requirements of a given area. Table 1 tabulates the effluent standards and design criteria for three different groups of standards evaluated during the study. Group I represents general secondary treatment requirements and applies to sewage discharges into the

Table 1. Effluent Standards* and Criteria Used for Design of the Wastewater Treatment Processes

Group	Classification	BOD ₅	TSS [*]	NH ₃ -N	TN ^{**}	TP ^{***}
I	Effluent Standards	30	30	-	-	-
	Design Criteria	20	20	-	-	-
II	Effluent Standards	10	12	1.5	-	-
	Design Criteria	5	10	0.75	-	-
III	Effluent Standards	10	12	-	1.5	1
	Design Criteria	5	10	-	0.75	0.5

All effluent standards and design criteria are expressed in mg/l.

* Total suspended solids.

** Total nitrogen.

*** Total phosphorus.

ocean. Group II effluent standards require much stricter BOD₅ and SS removal and involve some form of NH₄-N oxidation. The effluent standards represented by Group III depicts the highest degree of required treatment of the three involving both nitrogen and phosphorous removal. Design criteria values for BOD, SS, etc., are lower than the effluent standards as a safety measure, especially for nitrogen and phosphorus removal.

Figure 3 shows schematically a complete treatment process. The degree of required treatment would depend on effluent standards; for example, secondary treatment is required for Group I or Group II effluent standards, tertiary treatment is designed for Group III effluent standards.

Sewage and Condenser Cooling Water Characteristics

A. Municipal Raw Sewage

Typical municipal sewage characteristics used in this study are as suggested by the USEPA⁽¹³⁾ and are listed in Table 2. Generally, the raw sewage characteristic is typical of relatively weak sewage found in the midwestern and eastern U.S. The data in Table 2 are widely used as process influent for preliminary design of wastewater treatment alternatives. Metcalf and Eddy Inc.⁽¹⁴⁾ suggested the ranges of some major domestic wastewater characteristics and are comparable to the values listed in Table 2.

✓ Figure 3. A Schematic Diagram of Typical Treatment Processes for Municipal Sewage Treatment

Table 2. Raw Municipal Wastewater Characteristics Used
in the Study (Reference 13)

Parameter	Concentration mg/l
Solid Organic Carbon.	105
Solid Nonbiodegradable Carbon.	30
Solid Organic Nitrogen.	10
Solid Organic Phosphorus. (as P)	2
Solid Fixed Matter.	30
Solid 5-day BOD	140
Volatile Suspended Solids.	224
Total Suspended Solids.	254
Dissolved Organic Carbon.	43
Dissolved Nonbiodegradable Carbon	11
Dissolved Organic Nitrogen (as N)	19
Dissolved Phosphorus (as P)	4
Dissolved Fixed Matter.	500
Alkalinity. (as CaCO_3)	250
Dissolved 5-day BOD.	60
Ammonia Nitrogen as N.	15
Nitrate Nitrogen as N.	0

B. Condenser Cooling Water Discharged from Power Plant

The source of make-up water for the evaporative cooling facility (ECF) of the power plant was assumed to be from a sewage treatment plant. Thus the quality of the make-up water would depend on the treatment process employed. According to this assumption, the quality of the condenser cooling water discharged from power plants could be assumed to be the same as the effluent of wastewater treatment plants. Temperature and the flow of condenser cooling water would vary from power plant to power plant. In the Chicago area, the average winter temperature of closed-cycle condenser discharge varies between 28°C and 48°C, with about 38°C being typical as the condenser discharge temperature.

The flow of power plant condenser cooling water varies with the size of the power plant and with the site of the plant. In Chicago area, it was estimated that 882 MGD cooling water is required for a 2000 million-watt power plant (2 million people served).⁽¹⁵⁾ On a per capita per day basis, this flow is 441 gallon per capita per day and in this study, this figure was used to analyze all the sizes (5-MGD, 30-MGD and 300-MGD) of wastewater treatment facilities.

Process Considerations

In order to identify the most promising power plant and sewage treatment plant interactions, the study was divided into two principal areas of investigation.

1. Wastewater Treatment.

The following are four power plant-sewage treatment plant combinations which were studied in Reference 3.

A. Large power plant-large sewage treatment plant.

This system would serve approximately 2 million people with the wastewater treatment facilities being approximately 300 MGD capacity while the power generating facility would have approximately 2000 million-watt capacity.

B. Large power plant-small sewage treatment plant.

This interaction may be far more realistic than the first since many large power generating power plants are located in rural areas. The sewage treatment plant effluent would serve as make-up water for the cooling system of the power plant.

C. Medium power plant-medium sewage treatment Plant

This particular combination represents the 200-million-watt generating capacity for approximately 200,000 people and a sewage treatment capacity for the same number of people (30 MGD).

D. Small power plant-small sewage treatment plant.

Both of these facilities represent the power requirements and sewage treatment requirements for approximately 33,000 people (5 MGD, 33.3 million watt).

In the cases of combination A,C and D, the flow rates were matched on a per-capita basis. Item D is of special

practical interest because small municipalities often have small co-located utilities which would be easier to link together. For the most part, because the basic thermal and wastewater unit operations depend primarily on ratios of flows, these three cases can be studied together. However, benefits derived from economy of scale were also considered. Item B represents a large power plant near a small municipality which is often the case in practice because large power generation facilities tend to be built in outlying areas. In this case, the sewage treatment plant was presumed to supply only the necessary make-up water for evaporation losses and continuous blowdown. Blowdown flows are required in order to hold discharge and cooling water dissolved solids concentration to an acceptable level. In each of the above situations, the following processes were evaluated in terms of economic benefits derived in each of the three groups of effluent standards (see Table 1). In each instance waste heat in the form of condenser cooling water was recycled to each of the processes. Cost savings were then identified for temperatures from 10°C to 25°C.

Group I effluent standards:

- *Activated sludge process (ASP).
- *Trickling filter process (TFP).
- *Rotating biological contactors (RBC).
- *Evaporative cooling facility (ECF).

Group II effluent standards:

- *Activated sludge process.
- *Trickling filter process (as nitrification unit after the activated sludge process).
- *Rotating biological contactors.

Group III effluent standards:

- *Two-stage activated sludge process with chemical precipitation (Two-ASP).
- *Bardenpho process.

2. Sludge Disposal Alternatives.

Sludge produced from the three sizes of treatment plants studied in the above evaluations were reviewed. The possible economic benefit of utilizing power plant waste heat in the processing of sludge for disposal was also documented. The following processes which are potentially the most promising were studied and include:

- *Sludge thickening (from 1% to 4%).
- *Aerobic and Anaerobic sludge digestion.
- *Sludge dewatering by vacuum filtration.
- *Ultimate disposal by land application.

Design Methods

1. Primary Treatment Process.

The major technology for the primary treatment process is the sedimentation process which is assumed to be generally independent of temperature. Determination of size of the devices and costs estimation were achieved by using the "Executive Program"⁽¹³⁾ developed by the USEPA. The process flow diagram is shown in Figure 4. Screens, grit chamber and flow measurement device are collectively designed as preliminary treatment processes in the "Executive Program".⁽¹³⁾ The total head of the raw sewage pump was assumed to be 100 feet. The treatment efficiency of primary sedimentation basin is a function of the overflow rate, and equation (1) shows the expression used in the "Executive Program."

$$GPS = (2780 \times \ln FRPS) - 551.7 \quad (1)$$

where:

GPS: overflow rate, gpd/ft²

FRPS: treatment efficiency, fraction

Treatment efficiency for typical design is 0.5 which requires an overflow rate of 1375 gpd/ft².

2. Secondary Treatment Processes.

A. Activated sludge process

Basic Assumptions:

In the design and operation of an activated sludge plant wastewater temperatures between 10°C and 25°C are of little

Figure 4. Schematic Flow Diagram of Primary Treatment Process

concern in the oxidation of soluble organic matter. Although the rate of carbon oxidation is obviously affected by temperature, doubling every 10°C in the range of $5\text{--}25^{\circ}\text{C}$ ⁽²⁾, the activated sludge system is oversized for organic carbon removal and thus changes in temperature don't affect effluent quality, in terms of soluble organic matter. The reason activated sludge systems are "oversized," is the need to develop a well-settling sludge which also produces a well clarified effluent. The solids retention times (SRT's) required for good settling sludges may be 5 to 10 days while the SRT's needed for the oxidation of organic matter may be only 1 to 2 days. As an example of temperature effects on activated sludge process Sayigh and Malina⁽¹⁶⁾ have conducted experiments to show that the efficiency for carbonaceous organic matter (BOD, chemical oxygen demand COD) removal is relatively independent of temperature variations in the 4°C to 31°C range at sludge age (solids retention time, SRT) of 3 days or more. In practice, 5 days SRT should be maintained in order to produce a well settling sludge. In other words, temperature variations would generally have no effect on the activated sludge process for overall carbonaceous organic matter removal under 31°C of temperature. Thus in terms of improving BOD removal efficiency by increasing the temperature of the wastewater, little benefit would be derived in an activated sludge system.

There may be benefits in improved clarification by increasing the wastewater temperature; however, this has been difficult to document and thus difficult to model. The minimum sewage temperature used for design purposes was 10°C (50°F) which is the approximate sewage temperature typically found in the northern U.S. during the winter period.

Method of design:

The basis of the design method is concept of the solids retention time (SRT) developed by Lawrence and McCarty.⁽¹⁷⁾ An operational parameter the SRT is related to the performance of activated sludge process. Therefore, SRT is suggested for use as an independent parameter in the activated sludge process design and control. However in order to properly design an activated sludge system at a desired SRT, two important considerations must be evaluated. First of all, the MLSS or mixed liquor suspended solids level must be established, keeping in mind the solids loading limitations of the secondary clarifier. Secondly one must be aware of the wastewater characteristics which influence the MLSS which will be maintained at a desired SRT. The design method used, which is a mass balance approach under steady-state conditions, estimates three major components of a wastewater and predicts the effect of each component on the steady-state MLSS concentration at a desired SRT. Basically, the accumulation of suspended solids is a re-

sult of three fractions in a waste stream: biodegradable suspended solids, inert suspended solids, and suspended solids resulting from soluble BOD metabolism. Thus for a given SRT and a desired MLSS level, the design hydraulic retention time can be calculated and is based on the estimation of the three fractions in the wastewater. This design approach is summarized in greater detail in the appendix.

Table 3 lists the design criteria and kinetic coefficients used in the sizing of the reactors for the activated sludge process in treatment of a municipal wastewater.

Table 3. Design Criteria of Activated Sludge Process for Carbonaceous Oxidation

Design Parameters	Criteria
Temperature, °C	10
SRT, days	5
MLSS, mg/l	3000
K_d , (decay coefficient), day^{-1}	0.05
Y_C , mg cell yield/mg BOD utilized	0.5
f_1 , Fraction of Inert VSS	0.3
f_2 , Fraction of Biodegradable VSS	0.7
Overflow Rate, gpd/ft^2	700
Oxygen Transfer Efficiency	0.05

B. Trickling filter process

The design method used for designing the trickling filter process was as used by the "Executive Program",⁽¹³⁾ which utilized a program based on the equations developed by Eckenfelder.⁽¹⁸⁾ In using this program mixture temperature variations ranged from 10°C to 25°C, corresponding to recycle of cooling water to sewage flow varying from 0.0 to 1.14.* Table 4 summarizes the major design criteria as input data to "Executive Program".

Table 4. Design Criteria of Trickling Filter Process for Carbonaceous Oxidation

Design Parameters	Criteria
Effluent Total BOD, mg/l	20
Temperature, °C	10,15,20,25
Recycle Ratio, (Waste Heat Flow/Sewage Flow)	0,0.22,0.55,1.14
Hydraulic Loading, MGD/acre	10
Specific Surface Area of Media, ft ² /ft ³	10
Overflow Rate, gpd/ft ²	800

Specific surface area used in this program was only 10 ft²/ft³ which is on the low side for most materials. Figure 5 schematically illustrates the interaction of power plant and trickling filter processes.

* As obtained by an energy balance assuming wastewater at 10C and power plant discharge at 38C.

Figure 5. Interaction of Power Plant and Trickling Filter Process

C. Rotating biological contactors

Again the "Executive Program" ⁽¹³⁾ was used as the design method for rotating biological contactors. A design procedure based on hydraulic surface loading, with the temperature variations ranging from 10°C to 25°C. The criteria used for various design parameters was as suggested by the USEPA ⁽¹³⁾ and Autotrol Corporation ⁽¹⁹⁾ are shown in Table 5. Figure 6 illustrates the possible interaction of power plant and rotating biological contactor treatment process.

Table 5. Design Criteria of Rotating Biological Contactor for Carbonaceous Oxidation

Design Parameters	Criteria
Effluent Total BOD ₅ , mg/l	20
Temperature, °C	10,15,20,25
Recycle Ratio, (Waste heat flow/sewage flow)	0,0.22,0.55,1.14
Number of Stages	4
Hydraulic Loading, gpd/ft ²	7
Overflow Rate, gpd/ft ²	700

D. Evaporative cooling facility (ECF)

Spray canals and cooling towers are two general types of an evaporative cooling facility used for dispersing rejected heat from a power plant. If these two devices could be

Figure 6. Interaction of Power Plant and Rotating Biological Contactors

considered as secondary wastewater treatment systems, then the wastewater treatment plant would only need a primary treatment facility and sludge disposal facilities, which would result in a considerable savings. So far, no data are available to prove that evaporative cooling facilities have the ability to treat wastewater; the dilution effects are a significant factor since large amounts of condenser cooling water are used. There are two possibilities of using an evaporative cooling facility as a wastewater treatment process:

- 1) Using the spray canal as an oxidation ditch (a modification of the activated sludge process).

The mechanical spray system used for cooling in the canals could function as mechanical aerators. Dissolved oxygen data obtained from Dresden Power Station, Illinois are listed in Table 6. Dissolved oxygen values range from 12% to 27% over saturation, with an average dissolved oxygen around 7.2 mg/l. If the mechanical system used for thermal cooling could supply enough oxygen for the total BOD demand in wastewater, the spray canal could be used as an oxidation ditch. The process kinetics and efficiency would have to be evaluated from a pilot plant study, which may be done as future work. In addition, possible health hazards of potential pathogens in the spray mists would have to be considered.

Table 6. Dissolved Oxygen Data of Spray Canal Cooling System-Dresden Power Station, Illinois

Location	Dissolved Oxygen mg/l	% Saturation (40°C)
Condenser Discharge	5.9	94
After 6 Modules	7.5	125
After 11 Modules	7.0	112
After 26 Modules	7.1	116
After 51 Modules	7.8	127

2) Cooling tower as trickling filter.

Since no solids are allowed to enter to the cooling tower,⁽¹⁵⁾ it is difficult to design a system combining the treatment process and evaporative cooling facility.

One possible way would be to employ a filter.

3. Combined Carbon Oxidation -Ammonia Oxidation

A. Activated sludge process

Basic Assumptions:

Ammonia oxidation (nitrification) is achieved by autotrophic bacteria, Nitrosomonas and Nitrobacter. Generally, the maximum growth rate of Nitrosomonas is lower than Nitrobacter and is significantly lower than the heterotrophic bacteria which oxidize organic matter. Thus, the maximum

growth rate of nitrosomonas controls the required SRT of the activated sludge process. Downing and his coworkers (20,21) have developed the most widely accepted kinetic constant for the nitrifying organisms. The expression they developed for the effect of temperature on the maximum growth rate of Nitrosomonas is as expressed in Equation 2.

$$\mu_N = 0.47e^{0.098(T-15)} \quad (2)$$

where:

μ_N : maximum growth rate of nitrosomonas, day⁻¹

T: temperature °C

It is evident that the maximum specific growth rate is significantly affected by temperature and since the required SRT is related to the maximum specific growth rate the size of the reactor will also be affected. Dissolved oxygen (DO) in the reactor and pH value of wastewater also have significant effects on the specific rates of nitrifiers growth. It has been proposed that Equation 2 be changed (21)

to account for the effect of DO and pH as follows:

$$\mu_N = \frac{1}{\theta_C^m} = 0.47(e^{0.098(T-15)} \frac{DO}{DO+1.3})(1-0.833(pH-7.2)) \quad (3)$$

θ_C^m minimum SRT, days

DO: dissolved oxygen in aerator, mg/l

pH: pH value of sewage

With typical design parameters of 2 mg/l of DO and 7.2 pH value being used, Equation 3 was reduced to the following equation, relating θ_C^m as a function of temperature:

$$\frac{1}{\theta_C^m} = 0.285(e^{0.098(T-15)}) \quad (4)$$

Lawrence and McCarty⁽¹⁷⁾ have introduced the concept of a safety factor (SF) in the application of biological treatment process kinetics of design of activated sludge systems. The safety factor was defined as the ratio of the design SRT to the minimum SRT. A safety factor of 2.5 was used to determine the design SRT in this study.

Design Method for Nitrification

The process flow diagram for this system is shown as Figure 7. The design method is as described earlier for the activated sludge process and is in the Appendix and shown in Equation 7. Design criteria and values of the coefficients used are listed in Table 7.

B. Combined activated sludge - trickling filter process.

This treatment process was designed to follow the activated sludge process for ammonia oxidation. In order to minimize hydraulic effects, power plant cooling water was conveyed to the trickling filter only. Nitrification rates in trickling filters are related to the wetted surface area of media.⁽²¹⁾ Therefore the most rational criterion would be

Figure 7. Interaction of Power Plant and Activated Sludge Process

Table 7. Design Criteria of Activated Sludge Process
for Carbon Oxidation and Ammonia Oxidation

Design Parameters	Criteria
Temperature, °C	10,15,20,25
Recycle Ratio (Waste heat flow/sewage flow)	0,0.22,0.55,1.14
MLSS, mg/l	3000
Safety Factor	2.5
K_d , day ⁻¹	0.1
Y_C , mg cell yield/mg BOD utilized	0.5
Y_N , mg cell yield/mg NH ₃ -N utilized	0.15
f_1 , Inert Fraction of VSS	0.3
f_2 , Biodegradable Fraction of VSS	0.7
Overflow Rate, gpd/ft ²	700
Oxygen Transfer Efficiency	0.5

in terms of surface area. Unfortunately, information on specific surfaces was not always available and volumetric loading criteria must be used.

The pilot study at Midland, Michigan Wastewater Treatment Plant⁽²¹⁾ provided the most comprehensive set of data available to date. Wastewater at the pilot plant was good with BOD₅, SS and NH₄-N values ranging from 15 to 20, 15 to 20 and 8 to 18 respectively. This water quality is similar to the effluent of an activated sludge process for carbon oxidation. The surface area requirements used for nitrification of various temperatures were as described by USEPA.⁽²¹⁾ Figure 8 illustrates the process flow diagram. Two clarifiers were required in this process and both have a design overflow rate of 700 gpd/ft².

C. Rotating biological contactors (RBC's)

Many studies^(21,23,24) have shown that rotating biological contactors could be a potential nitrification process. In combined carbon and nitrogen oxidation, Antonie⁽²⁵⁾ had found no effect in BOD and NH₃-N oxidation at temperatures above 13°C. For temperatures of less than 13°C, temperature corrections have been derived from pilot plant data. The design method used was as described by Antonie⁽²⁵⁾ with the overflow rate used for the clarifiers being 700 gal/day/ft².

Figure 8. Interaction of Power Plant and Activated Sludge-Trickling Filter Process

4. Two-stage Activated Sludge Process

The two-stage activated sludge process can be adapted as a treatment process for denitrification and phosphorous removal. This process consists of two main reactors, with the first being an aeration basin for combined carbon and nitrogen oxidation as discussed previously, and the second reactor being an anoxic mixing basin for nitrate reduction to nitrogen gas (denitrification). Figure 9 shows how the power plant cooling system can interact with the two-stage treatment system. Two chemicals are added in the process, methanol which is added to the second reactor as carbon source for the microorganisms, and alum which is added after the second reactor in order to remove phosphorous by chemical precipitation.

Design methods and procedures of the first stage are the same as the activated sludge process for combined carbon and nitrogen oxidation which has been previously discussed. The procedure for designing a denitrification reactor is summarized by USEPA⁽²¹⁾.

The design criteria used in designing the denitrification reactor are listed in Table 8. The peak nitrate removal rate, q , is temperature dependent and has been determined for a number of studies (26,27,28). The values listed in Table 8 have been summarized by USEPA⁽²¹⁾ and represent conservative values. Theoretically, hydraulic detention time could be less than 1 hour based on the design formula; in

Figure 9. Interaction of Power Plant and Two-Stage Activated Sludge Process

Table 8. Design Criteria of the Denitrification Reactor in the Two-stage Activated Sludge Process

Design Parameters	Criteria
Minimum Hydraulic Retention Time, hr	2
Safety Factor	1.5
MLVSS, mg/l	2100
q at 10°C, 1b NO_3^- -N removed/lb VSS-day	0.05
q at 15°C, 1b NO_3^- -N removed/lb VSS-day	0.08
q at 20°C, 1b NO_3^- -N removed/lb VSS-day	0.15
q at 25°C, 1b NO_3^- -N removed/lb VSS-day	0.20
Overflow Rate of Clarifier, gpd/ft ²	700
Dosage of Methanol 1b/lb NO_3^- -N removed	3.0
Dosage of Alum 1b Al^{+3} /lb P removed	1.25

practice, 2 hours minimum hydraulic retention time should be maintained. (21)

5. Bardenpho Process

A recent development for nitrogen and phosphorous removal using both wastewater and endogeneous carbon for denitrification is shown in Figure 10 and is termed "Bardenpho Process". This process is a modified activated sludge process which according to the developer J. Barnard is able to remove between 90% and 95% of nitrogen and between 90% and 97% of phosphates without addition of any chemicals. (30) There are four reactors in the process, the first being an anoxic reactor in which there is first-stage BOD $\text{NO}_3\text{-N}$ removal. The second reactor is an aerobic reactor for BOD $\text{NH}_3\text{-N}$ oxidation, while the third reactor is an anoxic for reducing the $\text{NO}_3\text{-N}$ from the second stage to nitrogen gas. The final reactor is aerobic and is for both reaeration and stripping of any nitrogen gas prior to sedimentation. The possible interaction of a power plant and the Bardenpho process is shown in Figure 11. The design method used in this study for designing the Bardenpho process is as described by Barnard (30). In addition, the criteria used for the various parameters are as suggested by Barnard and are summarized in Table 9.

N_o : TOTAL NITROGEN CONCENTRATION.

$N_1, N_2, \dots$: NO_3 -N CONCENTRATION IN THE FIRST, SECOND, REACTOR.

$V_1, V_2, \dots$: VOLUME OF THE FIRST, SECOND, REACTOR.

DO: DISSOLVED OXYGEN IN THE SECOND REACTOR.

a: RECYCLE RATIO FROM THE SECOND REACTOR.

v: RECYCLE RATIO FROM THE FINAL CLARIFIER.

Figure 10. A Schematic Mass Balance Diagram of the Bardenpho Process

Figure 11. Interaction of Power Plant and Bardenpho Treatment Process

Table 9. Design Criteria and Constants Used in the Bardenpho Process (Reference 30)

Design Parameters	Criteria
MLSS, mg/l	5000
$DN_1(20)$, mg NO_3^- -N/g solids/hr	3.6
$DN_3(20)$, mg NO_3^- -N/g solids/hr	1.3
θ_1 , Temperature Correction Constant in the First Reactor	1.09
θ_3 , Temperature Correction Constant in the Third Reactor	1.20
b, Recycle Ratio from the Final Clarifier	1.0
N_1 , mg/l	0
N_3 , mg/l	0

6. Sludge Disposal Processes

Two sludge disposal trains were studied as potential sludge disposal systems, one is using anaerobic digestion as the sludge stabilization process which is a widely used process while the other system used aerobic digestion in order to stabilize the sludge.

A. Anaerobic digestion as the primary sludge stabilization unit:

The major portion of energy consumption of a wastewater treatment plant which includes an anaerobic digestion unit is the fuel cost for heating the sludge to 35°C (95°F) and keeping the sludge at this temperature in the

digester. If a power plant could provide sufficient heat to an anaerobic digester, then the fuel used in the digester can be saved or used elsewhere. The potential anaerobic digestion process interaction with power plant is as shown in Figure 12. The design procedure included two steps with the first step being the determination of the size of each unit process as shown in Figure 12. In sizing the units the "Executive Program" was used. The major design criteria for each unit of this process used in the "Executive Program" are given in Table 10.

Table 10. Design Criteria of the Sludge Disposal Processes

Disposal Unit	Design Parameters	Criteria
Gravity Thickener	Concentration of Effluent Sludge	4%
	Overflow Rate, gpd/ft^2	700
	Solid Flux, lb/day/ft^2	8.0
Anaerobic Digester	Detention Time, day	15
	Temperature, $^{\circ}\text{C}$	35
Vacuum Filter	Loading Rate, gph/ft^2	5.0
Land Disposal	Loading Rate, ton/acre/yr	15
	Hauling Distance, mile	10
	Hauling Capacity, gal/truck	1200

Figure 12. Interaction of Power Plant and Sludge Disposal Process

Determination of the dimensions of the digester and heat requirements were found in order to calculate the savings due to the utilization of power plant waste heat. The method of calculation was as described in the information provided by Water Pollution Control Federation⁽³¹⁾ (WPCF) and Metcalf and Eddy Inc.⁽¹⁴⁾

The heat required to raise the temperature of the incoming sludge can be expressed as:

$$H = WC(T_2 - T_1) \quad (5)$$

where:

H : amount of heat, BTU/hr

W : sludge entering the tank per hour, lb

C : mean specific heat of raw sewage (=1.0)

T₂: temperature of sludge in tank, °F

T₁: temperature of sludge entering tank, °F

The other major portion of heat requirements is the heat losses of the digester. The heat loss from the digestion tank can be expressed as:

$$H_L = UA(T_2 - T_1) \quad (6)$$

where:

H_L: heat loss from the digestion tank, BTU/hr

U : heat transfer coefficient, BTU/hr/ft²/°F

A : surface area of the tank, top bottom and sides,
ft²

T₂: temperature inside the tank, °F

T₁: temperature outside the tank, °F

Table 11 gives the heat transfer coefficients and the limitations of the digester dimension used to estimate the overall heat requirements in a sludge anaerobic digester. Temperatures outside the digester used are given in Table 12.

Table 11. Parameters Used for the Calculation of the Digester Heating Requirements (Reference 14,31)

Parameters	Data
Side Depth, ft	16 - 20
Mid Depth, ft	25 - 45
C, Mean Specific Heat of Raw Sewage	1.0
q_w , Heat Transfer Coefficient for Wall	0.12
q_f , Heat Transfer Coefficient for Floor	0.15
q_r , Heat Transfer Coefficient for Roof	0.16
specific Weight of Sludge after Thickener	1.02

Table 12. Temperature Data Used to Estimate Digester Heating Requirements, °F (Reference 15)

	Summer	Spring-Fall	Winter*
Air	73	51	28
Floor	78	51	36
Wall	84	74	58

* Calculation was based on water temperature.

B. Aerobic digestion as sludge stabilization unit:

Aerobic digestion is an alternative method of stabilizing organic sludges produced from various treatment operations. The degree of sludge stabilization is a function of SRT and is affected by temperature variations. Some studies (32,33) have developed design procedures for aerobic digestion, with consideration for temperature effects being made. In one study, results by Koers and Mavinic (33) were used as design criteria for aerobic digestion. In this study, digestion temperatures of 10°C, 15°C and 20°C were evaluated and cost comparisons were made. The design procedure involved determining the design SRT and then determining the reactor size by using the "Executive Program". Costs evaluated by "Executive Program" excluded the cost of heat exchange which cost was estimated.⁽³⁾

Economic Considerations

The capital, operational and maintenance (O+M) costs for various unit process of wastewater treatment plants were developed by using the cost function of "Executive Program". The basic cost data used in this study, shown in Table 13, are based on 1977 figures. The costs of two chemicals, methanol and alum, in Table 13 were from another study.⁽³⁴⁾ The cost of fuel oil was obtained by communication.⁽¹⁰⁾

Figures in Table 13 such as labor rate and land cost would have to be adjusted for a given area. The cost estimates were adjusted to 1980 dollars by extrapolating trends of cost increases for labor, materials and construction. The method used to adjust the cost figures which included capital, operation (labor) and maintenance (labor, material) costs from 1977 to 1980 was developed by Rao.⁽³⁾ For determining inflation rates of fuel oil, different escalation factors were used and are listed in Table 14.

The percentage increases from 1977 to 1980 are 18% for labor, 14% for materials, 90% for fuel oil and 29% for construction. Labor cost is the major portion of operation-and-maintenance cost, with an 18% inflation being used to estimate 1980 operation-and-maintenance cost.

The assumption that the wastewater treatment plant is located next to a power plant was made. This would be possible for a co-located system and the cost of transporting hot water or wastewater would be small. Economic results were reported as capital costs, operational and maintenance annual cost, and total annual treatment cost, the last item being the most important and significant in comparing all the alternatives.

Table 13. Cost Data Used to Develop Capital, Operation and Maintenance
Costs of Wastewater Treatment Plant, 1977 Basis Costs

Cost Items	Data	Reference
Construction Cost Index, 1957-1959 = 1	2,738	13
Wholesale Price Index, 1957-1959=1	1.675	13
Amortization Interest Rate	6%	13
Hourly Labor Rate, dollar/hr	6.00	13
Fraction of Direct Labor Rate Charged as Indirect Labor Rate	0.15	13
Cost of Land, dollar/acre	5000	13
Interest Rate for the Cost of Interest during Plant Construction	6%	13
Cost of Electric Power, dollar/KW-hr	0.03	13
Cost of Installed Concrete, dollar/yd ³	233	13
Cost of Methanol, dollar/lb	0.05	34
Cost of Alum, dollar/lb	0.57	34
Cost of Fuel Oil, dollar/10 ⁶ BTU*	2.33	10
Cost of Methane Gas, dollar/10 ⁶ BTU*	1.16	10

* 1976 basis.

Table 14. Fuel Costs and Escalation Factors (Reference 3).

Fuel Type	Cost, $\$/10^6$ BTU 1975	Proposed Value $\$/10^6$ BTU	Escalation Factors 1975-1984
Nuclear	0.45	0.45	1.79
Residual Oil	2.00 - 2.25	2.08	1.92
Distillate Oil	2.25 - 2.50	2.33	1.90
Low Sulfur Coal	1.25 - 1.35	1.25	1.54
High Sulfur Coal	1.00 - 1.10	1.03	1.54
Lignite Coal	0.80 - 1.30	1.26	1.52

CHAPTER III

RESULTS

In order to identify the major treatment systems which could possibly benefit from recycling waste heat, the results are divided into four major areas. The first three parts are concerned with identifying waste treatment processes meeting the three groups of effluent standards (namely, Group I, Group II, and Group III) and benefiting from waste heat recycling. The fourth major area was involved with evaluating the uses of waste heat in sludge disposal processes. The results of all of the process interactions considered are in the appendix, with only the favorable interactions included here.

Group I Effluent Standards

As explained earlier only the trickling filter and rotating biological contactor processes were considered as having possible benefits of recycling waste heat in order to achieve Group I effluent standards. The activated sludge process was not considered, since temperature has an unpredictable influence on the effluent quality of an activated sludge system due to the long cell residence times (SRT) maintained.

The benefits of recycling waste heat proved to be in all cases dependent on the size of the treatment facility.

No cost benefits were found for recycling waste heat to small (5MGD) scale treatment plants in any of the treatment processes investigated. In all instances no benefits in recycling waste heat were found for trickling filter systems meeting Group I standards. For rotating biological contactors meeting Group I standards the cost benefits are summarized in Tables 15 and 16. As indicated only marginal benefits were found for recycling waste heat to a 30 MGD RBC facility with the O&M and total annual treatment costs being reduced by 1.5 and 0.5 percent, respectively. However with a large RBC treatment plant the savings were more significant. At an optimum recycle ratio of 0.55, a savings was documented for capital and O&M costs being 3.5 and 7.0 percent, respectively. Overall, the total annual treatment costs were found to be reduced by about 5%, which amounts to about \$800,000 per year.

Group II Effluent Standards

The Group II effluent standards represent a higher level of treatment than Group I and in addition require nitrification, a temperature dependent process. The three process configurations investigated were: rotating biological contactors; activated sludge; and activated sludge - trickling filter.

1. Rotating Biological Contactors - In using RBC in meeting Group II standards, cost benefits were identified

Table 15. The Cost Benefits in Recycling Waste Heat From a Co-located Power Plant to a Medium Scale (30 MGD) Municipal Wastewater Treatment Plant¹ (Rotating Biological Contactor) Designed to Meet Group I Effluent Standards

Parameter	Waste Heat Utilization		% Savings
	Without	With	
Temp., °C	10	15	-
Recycle Ratio ²	0	0.22	-
Capital Costs (in \$ 10 ⁶)	17.93	17.96	-
O&M Annual Cost (in \$ 10 ⁶)	0.68	0.67	1.5
Total Annual Treatment	2.087	2.076	0.5

¹ Primary Treatment - Rotating Biological Contactors

² Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 16. The Cost Benefits of Recycling Waste Heat from a Co-located Power Plant to a Large Scale (300 MGD) Municipal Wastewater Treatment Plant¹ (Rotating Biological Contactors) Designed to Meet Group I Effluent Standards

Parameter	Waste Heat Utilization		Cost & Savings
	Without	With	
Temp., °C	10	20	-
Recycle Ratio ²	0	0.55	-
Capital Costs	153.0	147.7	3.5
O&M Annual Costs	5.86	5.45	7.0
Total Annual Treatment Costs (in \$ 10 ⁶)	17.83	17.00	4.7

¹ Primary Treatment - Rotating Biological Contactors

² Recycle Ratio = Waste Heat Flow/Sewage Flow

for all three types of plant sizes investigated. Tables 17, 18, and 19 tabulate the cost savings for a small, medium, and large RBC facility designed to meet Group II standards. Again, the size of the plant dictated the amount of the cost savings. In all three cases the optimum recycle ratio was 0.12, which is the ratio required to raise the wastewater temperature to 13°C which is lowest temperature at which nitrification is unaffected.⁽²¹⁾ For a small (5MGD) RBC facility, recycling waste heat would save about 7% of capital, O&M annual costs, and overall total annual treatment costs, while a medium (30MGD) RBC plant could save about 10% in all three categories. The largest savings realized was for the large scale (300 MGD) RBC plant, with the savings estimated to be around 13% for capital, O&M annual costs, and total annual treatment costs. Total annual treatment costs for a large scale RBC treatment plant could be reduced by about \$3.5 million a year by recycling waste heat.

2. Activated Sludge - In using the activated sludge process in meeting Group II standards, no cost benefits were identified in recycling waste heat to a small scale waste treatment system. In recycling waste heat to a medium (30 MGD) and a large (300 MGD) scale activated sludge system cost benefits were found and are shown in Tables 20 and 21, respectively. For the medium scale activated sludge system, a waste heat recycle ratio of 0.22 was found to be the optimum, with the resulting reactor temperature being 15°C. Under

Table 17. The Cost Benefits of Recycling Waste Heat from a Co-located Power Plant to a Small Scale (5 MGD) Municipal Wastewater Treatment Plant¹ (Rotating Biological Contactors) Designed to Meet Group II Effluent Standards

Parameter	Waste Heat Utilization Without	With	% Cost Savings
Temp., °C	10	13	-
Recycle Ratio ²	0	0.12	-
Capital Costs (in \$10 ⁶)	5.55	5.17	6.8
O&M Annual Costs (in \$10 ⁶)	0.200	0.187	6.5
Total Annual Treatment Costs (in \$10 ⁶)	0.634	0.591	6.7

¹ Primary Treatment - Rotating Biological Contactors

² Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 18. The Cost Benefits of Recycling Waste Heat From a Co-located Power Plant to a Medium Scale (30 MGD) Municipal Wastewater Treatment Facility¹ (Rotating Biological Contactor) Designed to Meet Group II Effluent Standards

Parameter	Waste Heat Utilization		% Cost Savings
	Without	With	
Temp., °C	10	13	-
Recycle Ratio ²	0	0.12	-
Capital Costs (in \$10 ⁶)	25.62	22.95	10.4
O&M Annual Costs (in \$10 ⁶)	0.895	0.806	9.9
Total Annual Treatment Costs (in \$10 ⁶)	2.90	2.60	10.3

¹ Primary Treatment - Rotating Biological Contactors

² Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 19. The Cost Benefits in Recycling Waste Heat from a Co-located Power Plant to a Large Scale (300 MGD) Municipal Wastewater Treatment Plant¹ (Rotating Biological Contactors) Designed to Meet Group II Effluent Standards

Parameter	Waste Heat Utilization		% Cost Savings
	Without	With	
Temp., °C	10	13	-
Recycle Ratio ²	0	0.12	-
Capital Costs (in \$10 ⁶)	230.30	199.1	13.5
O&M Annual Cost (in \$10 ⁶)	8.08	7.07	12.5
Total Annual Treatment Costs (in \$10 ⁶)	26.09	22.64	13.2

¹ Primary Treatment - Rotating Biological Contactors

² Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 20. The Cost Benefits of Recycling Waste Heat from a Co-located Power Plant to a Medium Scale (30 MGD) Municipal Wastewater Treatment Plant¹ (Activated Sludge) Designed to Meet Group II Effluent Standards

Parameter	Waste Heat Utilization		% Savings
	Without	With	
Temp., °C	0	15	-
Recycle Ratio ²	0	0.22	-
Capital Cost (in \$10 ⁶)	13.49	13.20	2.1
O&M Annual Cost (in \$ 10 ⁶)	0.63	0.64	-
Total Annual Treatment Costs (in \$ 10 ⁶)	1.68	1.67	0.6%

¹ Primary Treatment - Activated Sludge

² Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 21. The Cost Benefits in Recycling Waste Heat from a Co-located Power Plant to a Large Scale (300 MGD) Municipal Wastewater Treatment Plant (Activated Sludge) Designed to Meet Group II Effluent Standards

Parameter	Waste Heat Utilization		% Cost Savings
	Without	With	
Temp., °C	10	20	-
Recycle Ratio	0	0.55	-
Capital Costs (in \$ 10 ⁶)	106.7	91.70	14.1
O&M Annual Costs (in \$ 10 ⁶)	4.98	4.55	8.6
Total Annual Treatment Costs (in \$10 ⁶)	13.33	11.72	12.1

¹ Primary Treatment - Activated Sludge

those conditions, a small savings in capital costs of 2.1% could be realized. However, the total annual costs savings were small and were found to be less than 1%. For the larger scale (300 MGD) plant the cost savings were significantly increased by recycling waste heat to an activated sludge system. The optimum temperature was calculated to be 20°C which required a recycle ratio of 0.55. The savings in capital costs were significant and amounted to 14.1%, while the savings in O and M costs were 8.6%. Overall, the total annual treatment costs were found to be reduced by 12% by recycling waste heat.

3. Activated Sludge - Trickling Filter

A two stage system, an activated sludge system for carbonaceous removal followed by a trickling filter for nitrification was investigated as having possible benefits from recycling waste heat from a power plant. As was the case for the small scale activated sludge system, the small scale (5 MGD) activated sludge-trickling filter system showed no economic benefits in recycling waste heat. For the medium scale and large scale plants some benefits were achieved and are listed in Tables 22 and 23, respectively. For both the medium scale and the large scale system the optimum temperature was 13°C and required a recycle ratio of 0.12. For both the medium scale and large scale systems a 4% reduction in capital costs could be achieved if the waste heat were recycled to the waste treatment processes.

Table 22. The Cost Benefit of Recycling Waste Heat from a Co-located Power Plant to a Medium Scale (30 MGD) Municipal Wastewater Treatment Plant¹ (Activated Sludge - Trickling Filter) Designed to Meet Group II Effluent Standards

Parameter	Waste Heat Utilization		% Cost Saving
	Without	With	
Temp., °C	10	13	-
Recycle Ratio ²	0	0.12	-
(in \$ 10 ⁶)	19.54	18.71	4.2
O&M Annual Costs	0.64	0.66	-
(in \$ 10 ⁶)			
Total Annual Treatment Costs (in \$10 ⁶)	2.17	2.12	2.3

¹ Primary Treatment - Activated Sludge - Trickling Filter

² Recycle Ratio = Waste Heat Flow/Sewage Flow.

Table 23. The Cost Benefits in Recycling Waste Heat from a Co-located Power Plant to a Large Scale (300 MGD) Municipal Wastewater Treatment Plant (Activated Sludge - Trickling Filter) Designed to Meet Group II Effluent Standards

Parameter	Waste Heat Utilization		\$ Cost Savings
	Without	With	
Temp., °C	10	13	-
Recycle Ratio ²	0	0.12	-
Capital Costs (in \$ 10 ⁶)	147.38	141.4	4.1
O&M Annual Cost (in \$10 ⁶)	4.57	4.75	-
Total Annual Treatment Costs (in \$10 ⁶)	16.10	15.81	1.8

¹ Primary Treatment - Activated Sludge - Trickling Filter

However, since both systems showed an overall increase in O&M costs by recycling waste heat, the savings in total annual cost were only 0.7% for the medium scale system and 2.4% for the large scale system.

Group III Effluent Standards

The Group III effluent standards are the strictest, requiring total nitrogen and total phosphorus removal as well as a low BOD and suspended solids in the effluent. Two processes were investigated as having possible benefits of recycling waste heat from a cooling system of a co-located power plant. The two process types were the two-stage activated sludge process (nitrification-denitrification, and phosphorus removal by chemical addition) and the Bardenpho process a promising and relatively new process.

1. Two-stage Activated Sludge: The two-stage process consists of first stage nitrification-carbonaceous removal and a second stage denitrification system. Phosphorus removal is accomplished by adding a chemical coagulant before the second stage clarifiers. For the small scale system no benefits were found in recycling waste heat. For the medium scale and large scale systems some economic benefits were found and are shown in Tables 24 and 25. The optimum temperature of the medium scale system was found to be 15°C and required a recycle ratio of 0.22. A capital cost reduction of approximately 5% was calculated for the medium scale system which used the waste heat. However due to

Table 24. The Cost Benefits in Recycling Waste Heat from a Co-located Power Plant to a Medium Scale (30 MGD) Municipal Wastewater Treatment Plant¹ (Two-Stage Activated Sludge) Designed to Meet Group III Effluent Standards

Parameter	Waste Heat Utilization		% Cost Savings.
	Without	With	
Temp., °C	10	15	-
Recycle Ratio ²	0	0.22	-
Capital Costs (in \$10 ⁶)	18.17	17.33	4.6
O&M Annual Costs (in \$ 10 ⁶)	1.26	1.31	-
Total Annual Treatment	2.69	2.67	0.7

¹ Primary Treatment - Two-Stage Activated Sludge

² Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 25. The Cost Benefits in Recycling Waste Heat from a Co-located Power Plant to a Large Scale (300 MGD) Municipal Wastewater Treatment Plant¹ (Two-Stage Activated Sludge) Designed to Meet Group III Effluent Standards

Parameter	Waste Heat Utilization		% Savings
	Without	With	
Temp., °C	10	20	-
Recycle Ratio ²	0	0.55	-
Capital Costs	146.44	127.39	13.0
O&M Annual Cost (in \$10 ⁶)	11.22	11.16	0.5
Total Annual Treatment Costs (in \$ 10 ⁶)	22.68	21.12	6.9

¹ Primary Treatment - Two Stage Activated Sludge

² Recycle Ratio = Waste Heat Flow/Sewage Flow

an overall increase in O&M costs, the savings in total annual treatment was only 0.7%. For the large scale system (300 MGD) the optimum temperature was calculated to be 20°C and required a recycle ratio of 0.55. The capital costs were significantly reduced by 13% when recycling waste heat to a medium scale two-stage activated sludge system. Overall the total annual treatment costs were reduced by about 7%.

2. Bardenpho Process: The Bardenpho process is a relatively new process in which it is claimed that both nitrogen and phosphorus can be removed without the addition of chemicals. Moreover it is a temperature dependent process which may benefit from the recycling of waste heat. However in the recycling of waste heat to a small scale system no benefits were found. In recycling waste heat to the medium and large scale Bardenpho systems some cost benefits were calculated and are listed in Tables 26 and 27, respectively. For the medium scale plant the optimum wastewater temperature was determined to be 15°C at a recycle ratio of 0.22. By recycling waste heat to the medium scale Bardenpho plant 4.6% savings in capital costs could be made, while the overall annual costs could be reduced by 2.4%. For the large scale system the benefits are much greater with the capital cost, the annual O&M cost, and the total annual treatment costs being reduced by 13, 7, and 11% respectively. The optimum temperature was found to be 20°C and the recycle ratio was 0.55.

Table 26. The Cost Benefits in Recycling Waste Heat from a Co-located Power Plant to a Medium Scale (30 MGD) Municipal Wastewater Treatment Plant¹ (Bardenpho Process) Designed to Meet Group III Effluent Standards

Parameter	Waste Heat Utilization		% Savings
	Without	With	
Temp., °C	10	15	-
Recycle Ratio ²	0	0.22	
Capital Costs (in \$ 10 ⁶)	18.17	17.33	4.6
O&M Annual Costs (in \$ 10 ⁶)	0.70	0.72	-
Total Annual Treatment Costs (in \$ 10 ⁶)	2.12	2.07	2.4

¹ Primary Treatment - Bardenpho Process

² Recycle Ratio = Waste Heat Flow/Sewage Flow.

Table 27. The Cost Benefits in Recycling Waste Heat from a Co-Located Power Plant to a Large Scale (300 MGD) Municipal Wastewater Treatment Plant¹ (Bardenpho System) Designed to Meet Group III Effluent Standards

Parameter	Waste Heat Utilization		% Savings
	Without	With	
Temp., °C	10	20	-
Recycle Ratio ²	0	0.55	-
Capital Costs (in \$ 10 ⁶)	146.44	127.39	13.0
O&M Annual Costs (in \$10 ⁶)	5.38	5.00	7.1
Total Annual Treatment Costs (in \$ 10 ⁶)	16.84	14.96	11.2

¹ Primary Treatment - Bardenpho Process

² Recycle Ratio = Waste Heat Flow/Sewage Flow

Sludge Disposal Processes

An economic analysis of sludge disposal processes was made for the sludge produced from the treatment processes for each group of effluent standards. Two stabilization processes were considered as benefiting from waste heat and were the anaerobic and aerobic digestion processes.

The results of recycling waste heat to the anaerobic digestion process are shown in Table 28. It should be noted that the capital cost would remain the same since the temperature must remain constant, usually at about 95°F. In addition, the O&M cost with recycling waste heat includes a 3-month fuel cost for the winter in which the power plant could not supply sufficient heat to the anaerobic sludge digestion process. For disposing the sludge produced from the processes meeting the three groups of effluent standards, significant savings were made, with the percent savings ranging from 12% to about 17%.

Cost benefits were also identified for sludge disposal systems which incorporate aerobic digestion as the process for sludge stabilization. In Tables 29 and 30 a comparison is made between a sludge disposal system using aerobic digestion with and without recycling waste heat. In Table 29 the sludge processed is from wastewater processed meeting Group I standards, while the results of the sludge produced

Table 28. Comparison of Sludge Disposal Costs with and Without Recycling of Waste Heat to an Anaerobic Digestion Process

Effluent Standards	Plant Size	O+M Annual Cost Without Recycling Waste Heat, 10^6 \$/yr	O+M Annual Cost With Recycling Waste Heat for 9 month, 10^6 \$/yr	% Savings
Group I	Small	0.131	0.114	13.
	Medium	0.637	0.535	16
	Large	5.758	4.743	17.6
Group II	Small	0.114	0.100	12.3
	Medium	0.556	0.480	13.7
	Large	5.260	4.616	12.2
Group III	Small	0.114	0.100	12.3
	Medium	0.556	0.480	13.7
	Large	5.260	4.616	12.2

from processes meeting Group II and Group III standards are shown in Table 30. In all cases waste heat was transferred through a heat exchanger in order to raise the sludge temperature to 20°C which is considered optimum for the aerobic sludge digestion process. The reactor size and subsequent O&M costs were based on the minimum digestion temperatures which in our study was assumed to be 10°C. Although the cost savings were not as high as with anaerobic sludge digestion, the benefits were substantial and ranged from 8 to 15%.

Table 29. Comparison of Sludge Disposal Costs with and Without Recycling Waste Heat to an Aerobic Digestion Process (Sludge from Processes Meeting Group I Standards)

Plant Size	Temp. ° C	Capital Cost in \$ 10 ⁶	O&M Annual Cost in \$ 10 ⁶	Annual Treatment Cost in \$ 10 ⁶	% Savings (Annual Treatment Costs)
Small	10	3.39	0.20	0.46	-
(5 MGD)	20 ¹	3.22	0.16	0.41	10.9
Medium	10	12.84	0.90	1.90	-
(30 MGD)	20 ¹	11.68	0.71	1.62	14.7
Large	10	114.36	7.91	16.85	-
(300 MGD)	20 ¹	102.88	6.72	14.77	12.3

¹ Utilization of Waste Heat from a Power Plant

Table 30. Comparison of Sludge Disposal Costs With and Without Recycling Waste Heat to an Aerobic Digestion Process (Sludge from Processes Meeting Group II and Group III Standards)

Plant Size	Temp °C	Capital Cost in \$10 ⁶	O&M Annual Cost in \$ 10 ⁶	Annual Treatment Cost in \$ 10 ⁶	% Savings (Annual Treatment Cost)
Small	10	3.13	0.18	0.42	-
(5 MGD)	20 ¹	2.99	0.14	0.37	11.9
Medium	15	11.22	0.74	1.61	-
(30 MGD)	20 ²	10.81	0.64	1.48	8.1

1. Utilization of Waste Heat from a Power Plant.
2. No Recycle Waste Heat Required (Effluents from this Operation are at 20°C)

CHAPTER IV

DISCUSSION

As pointed out in the results section, a number of wastewater treatment processes can benefit from waste heat utilization by being co-located at a electric power generating facility. In general, processes meeting Group II and Group III standards and over 30 MGD in design capacity benefited from the recycling of waste heat. In addition, no cost benefits were found for recycling waste heat back to a wastewater treatment plant which is less than 5 MGD. Overall, the sludge processes benefited the most from the recycling of waste heat. In particular the sludge stabilization through anaerobic and aerobic digestion was found to have significant benefits from the recycling of waste heat. In the following sections, the optimum wastewater treatment systems (in terms of costs) benefiting from recycling waste heat for all of the plant sizes and effluent standards investigated will be discussed. The treatment systems includes sludge processing and disposal as well as primary treatment.

The Optimum Wastewater Treatment Processes

For achieving Group I effluent standards, the optimum waste treatment system in terms of costs was found to be a secondary treatment plant using the activated sludge, with

the sludge stabilization process using an anaerobic digester. Even though the activated sludge process did not benefit from recycling waste heat, it was chosen as the process due to its overall costs when compared to the trickling filters and rotating biological contactors (see appendix). For achieving Group II effluent standards the single stage activated sludge process was found to be the optimum process, with anaerobic digester being the optimum process for sludge stabilization. In terms of costs the Bardenpho process was the best process for achieving Group III standards, with again the anaerobic sludge digester being used for sludge digestion.

A summary of the cost benefits of recycling waste heat to each of the above three treatment systems at three different plant sizes is presented in Table 31. Significant savings can be achieved for co-located wastewater treatment plants of all sizes and in all three groups of effluent standards. For the small plants (5 MGD) the % savings ranged from 1.5% to 2.3% while the % savings for the large plants (300 MGD) ranged from 4.3% to 9.9%.

Other Considerations

Electric power plants do on occasion shut down for scheduled maintenance or unforeseen mechanical problems. On these occasions the cooling water temperature may be insufficient to supply enough heat to the co-located wastewater treatment facility. This would be especially significant

Table 31. Cost Benefits of Recycling Waste Heat to a Municipal Treatment Plant
(in million dollars per year)

Effluent Standards	Plant Size	Cost Without Recycling Waste Heat	Cost with Recycling Waste Heat at Optimum Temperature	Cost Savings	
				10 ⁶ dollars	% savings
Group I	Small ¹	0.754	0.737	0.017	2.3
	Medium ²	2.905	2.803	0.102	3.5
	Large ³	23.765	22.750	1.015	4.3
Group II	Small	0.792	0.778	0.014	1.8
	Medium	3.137	3.050	0.087	2.8
	Large	27.580	24.972	2.608	9.5
Group III	Small	0.908	0.894	0.014	1.5
	Medium	3.573	3.449	0.124	3.5
	Large	31.089	28.204	3.065	9.9

¹ 5 MGD

² 30 MGD

³ 300 MGD

during the winter when the wastewater temperature is the lowest. In addition, the sludge stabilization process would also be affected. Of the more important biological processes which would be affected are the nitrification and denitrification processes, which would be part of a total nitrogen removal process that is required in Group II and Group III effluent standards. During the periods of plant shutdown during the critical periods of the year when these processes would be affected (winter period), provision could be provided to employ breakpoint chlorination for nitrogen removal. As mentioned earlier it was assumed that the anaerobic-digestion process heating system would be supplemented with fuel oil during the winter period and thus a power plant shutdown during this period would not be significant. Power plant shut downs during other parts of the year would reduce the O&M savings, but would not adversely affect treatment efficiency.

CHAPTER V

CONCLUSIONS

This study was conducted in order to identify the wastewater treatment systems which could benefit from the waste heat generated from a co-located electric power generating plant. Three different plant sizes and three groups of effluent standards were evaluated. The study was based on climatic conditions found in the northern midwestern states. The results indicate that a possible savings in annual treatment costs could be realized for co-located wastewater treatment plants in all treatment plant sizes and all of the three groups of effluent standards investigated. In addition, the size of the treatment facility was an important factor in the percentage cost savings which could be made. For small treatment plants (5 MGD) utilizing waste heat, approximately a 2% savings in annual costs could be made for all three levels of effluent standards. For a 30 MGD facility using waste heat about 4% savings could be made, while for the larger facility (300 MGD) from 4 - 10% in annual costs could be saved with increasing standards.

The processes which benefited the most from waste heat utilization were found to be the anaerobic sludge digestion process and the rotating biological contactors. It was estimated that approximately 12-18% in O&M costs could be

saved by utilizing waste heat with the anaerobic digestion of municipal sludge.

APPENDIX A

A. Development of Design Procedure of the Activated Sludge Process.

MLSS in the aeration tank is composed of three parts, inert suspended solids (M_1), biodegradable suspended solids (M_2) and suspended solids produced from soluble BOD metabolism (M_3). If the reactor is designed for nitrification, additional suspended solids nitrified (M_4) should be considered.

$$MLSS = M_1 + M_2 + M_3 + M_4 \quad (A-1)$$

The following diagram shows the material changes through the reactor:

The overall mass balance equation is as follow:

$$V\left(\frac{d(\text{MLSS})}{dt}\right) = QX - Q_w(\text{MLSS}) - QX_e \quad (\text{A-2})$$

Changes of inert suspended solids:

The changes of inert suspended solids can be expressed as Equation A-3 which is derived from the mass balance diagram and Equation A-1.

$$V\left(\frac{dM_1}{dt}\right) = QX_1 - Q_w M_1 - (Q - Q_w)X_{e1} \quad (\text{A-3})$$

At steady state, assume that $Q \gg Q_w$, then $Q - Q_w \approx Q$. Equation A-3 can be rearranged to Equation A-4:

$$Q(X_1 - X_{e1}) = Q_w M_1 \quad (\text{A-4})$$

Since $\text{SRT} = V/Q_w = \theta_c$ and $\text{HRT} = V/Q = \theta$, Equation A-4 is changed to Equation A-5:

$$\begin{aligned} \frac{Q(X_1 - X_{e1})}{V} &= \frac{Q_w M_1}{V} \\ (X_1 - X_{e1})/\theta &= M_1/\theta_c \\ M_1 &= \theta_c/\theta(X_1 - X_{e1}) \end{aligned} \quad (\text{A-5})$$

Changes of biodegradable suspended solids:

Mass balance equation for the changes of M_2 is shown as Equation A-6:

$$V\left(\frac{dM_2}{dt}\right) = QX_2 - QX_{e2} - Q_w M_2 - k_d M_2 V \quad (\text{A-6})$$

$k_d M_2 V$ represents the suspended solids reduced due to decay.

At steady state, Equation A-6 can be changed to Equation A-7:

$$V(dM_2/dt) = 0 = QX_2 - QX_{e2} - Q_w M_2 - K_d M_2 V$$

$$Q(X_2 - X_{e2})/V = M_2(Q_w + k_d V)/V$$

$$M_2 = \theta_c / \theta ((X_2 - X_{e2}) / (1 + k_d \theta_c)) \quad (A-7)$$

Changes of M_3 in the reactor:

The mass balance for M_3 is expressed as following:

$$V(dM_3/dt) = Y_c(QS_o - QS_e) - Q_w M_3 - k_d M_3 V \quad (A-8)$$

At steady state, Equation A-8 can be modified to Equation A-9:

$$V(dM_3/dt) = 0 = Y_c(QS_o - QS_e) - Q_w M_3 - V k_d M_3$$

$$Y_c(QS_o - QS_e)/V = (Q_w M_3 + k_d V M_3)/V$$

$$M_3 = \theta_c / \theta (Y_c(S_o - S_e) / (1 + k_d \theta_c)) \quad (A-9)$$

Changes of M_4 in the reactor

The mass balance for M_4 is as Equation A - 10:

$$V(dM_4/dt) = Y_N (QN_o - QN_e) - Q_w M_4 - V k_d M_4 \quad (A-10)$$

At steady state, Equation A-10 could be rearranged to Equation A - 11:

$$V(dM_4/dt) = 0 = Y_N(QN_o - QN_e) - Q_w M_4 - V k_d M_4$$

$$Y_N Q(N_o - N_e)/V = M_4(Q_w + V k_d)/V$$

$$M_4 = \theta_c / \theta (Y_N(N_o - N_e) / (1 + k_d \theta_c)) \quad (A-11)$$

MLSS is the sum of M_1 , M_2 , M_3 and M_4 ,

$$MLSS = M_1 + M_2 + M_3 + M_4$$

$$= \frac{\theta_c}{\theta} \left((X_1 - X_{e1}) + \frac{X_2 - X_{e2}}{1 + k_d \theta_c} + \frac{Y_c(S_o - S_e)}{1 + k_d \theta_c} + \frac{Y_N(N_o - N_e)}{1 + k_d \theta_c} \right) \quad (A-12)$$

B. Design Example of ASP.

I. Design Procedure of Large Scale (300 MGD) ASP for Group I.

1. Flow:

Influent of aerator is 299 MGD (after primary treatment).

2. Calculation of HRT (θ) :

$$MLSS = \frac{\theta_c}{\theta} \left((X_1 - X_{e1}) + \frac{X_2 - X_{e2}}{1 + k_d \theta_c} + \frac{Y_c (S_0 - S_e)}{1 + k_d \theta_c} \right)$$

$$X_1 = TSS - VSS + f_1 VSS = 127 - 112 + 0.3 \times 112 = 48.6 \text{ mg/l}$$

$$X_{e1} = \text{negligible}$$

$$X_2 = f_2 VSS = 0.7 \times 112 = 78.4 \text{ mg/l}$$

$$X_{e2} = \text{negligible}$$

$$S_0 - S_e = 60 - 8 = 52 \text{ mg/l}$$

$$MLSS = 3000 \text{ mg/l}$$

$$\theta_c = 5 \text{ days}$$

$$Y_c = 0.5$$

$$k_d = 0.05$$

$$3000 = 5/\theta (48.6 + 78.4/(1 + 0.05 \times 5) + (0.5 \times 52)/(1 + 0.05 \times 5))$$

$$\theta = \text{HRT} = 0.22 \text{ days} = 5.3 \text{ hrs.}$$

3. Volume of aerator (V):

$$V = Q\theta = 299 \times 0.22 = 66 \text{ MG}$$

4. Sludge Production:

$$TSS = (3000 \times 66 \times 8.34)/5 = 330300 \text{ \#/day}$$

$$VSS = (2100 \times 66 \times 8.34)/5 = 231200 \text{ \#/day}$$

5. Waste Flow (Q_w):

$$Q_w = \text{TSS}/(\text{MLSS}_R \times 8.34) = 330,300/(10,000 \times 8.34) \\ = 4.0 \text{ MGD}$$

6. Oxygen Requirements (O_2):

$$O_2 = (130-20) \times 8.34 \times 299/0.68 - (1.42 \times 231,200) \\ = 75,100 \text{ \#/day}$$

7. Blower Size (BSIZE):

$$\text{BSIZE} = 75,100/(0.075)(0.232)(0.05)(1440) = 60,000 \text{ cfm}$$

8. Food - Mass Ratio (F/M):

$$F/M = (130 \times 299 \times 8.34)/(2100 \times 66 \times 8.34) \\ = 0.28 \text{ \#BOD applied / \# VSS}$$

9. Area of Clarifier (A)

$$A = (299 \times 10^6)/700 = 427,150 \text{ ft}^2$$

10. Return Flow (Q_r):

$$3000(299 + Q_r) = 10,000 \times Q_r$$

$$Q_r = 128 \text{ MGD}$$

$$R = 128/299 = 0.43$$

11. Solid Flux (G):

$$G = (10,000 \times 128 \times 8.34)/427,150 = 25 \text{ \#/ft}^2/\text{day}$$

II. Design Procedure of Large Plant (300 MGD) ASP forGroup II.1. Calculation of Hot Water Flow (Q_H):

$$\frac{(10 \times 299) + (38 \times Q_H)}{299 + Q_H} = 20^\circ\text{C}$$

$$Q_H = 165 \text{ MGD}$$

2. Total Flow (Q):

$$299 + 165 = 464 \text{ KGD}$$

3. Determination of Minimum SRT (θ_c^m):

$$1/\theta_c^m = 0.285(e^{0.098(20-15)}) = 0.465$$

$$\theta_c^m = 2.15 \text{ days}$$

4. Determination of Design SRT (θ_c^d):

$$\theta_c^d = 2.15 \times 2.5 = 5.4 \text{ days}$$

5. Calculation of HRT (θ):

$$MLSS = \frac{\theta_c}{\theta} \left((X_1 - X_{e1}) + \frac{X_2 - X_{e2}}{1 + k_d \theta_c} + \frac{Y_c(S_0 - S_e)}{1 + k_d \theta_c} + \frac{Y_N(N_0 - N_e)}{1 + k_d \theta_c} \right)$$

$$TSS = ((127 \times 299) + (12 \times 165)) / 464 = 86 \text{ mg/l}$$

$$VSS = ((112 \times 299) + (6 \times 165)) / 464 = 74 \text{ mg/l}$$

$$S_0 = ((60 \times 299) + (3 \times 165)) / 464 = 40 \text{ mg/l}$$

$$N_0 = ((15 \times 299) + (1.5 \times 165)) / 464 = 10 \text{ mg/l}$$

$$X_1 = TSS - VSS + 0.3VSS = 86 - 74 + 0.3 \times 74 = 34 \text{ mg/l}$$

$$X_{e1} = \text{negligible}$$

$$X_2 = 0.7VSS = 0.7 \times 74 = 52 \text{ mg/l}$$

$$X_{e2} = \text{negligible}$$

$$S_0 - S_e = 40 - 2 = 38$$

$$N_0 - N_e = 10 - 0.75 = 9.25$$

$$Y_c = 0.5$$

$$Y_N = 0.15$$

$$k_d = 0.1$$

$$3000 = \frac{5.4}{\theta} \left(34 + \frac{52}{1 + 0.1 \times 5.4} + \frac{0.5 \times 38}{1 + 0.1 \times 5.4} + \frac{0.15 \times 9.25}{1 + 0.1 \times 5.4} \right)$$

$$\theta = 0.146 \text{ days} = 3.5 \text{ hr}$$

6. Volume of Aerator (V):

$$V = Q\theta = 464 \times 0.146 = 67.7 \text{ MG}$$

7. Sludge Production:

$$\text{TSS} = (3000 \times 67.7 \times 8.34)/5.4 = 314000 \text{ \#/day}$$

$$\text{VSS} = (2100 \times 67.7 \times 8.34)/5.4 = 219600 \text{ \#/day}$$

8. Waste Flow (Q_w):

$$\begin{aligned} Q_w &= \text{TSS}/(\text{MLSS}_R \times 8.34) = 314000/(10000 \times 8.34) \\ &= 3.8 \text{ MGD} \end{aligned}$$

9. Oxygen Requirement (O_2):

$$\begin{aligned} O_2 &= ((88-5) \times 464 \times 8.34)/0.68 - 1.42(219600) \\ &\quad + (10-0.75) \times 4.6 \times 464 \times 8.34 = 325000 \text{ \#/day} \end{aligned}$$

10. Blower Size (BSIZE):

$$\begin{aligned} \text{BSIZE} &= 325000/(0.075 \times 0.232 \times 0.05 \times 1440) \\ &= 259600 \text{ cfm} \end{aligned}$$

11. Food-Mass Ratio:

$$\begin{aligned} &(88 \times 464 \times 8.34)/(2100 \times 67.7 \times 8.34) \\ &= 0.29 \text{ \#BOD applied/\#-VSS} \end{aligned}$$

12. Area of Clarifier (A):

$$A = (464 \times 10^6)/700 = 663000 \text{ ft}^2$$

13. Return Flow (Q_r):

$$3000(464 + Q_r) = 10000 Q_r$$

$$Q_r = 199 \text{ MGD}$$

$$R = 199/464 = 0.43$$

14. Solid Flux (G):

$$G = (10000 \times 199 \times 8.34)/663000 = 25 \text{ \#/ft}^2/\text{day}$$

APPENDIX B

Table 32. The Effect on Annual Treatment Costs of Recycling Waste Heat to Small Scale (5MGD) Municipal Treatment Facilities Designed to Meet Group I Effluent Standards

Process	Recycle [*] Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Activated Sludge	0	10	2.840	0.134	0.356
Trickling Filter	0	10	3.900	0.120	0.425
	0.22	15	4.199	0.133	0.461
	0.55	20	4.483	0.142	0.493
	1.14	25	4.700	0.155	0.523
Rotating Biological Contactors	0	10	4.079	0.157	0.476
	0.22	15	4.149	0.158	0.483
	0.55	20	4.458	0.163	0.512
	1.14	25	4.868	0.163	0.544

*Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 33. The Effect on Annual Treatment Costs of Recycling Waste Heat to Medium Scale (30MGD) Municipal Treatment Facilities Designed to Meet Group I Effluent Standards

Process	Recycle* Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Activated Sludge	0	10	10.265	0.493	1.296
Trickling Filter	0	10	16.686	0.454	1.759
	0.22	15	17.331	0.491	1.847
	0.55	20	18.404	0.535	1.975
	1.14	25	20.527	0.597	2.203
Rotating Biological Contactors	0	10	17.929	0.684	2.087
	0.22	15	17.955	0.671	2.076
	0.55	20	18.402	0.663	2.103
	1.14	25	19.928	0.673	2.232

*Recycle Ratio = Waste Heat Flow/ Sewage Flow

Table 34. The Effect on Annual Treatment Costs of Recycling Waste Heat to a Large Scale (300MGD) Municipal Treatment Facility Designed to Meet Group I Effluent Standards

Process	Recycle* Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Activated Sludge	0	10	72.092	3.615	9.255
Trickling Filter	0	10	132.880	3.386	13.781
	0.22	15	133.990	3.639	14.121
	0.55	20	138.123	3.977	14.782
	1.14	25	159.875	4.522	17.029
Rotating Biological Contactors	0	10	152.980	5.858	17.825
	0.22	15	148.696	5.622	17.254
	0.55	20	147.653	5.449	17.000
	1.14	25	164.137	5.697	18.537

*Recycle Ratio = Waste Heat Flow/Sewage Flow.

Table 35. The Effect on Annual Treatment Costs of Recycling Waste Heat to a Small Scale (5 MGD) Municipal Waste Treatment Facility Designed to Meet Group II Effluent Standards

Process	Recycle* Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/Yr	Annual Treatment Cost 10 ⁶ \$/yr
Activated Sludge	0	10	3.428	0.160	0.429
	0.22	15	3.554	0.168	0.447
	0.55	20	3.628	0.162	0.445
	1.14	25	4.217	0.170	0.500
Activated Sludge - Trickling Filter	0	10	4.807	0.173	0.549
	0.12	13	4.956	0.183	0.571
	0.22	15	5.361	0.192	0.611
Rotating Biological Contactors	0	10	5.548	0.200	0.634
	0.12	13	5.170	0.187	0.591
	0.22	15	5.279	0.191	0.605

* Recycle Ratio = Waste Heat Flow/Sewage Flow.

Table 36. The Effect on Annual Treatment Costs of Recycling Waste Heat to a Medium Scale (30 MGD) Municipal Waste Treatment Facility Designed to Meet Group II Effluent Standards

Process	Recycle* Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Activated Sludge	0	10	13.492	0.629	1.684
	0.22	15	13.202	0.640	1.673
	0.55	20	13.447	0.631	1.683
	1.14	25	15.367	0.615	1.817
Activated Sludge - Trickling Filter	0	10	19.536	0.637	2.165
	0.12	13	18.714	0.660	2.124
	0.22	15	19.058	0.665	2.158
Rotating Biological Contactors	0	10	25.624	0.895	2.903
	0.12	13	22.946	0.806	2.601
	0.22	15	23.379	0.820	2.649

* Recycle Ratio = Waste Heat Flow/ Sewage Flow.

Table 37. The Effect on Annual Treatment Costs of Recycling Waste Heat to a Large Scale (300MGD) Municipal Waste Treatment Facility Designed to Meet Group II Effluent Standards

Process	Recycle [*] Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Activated Sludge	0	10	106.742	4.978	13.328
	0.22	15	96.320	4.984	12.520
	0.55	20	91.695	4.551	11.724
	1.14	25	105.735	4.512	12.785
Activated Sludge - Trickling Filter	0	10	147.384	4.569	16.104
	0.12	13	141.430	4.746	15.810
	0.22	15	141.958	4.772	15.877
Rotating Biological Contactors	0	10	230.300	8.075	26.091
	0.12	13	199.070	7.066	22.639
	0.22	15	203.200	7.191	23.087

* Recycle Flow = Waste Heat Flow/Sewage Flow

Table 38. The Effect on Annual Treatment Cost of Recycling Waste Heat to a Small Scale (5 MGD) Municipal Treatment Facility Designed to Meet Group III Effluent Standards

Process	Recycle* Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Two-Stage Activated Sludge	0	10	4.629	0.281	0.643
	0.22	15	4.659	0.297	0.661
	0.55	20	4.847	0.300	0.679
Bardenpho Process	0	10	4.629	0.183	0.545
	0.22	15	4.659	0.195	0.559
	0.55	20	4.847	0.196	0.575

* Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 39. The Effect on Annual Treatment Cost of Recycling Waste Heat to a Medium Scale (30 MGD) Municipal Treatment Facility Designed to Meet Group III Effluent Standard

Process	Recycle* Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Two-Stage Activated Sludge	0	10	18.171	1.264	2.685
	0.22	15	17.332	1.313	2.669
	0.55	20	17.897	1.333	2.733
Bardenpho Process	0	10	18.171	0.699	2.120
	0.22	15	17.332	0.716	2.072
	0.55	20	17.897	0.715	2.115

* Recycle Ratio = Waste Heat Flow/Sewage Flow

Table 40. The Effect on Annual Treatment Cost of Recycling Waste Heat to a Large Scale (300 MGD) Municipal Treatment Facility Designed to Meet Group III Effluent Standards

Process	Recycle* Ratio	Temperature °C	Capital Cost 10 ⁶ \$	O+M Annual Cost 10 ⁶ \$/yr	Annual Treatment Cost, 10 ⁶ \$/yr
Two-Stage Activated Sludge	0	10	146.440	11.222	22.678
	0.22	15	130.341	11.492	21.688
	0.55	20	127.388	11.159	21.124
	1.14	25	152.610	11.730	23.669
Bardenpho Process	0	10	146.440	5.381	16.837
	0.22	15	130.341	5.405	15.601
	0.55	20	127.388	4.995	14.960
	1.14	25	152.610	4.989	16.928

* Recycle Ratio = Waste Heat Flow/Sewage Flow

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