# THERMAL POLLUTION ABATEMENT
# EVALUATION MODEL FOR POWER PLANT SITING

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## ENERGY LABORATORY

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# ABSTRACT

## A THERMAL POLLUTION ABATEMENT EVALUATION MODEL FOR POWER PLANT SITING

A thermal pollution abatement model for power plant siting is formulated to evaluate the economic costs, resource requirements, and physical characteristics of a particular thermal pollution abatement technology at a given site type for a plant alternative. The model also provides a screening capability to determine which sites are feasible alternatives for development by the calculation of the resource requirements and a check of the applicable thermal standards, and determining whether the plant alternative could be built on the available site in compliance with the thermal standards.

The thermal pollution evaluation model analyzes the abatement technologies of surface discharge, diffuser, cooling pond, spray canal, and wet mechanical draft cooling towers. The typical site types evaluated are a river, small lake, great lake, coastal, estuary, offshore ocean, and water poor site.

The model will be used in conjunction with a Plant Evaluation Model, which analyzes the effects of fuel costs and air pollution abatement, a Plant Expansion Model, and a Generation Expansion Model to determine the optimal operating and generating plan for an electric utility. The model may also be used in conjunction with the Plant Evaluation Model to evaluate the trade offs between the dollar cost of electric power generation, reliability, and air and thermal pollution. The model may also be used to determine, for a single plant site alternative, which abatement technologies would be feasible, and to make an economic and resource requirement comparison between these alternatives. Finally, the model could be used to examine the economic and locational aspects of the implementation of a plan limiting the waste heat discharge to natural bodies to zero discharge.

# ACKNOWLEDGEMENTS

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# CHAPTER ONE

## INTRODUCTION

A study of an energy system is a quantitative analysis of demand, supply, and the technological, environmental, and institutional interactions within the system using an approach including analytical, economic, and simulation techniques to establish models which would be useful for planning or management. The National Science Foundation, through a grant for a program entitled "Dynamics of Energy Systems", has supported work here at M.I.T. which has resulted in the setting up of such a study for electrical energy. This system study relied heavily upon the use of mathematical models to analyze system behavior and policy implications.

The objectives of the study were twofold. The first objective was to give decision-makers more effective tools to analyze national energy policy questions and to evaluate the effects of regulatory actions, resource allocation, taxes, etc., on supply patterns which are consistent with national economic, environmental, and social goals. The second objective was to develop tools for a detailed regional or industry wide study to yield an insight into the technology needs and growth patterns required to meet social and economic requirements.

Among the data and sub-models required within this study were the cost and technology requirements of the imposition of environmental standards, the effects of electrical energy use upon the natural environment, and the socio-economic factors, as best as they could be evaluated. An attempt was made in the study, therefore,

to understand the environmental effects of electrical energy use
and then to use this knowledge in the development of models to be
used in the planning and conducting of research and development on
electrical energy technology.

The development of energy models, and their verification and
utilization, is a continuing process which evolves based on the
analysis of past and present practices plus trial and error fitting
of models to actual system performance. The magnitude of work
involved in the development of such an electrical system study,
however, is beyond the capability of a small group of people if
original research is carried out for all the necessary steps of the
study. However, in this case, fragments of research had been done
previously, so that a substantial portion of the work involved
collection, analysis, organization, and extension of previous work
in related areas to fit the models. Thus, the models and the
procedure for analysis developed in this study are suitable for
handling the first estimates and evaluating alternatives for the
electrical energy system. It should be noted, however, that the
output of the study is simply tools and information for decision-
makers, rather than policy recommendations.

## I. A. Objectives

Among the problems resulting from the rapid expansion of the
electrical energy system is the increasing discomfort caused by the
deterioration of the environment. This adverse environmental impact,
which has led to the adoption of new environmental quality standards,

is the most significant disturbance in the electrical system today. The National Environmental Policy Act of 1969 resulted in much attention being focused on the environmental impact of waste heat from thermal electric generating stations. The court decisions arising from the implementation of this Act have drastically altered both the outlook and procedural requirements of both the federal regulatory agencies and the electric utilities concerning thermal discharge. In additional to considering the environmental impact of a given planned action, the current requirements now include determining and comparing the environmental impacts of the alternatives to the planned action. The Federal Water Pollution Control Act of 1972, which has upheld the concept of water quality standards, includes: new requirements for discharge permits; requirements for the use of the best practicable and the best available technology to work towards the goal of zero discharge; and the setting forth of requirements which effluents from new sources of discharge, including steam-electric generating stations, must meet prior to discharge into a water body. These requirements for temperature rise in cooling water, along with restrictions on fuels and requirements for removal of elements from the stack gas, have arisen out of increased attacks on the thermal, gaseous, and particulate emissions from power plants. Thus, new constraints of preservation of environmental quality and land use have been imposed on power plant siting, and the electrical energy suppliers must now go beyond the mere delivery of electrical energy at a competitive price. The goal now is to deliver energy at a competitive price with major attention as to how the electrical

energy system affects the environment. Requirements are now being proposed by government agencies, industry, and concerned citizens, that the total cost of the electricity be made to include, in addition to the normal costs of delivery of the energy, the costs of the environmental degradation. One objective of this report was to develop methods to make this determination. The study developed methods to determine these costs, to make present vague statements about environmental impact more precise, and to establish procedures for evaluating alternatives in the electrical energy system. Among the considerations involved were: the technology required to attain a level of environmental quality; the cost of alternative levels of pollution abatement; the allowable land use for electrical energy systems; and the preferred generation facilities for minimum environmental disturbance consistent with supply, availability, and economic costs.

The specific objective of this report was to investigate the thermal electric portion of the energy system and the impact of its waste heat upon the aquatic environment. This was accomplished by the development of an analysis procedure which evaluates the alternatives which are available to meet aquatic temperature standards for a limited number of abatement technologies at a given site for an electric generating station. Models were developed and analyzed for electric generation emissions of waste heat to ascertain the environmental impact both locally and within a region. The procedure for analysis determines the ability of a given plant at a site with a particular thermal pollution abatement technology to meet

temperature standards for a prescribed mixing zone. The capital and operating costs of the abatement technology are calculated, and the resource requirements for land area, make-up water, and total heated water surface area are computed. The design characteristics of the abatement alternative are also determined. Finally, the new inlet temperature of the plant and the power consumption of the abatement technology are calculated to allow for a determination of the losses in plant performance. The organization of this procedure required the development and analysis of: temperature prediction methodology in water bodies, thermal pollution standards and criteria, cost data, resource requirements for the various alternatives, and models to analyze this data. Special attention was paid to identify impacts in a physical and societal sense and to address local regulations involved in environmental impact statements.

The analysis procedure may be used to more accurately identify and quantify the trade offs between economic growth and environmental quality so that rational decisions can be made concerning levels of electric energy production consistent with different statements of environmental preference, and the economic cost in terms of efficiency losses and added technologic investment which are necessary to meet varying environmental standards. The procedure also provides a screening capability for resource requirements at alternative sites with various abatement technologies. If the resource requirements are not available, the model will declare the site and abatement combination not feasible. Thus, the procedure will provide decision-makers with the information necessary to

make an evaluation among site alternatives and the thermal pollution abatement technologies to aid them in the process of establishing a policy for the expansion of generating capacity.

Finally, the thermal pollution evaluation system was developed primarily as a part of a larger plant evaluation model which will also analyze the effects and requirements of air pollution. This Plant Evaluation Model will be used as a section of a Generation Expansion Model which will provide decision-makers with the ability to examine a comprehensive selection of design parameters and system configurations to determine the optimal design for a given system or to select the most economical system from several competing alternatives. It is important to note that the cost analysis for the electrical energy system was done such that the total cost for a specific planning horizon for the entire system, including plant performance losses, was considered.

## I. B. Outline of the Report

Chapter Two provides a general background to the problem of thermal pollution and the abatement techniques available to control this problem. The demand for electric power is discussed in an effort to give a background on the expected magnitude of the problem, and the definition of thermal pollution is considered along with a brief background on the generation of waste heat. A rather extensive discussion of temperature standards and criteria is presented including sections on the Environmental Protection Agency (EPA) criteria, a review of currently adopted temperature standards, the

administration of standards, and the Federal Water Pollution Control Act of 1972. The mixing zone and zone of passage concept is discussed including the EPA criteria, and a brief review of the definitions adopted by the States. A brief summary of the ecological aspects of thermal pollution is provided. The alternatives available for thermal pollution abatement are described including plant location, plant operation, once-through cooling systems, cooling ponds, spray canals, cooling towers, beneficial uses, decentralized power generation systems, and the aesthetic considerations. Finally, the losses of water due to evaporation and the effects of thermal pollution on alternate water uses are discussed.

The effects of thermal pollution on power plant siting are discussed in the third chapter. A general discussion of the economic theory of thermal pollution management is presented and the economic costs of the abatement alternatives are developed and analyzed including plant location, plant operation, and the various means available for waste heat disposal. The physical aspects required for the model development are discussed, including the state of the art, evaporative losses, and a description of the models selected for use in this study for a surface discharge, a diffuser, cooling ponds, spray canals, and cooling towers.

The background development for the plant evaluation model is presented in Chapter Four. The detailed description of the thermal pollution abatement evaluation model includes a summary of the state of the art, the problem formulation and solution. The overall plant evaluation model and its applications are briefly discussed.

Chapter Five presents the system planning model which was developed by others working on the electrical energy system study. The model development and its application are briefly discussed with particular emphasis on the manner in which the thermal pollution abatement evaluation procedure provides input to the overall regional system model. The results of a case study run with the thermal pollution abatement evaluation system, including the scope of the study, the data used, results, and the necessary comments on the output are included in the sixth chapter.

Chapter Seven presents the conclusions of the report. The chapter includes a discussion of the results and improvements which might be made on the work if continued in the future.

The appendix includes a listing of temperature standards and mixing zone requirements adopted by the fifty States, the National Technical Advisory Committee recommendations made in its publication Water Quality Criteria (1968) for temperature standards and mixing zones. A listing of the thermal pollution evaluation model, a list of the variables used in the model, and the required input for the surface discharge model **will be available in a supplementary volume which is currently under preparation at the Energy Laboratory at MIT. Inquiries concerning this volume and the program deck should be addressed to Prof. David C. White, Director, Energy Laboratory, MIT Cambridge, Mass. 02139.**

CHAPTER TWO

THERMAL POLLUTION

A comprehensive analysis of the thermal pollution problem

requires consideration of: the generation of waste heat in electric

power production; temperature standards and criteria, including

mixing zones; the ecological effects of the introduction of waste

heat to a water body; the waste heat disposal system; evaporation and

other consumptive water use; and the effects of heating the water on

alternate water uses.


## II. A. Demand for Electric Power

The demands for electric power have been approximately doubling

each decade for the past several decades due to the increasing popu-

lation and the growing economy in this country. The current fore-

casts for load growth indicate that the rate of load expansion can be

expected to generally follow this past trend until 1990. Although

recent statistics indicate that the total rate of growth for all

forms of energy fell from 3.1% per annum in 1970 to 2.8% in 1971,

within this statistic, the growth rate in demand for electric power

remained constant at approximately 6% for both years. This indicates

that electric power generation is assuming more of the total demand

for energy and that its exponential growth rate shows no signs of

diminishing on a national basis.

According to Nassikas (1971), the per capita growth in energy

use has grown from an average of 1.2% over the past fifty years, to a

2.0% average when the last 30 years are considered, to a 2.7%

average over the last decade, and finally to a 4.9% average for the past 5 years. Also, the energy use per dollar of Gross National Product which had slowly decreased since 1920 began to rise again in 1968. In 1970, the total energy consumption was 68 X $10^{15}$ British Thermal Units (BTU), and, if present growth rates continue, this number may more than double before the year 2000. This growing use of energy is in turn resulting in increased environmental degradation and supply shortages which have become a matter of national concern. The utilization of energy in the United States was 45 X $10^{15}$ BTU in 1960, 54 X $10^{15}$ BTU in 1965, 66 X $10^{15}$ BTU in 1969, with projections for 75 X $10^{15}$ BTU in 1975, 95 X $10^{15}$ BTU in 1980, and 140 X $10^{15}$ BTU in 1990.

The pattern of energy utilization displayed by the United States in 1960 was 20% for transportation, 21% for electricity, 48% for heat use, and 11% for non-energy use. By 1970, the percentage of the electricity component had increased to 25%. As stated previously, the projected energy usage in the United States is a near four fold increase during the period of 1960 to 2000. The use of electrical energy is projected to increase during the period also, from 20% of the total energy used in 1960 and 25% of the total in 1970 to projections of 45% to 50% of the total by the year 2000, according to Nassikas (1971). Thus, between 1960 and 2000 the electrical energy usage forecast is for up to a nine fold increase. This exponential growth of electrical energy has already resulted in some visible effects in the 1970's in the frequent brownouts and blackouts along with air pollution from fossil fueled plants, thermal pollution

of water bodies, and the aesthetic degradation caused by the plants
and their accompanying transmission facilities. The projected major
portion of electrical energy coming from nuclear sources along with
their resulting increased waste heat generation may require the
off-shore location of these units or a power plant complex in
which plans are made for beneficial uses of waste heat in future
years.

The electrical energy component has had a growth rate of 7.5%
average annual over the past 50 years with the rate rising to 9% for
the years of 1968 and 1969, with the current rate of approximately
6%. This growth rate indicates a doubling period of approximately
10 years which includes a requirement for new plant sites and
equipment which may not be able to be met by sources which have
been available in the past. Indeed, the doubling time is now
approaching the time required to plan, order, and install a single
plant.

The following table from Dynatech (1970) presents a breakdown
in the distribution of electric power consumption for 1965 with
projections for the years 1980 and 2000. It should be noted that
the trend for the future indicates a growth in the industrial
sector with a corresponding decrease in the commercial sector.
(see table 2.1) The total energy per household required for
space heating is expected to decrease before the year 2000 due to
increased usage of the heat pump concept, population shifts to
warmer climates, and increasing use of multiple unit dwellings.
However, the kilowatt hour (kwhr) usage per household has been

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Table 2.1

Electric Power Consumption

| | 1965 | | 1980 | | 2000 | |
|---|---|---|---|---|---|---|
| | % | bkwh* | % | bkwh | % | bkwh |
| Industrial | 45 | 475 | 55 | 1100 | 56 | 2240 |
| Commerical | 21 | 222 | 15 | 308 | 14 | 554 |
| Residential | 30 | 317 | 30 | 594 | 30 | 1188 |
| Other | 4 | 41 | -- | --- | -- | ---- |

*billion kilowatt hours

predicted as 8137 kwhr in 1980 and 11,952 kwhr in the year 2000 with a 1960 base figure of 3669 kwhr.

The electric utility industry had an installed generating capacity of 340,000 Mw in 1970, which produced over 1.5 trillion kwhr of electrical energy annually, with projections made for 665,000 Mw in 1980 and 1,260,000 Mw by 1990, with an annual power generation approaching 6 trillion kwhr, according to Nassikas (1971). (See table 2.2.) This would represent a four-fold increase of growth in 20 years. The increase in growth has resulted in a Federal Power Commission (FPC) projection of 300 plant sites required during the next two decades. (See table 2.3.) Also, to meet the projected demand with this number of sites, the average plant size would be 3,000 Mw. These large electric power plant sizes (in excess of 2,000 Mw) may introduce unique environmental problems even at remote locations.

According to the FPC (1969), the once-through system of cooling was projected for plants in coastal areas or in the vicinity of large lakes and streams. The large plants would make use of cooling ponds or reservoirs. Although no study was made for the specific

## Table 2.2

### Projection of Generating Capacity

| | 1970 | | 1980 | | 1990 | |
|---|---|---|---|---|---|---|
| | Mw | % | Mw | % | Mw | % |
| Conventional hydro | 51,400 | 14.9 | 68,000 | 10.2 | 81,945 | 6.5 |
| Pumped storage hydro | 3,600 | 1.1 | 27,000 | 4.0 | 70,000 | 5.5 |
| Fossil steam | 261,200 | 75.9 | 396,000 | 59.3 | 559,000 | 44.3 |
| Internal combustion and gas turbine | 16,200 | 4.7 | 30,000 | 4.5 | 50,000 | 4.0 |
| Nuclear | 11,600 | 3.4 | 147,000 | 22.0 | 500,000 | 39.7 |
| Total | 344,000 | 100.0 | 668,000 | 100.0 | 1,260,945 | 100.0 |

from: Warren (1969)

## Table 2.3

### National Data

| | Thermal Power Capacity* | | Waste Heat** | Sites*** |
|---|---|---|---|---|
| | Thous. Mw | | Trillions BTU | New Sites |
| Periods | Added | Total | | |
| 1970 | ---- | 202 | 5,333 | ---- |
| '71-'80 | 283 | 485 | 7,454 | 163 |
| '81-'90 | 540 | 1025 | 15,580 | 127 |

*Estimated 1000's Mw capacity in thermal generating plants 500 Mw and up

**Annual discharge to water coolant

***Required for new capacity in each decade

from: Warren (1969)

Note: This table does not include conventional hydro and pumped hydro plants.

sites, an estimate was made that at least 158 plants would require

cooling towers assuming a $15^o$ F condenser rise and the total with-

drawl requirements. The withdrawls were estimated for plants

projected to be in operation in 1980 or 1990 and were taken as the

sum of the condenser flows for once-through systems plus the

required make-up water for cooling ponds and towers. The total

estimated fresh water withdrawl was at an annual rate of 300,000

cubic feet per second (cfs) in 1990 which is equivalent to one-sixth

of the total average annual rate of stream runoff in the ccterminus

United States. It should be noted, however, that the water may be

withdrawn for cooling purposes at several locations along the same

river.

Thus, the expected continuation of exponential growth in the

demand for electric power during the next two decades will require

the establishment of national energy policies, tax laws, and

regulatory practices. In order to successfully implement these

policies, decision-makers will need fundamental knowledge of the

interactions within the energy system, and some form of system

modeling which will allow alternate policies to be tested and

evaluated. The work of this report will attempt to contribute to

the development of such a system model.


## II. B. Thermal Pollution

### II. B. 1. Definition of Thermal Pollution

Physical and biological changes in the receiving water body will

result from all discharges of heated water. These changes may be

insignificant, beneficial, or detrimental depending on the ecology of the particular water body and the uses of the water. When the discharge of heated condenser cooling water results in effects which are detrimental to the other desired uses of the water thermal pollution has occurred. This particular type of pollution is unique, however, in as much as no foreign matter is added to the water body and thus the receiving waters do not become befouled. However, since the aquatic environment can be altered unfavorably by the addition of heat to the water body, the heat must be regarded as a polluting agent.

It should be noted, however, that the thermal pollution problem is not defined in terms of the total heat rejected from the power plant, but it is the local nature of the thermal discharge which gives rise to the problems. Thus, even though large amounts of heat are involved in thermal discharge, on a global scale they are small in terms of the overall heat balance on the surface of the earth. More significant is the problem of the discharge of heat to a river or stream. Also, in considering the release of heat to the environment the useful electric power generated and "waste heat" created must both be considered since almost all of the generated power is dissipated to the surroundings in the form of heat.

Thus, according to Dynatech (1970), with these considerations in mind, a solution to the problem of thermal pollution would have to do one of the following things: reject the heat directly to the atmosphere, not involving water bodies; reject the heat over a wide area; use the heat beneficially to reduce the demand for

electricity (space heating); or use the heat to generate additional
income to help defray the costs of the abatement equipment.

The problem of localization of generating plants has been
intensified by the economics of electric power production. However,
while economics has led to single unit sizes of 1000 Mw or above,
an opposite trend would be more favorable from the point of view of
thermal pollution. In this case, smaller individual generator
units would improve the thermal pollution situation, but trade offs
would be made in the areas of maintenance and air pollution. Since
the demand for electricity is generally located in densely populated
urban regions, however, the power plants cluster in such locations
to minimize transmission costs and tend to minimize condenser
temperature rises and use once-through cooling. Thus, the rejected
heat frequently intrudes on the environment in large concentrations
with tremendous quantities of energy in small areas.


II. B. 2. Generation of Waste Heat

One characteristic of the operation of a steam-electric heat is
the large flow of water which is required through the condenser to
convert the exhaust steam from the turbine to water in order to
maximize the energy conversion prior to recirculation of the
condensate back to the boiler or the reactor. The condenser cooling
water may be heated from 10 to $30^{\circ}$ F. in passing through the
condenser depending upon the design of the plant. The amount of the
waste heat which is discharged to the condenser is a function of the
heat rate (plant efficiency) as well as the type of plant. A good

indication of the quantity of waste heat produced can be obtained

from the fact that in the most efficient plants in operation today,

the heat wasted ranges from nearly equal to the heat equivalent of

the electric energy generated to approximately double this amount.

Both nuclear and fossil-fueled steam-electric plants operate

through the thermodynamic process known as the Rankine cycle. The

steam which is produced in the reactor or boiler at high temperature

and pressure flows through the turbine where it gives up energy to

the turbine rotor which then drives a generator in order to produce

electricity. The steam is then condensed at the exhaust of the

turbine and returned to the boiler for a repetition of the cycle.

During the condensing process, a large amount of heat is given up to

the cooling water which is circulated through the condenser. This

heat which is added to the cooling water is eventually dissipated

to the atmosphere.

The maximum possible efficiency attainable with the Rankine

cycle is a function of the maximum and minimum steam temperatures

measured on the absolute scale. With the current temperatures

found in large fossil-fueled plants, and through the use of

auxiliary equipment such as feedwater heaters, reheats, and extrac-

tion steam, the maximum theoretical thermal efficiency attainable

is approximately equal to 60%. At present, when thermal, mechanical

and electrical losses are taken into account, the best overall

attainable efficiency is about 40%. Any substantial increases in

the theoretical and overall efficiencies can only result from

higher steam temperatures and pressures and this will require new

material technology according to FPC (1969). The actual efficiencies

also depend on the plant type with fossil-fueled generally in a

range from 38 to 40%, lightwater nuclear reactors from 30 to 33%,

and gas-cooled nuclear reactors from 37 to 39%. It should be noted,

however, that these actual operating efficiencies represent an

economic optimization since the increase in plant capital costs

required to operate at the higher efficiencies is greater than the

recovery due to reduced operating costs. Also, even though moves

towards the theoretical maximum efficiency would result in

significant reductions in the quantities of waste heat, the growth

rate in electric power consumption would tend to negate these

gains on an absolute basis.

The heat equivalent of one kilowatt-hour of electricity is

3413 BTU. Thus, with an overall efficiency of 40% found in a fossil

plant,  a heat input of 8,600 BTU will be required for each

kilowatt-hour of energy produced. According to FPC (1969), this

input for the "most efficient fossil plant" may be compared  with

the current national average heat rate for all plants of 10,300

BTU/kwhr. It appears possible, however, that improvements in fossil

plant technology will reduce the heat rate in future plants to

about 8,000 BTU/kwhr. For the current light water reactor nuclear

plants, due to limitations on operating temperatures and pressures,

the heat rate is usually 10,000 BTU/kwhr, or higher. It is

expected, however, that future breeder reactors may be able to

operate with heat rates approaching the most efficient fossil-

fueled plants.

The amount of waste heat discharged to the condenser is related both to the heat rate and the type of plant. In a fossil plant, approximately 15% of the heat input is lost through the stack and other in-plant losses, with the remainder lost in the condensing process. Thus, for the most efficient plant with a heat rate of 8,600 BTU, the condenser heat loss would be approximately 3,900 BTU/kwhr generated. For the average plant with a rate of 10,300 BTU the condenser loss would be 5,300 BTU/kwhr generated. In future plants, if the 8,000 BTU rate could be attained, the condenser loss could be reduced to 3,400 BTU/kwhr. In nuclear plants, since there are no stack losses, the in-plant losses are reduced to 5.0% or less of the input. Thus the percentage of heat discharged through the condenser is substantially larger than the fossil-fueled plant. For a light water reactor with a heat rate of 10,500 BTU, the condenser loss would be 6,700 BTU/kwhr generated. For a future breeder reactor with a heat input of 8,200 BTU/kwhr, the condenser discharge would be about 4,500 BTU/kwhr generated, according to the FPC (1969).

For a given rate of heat removal, by the condenser, the temperature rise in the cooling water is inversely proportional to the amount of water circulated through the condenser. Both the amount of water circulated and the size of the condenser can be varied substantially. The designs most frequently employed have a temperature rise through the condenser of 10 - 20° F, with the average value approximately 15° F. The flow of cooling water required for a 15° F temperature rise would range from 30 gallons

per kwhr generated for the most efficient fossil plants to 55 gallons per kwhr generated for large nuclear plants currently in operation.

More than 80% of the current electric energy produced in this country is generated in steam-electric plants. The other principal source of electric energy, hydroelectric power, has few favorable sites left for development and the other modes of generation currently in use are not likely to account for a sizeable portion of the future electric energy demand. Therefore, even though considerable research is currently underway to develop new means of electric energy generation, the foreseeable future (up to 1990) will probably see the bulk of electric generation produced by steam-electric plants, either nuclear or fossil. The trend towards larger installations of this steam-electric capacity has also developed during recent years to realize economies of scale. According to Brown (1970), late in the 1950's, a unit with a size of 300 Mw was still considered as a maximum. The trend has currently reached the point where units of 1,300 Mw are on order, and units with a capacity of 2,000 Mw are contemplated for development prior to 1990. With units of this capacity available, individual plant sizes of 4,00 Mw could be expected, and even larger site developments would be possible with the power park concept.

Concerning the waste heat disposal to the aquatic environment, the steam-electric generation facilities represent the greatest non-consumptive demand for water which is used as a heat transfer medium. In 1958, this use of water in the United States amounted to 90 billion gallons of water, according to Mihursky (1967). The

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current use by the electric utility industry is over 80% of the total use of water for cooling purposes in this country. This figure also represents nearly one-third of the total water use for all purposes, according to FPC (1969). This use of water in the production of power is principally for the disposal of the waste heat inherent in the production of electric energy in the steam-electric plants.

It has been predicted that by 1980, the power demands will require the use of between one-fifth and one-sixth of the total freshwater runoff in this country to be used for cooling water. Since high spring flood flows occur during one-third of the year and amount to approximately two-thirds of the total runoff, the steam-electric industry may require as much as 40-50% of the toal freshwater runoff for cooling purposes during the remainder of the year.

This already difficult problem has become further complicated by the decision to develop nuclear power. These nuclear units must be constructed in large capacity units in order to be economically competitive with fossil-fueled plants. This large capacity and their lower energy conversion efficiency due to limitations on steam temperatures and pressures will result in much larger quantities of waste heat being rejected into the adjacent bodies of water at future power plant installations of this type.

In conclusion, since about 80% of the electrical energy is currently produced in steam-electric plants, the waste heat generated from such plants may be equivalent to as much as one-fifth

of the total energy consumed, including energy used in heating and transportation as well as electric power production. With the view of increasing demands for electricity and anticipating that a large portion of this demand will continue to be met by steam-electric plants, the waste heat disposal problem will continue to grow in significance. The annual waste heat discharge has been estimated to increase from the present level of $6 \times 10^{15}$ BTU to more than $20 \times 10^{15}$ BTU in 1990 according to FPC (1969).

II. B. 3. Temperature Standards and Criteria

The use of standards, a nationwide strategy for water quality management, involves four major components: the use which will be made of the interstate water; the criteria which are necessary to protect these uses; implementation plans and enforcement plans and finally an antidegradation statement to protect existing high quality waters. The minimum water quality criteria, that is, numerical specifications of physical, chemical, temperature, and biological levels, were set forth in the National Technical Advisory Committee report to the Secretary of the Interior, Water Quality Criteria, which was dated on April 1, 1968. The unavailability of this report before June 30, 1967, the date on which standards had to be submitted for approval, has resulted in some variations between the State-adopted and NTAC minimum criteria. This report is currently being updated, according to the EPA, due to new scientific and technical information and is scheduled for publication in the near future.

The focus of attention in water quality standards during recent years has been upon the use of water for fish or other aquatic life since this particular use is usually more sensitive to temperature increases than are municipal and industrial uses. This program of water quality standards was designed to protect the beneficial uses of interstate waters through the application of numerical and narrative limits on pollution and specification of the required control and treatment measures. According to Krenkel (1969), the Water Quality Act of 1965 was the legal basis for this standards approach. This Act encouraged the States to establish water quality standards for interstate streams and coastal waters by June 30, 1967. Since the passage of this bill all fifty States developed and adopted standards for such waters and these standards were then forwarded to the Secretary of the Interior within the required time. The standards for all the States and other jurisdictions were approved by the Secretary of the Interior, although some of the approvals included reservations, especially in the area of temperature criteria.

The adoption of these standards has become even more important due to the remarkable growth of the electric power industry in recent years. Since the capacity of the aquatic environment to absorb heat without suffering damage has already been exceeded at some sites and the critical point was also being reached in some cases, standards provided a valid approach to managing the aquatic environment.

Standards provide one way of approaching the problem of thermal pollution by protecting the ecosystem which nature has successfully

maintained over a period of years in spite of significant natural fluctuations of water temperature on a seasonal or even a daily basis. The standards approach, however, requires: that site location receive greater attention; increased attention to the long range use of power as it affects peak versus base loads; the toal management of river systems with consideration of flow regulation; and the acquisition of a better understanding of the effects of waste heat upon the aquatic environment.

The responsibility for operating water quality management programs has traditionally been at the State level. In recent years, however, the legislative and administrative efforts at this level have been expanded from a focus solely upon the public health aspects of water quality to aesthetic, recreational, ecological, and other environmental damage considerations due to the increase in public concern within these areas. As a result of the change of concerns, the transfer of administrative responsibilities has taken place in many instances from publich health agencies to comprehensive water pollution control agencies.

The Federal government has been given an increased role in the control of water pollution for interstate and coastal waters as a result of recent Federal legislation, especially the Federal Water Pollution Control of 1972 which will be discussed in this section. The role of the Federal government includes subsidizing municipal waste treatment facilities; research and development activities; and the general supervision and stimulation of State and interstate regulatory activities as they relate to coastal and interstate

waters. At the present time, the State control procedures must

conform to the Federal guidelines. However, although the Federal

agencies reserve the power of approval of the regulatory activities

of the State and the prerogative to issue and enforce abatement

schedules for an individual waste discharge, the primary direct-

control responsibilities are currently exercised by State level

agencies.

The procedure which has been employed up until the present time

for water quality management practices is: classification of water

bodies according to water quality standards based upon scientific

criteria and estimates of use both for existing and target levels;

determination of the reduction in present loads required to raise

existing water quality levels to standards; allocation of shares of

the abatement program among the individual dischargers; and finally,

monitoring and enforcement actions to assure compliance with abate-

ment orders. However, this overall process is a dynamic one which

is subject to continual revision with regards to social and political

pressures, production conditions, and advances in the state of

technical knowledge. Administrative, legislative, and judicial

decisions also aid in the resolution of conflicting viewpoints which

may arise over the adoption of criteria. The trend in the most

recent public opinion and political decisions has been to favor

increased governmental responsibility for the preservation and

improvement of environmental quality.

The shortcomings in efficiency of these present approaches

arises from the administrative practices used to implement the system

rather than the basic concept of water quality classification. The economic efficiency has not increased in every case of application of control efforts since the social cost and benefit principles have not yet been applied in a systematic manner in the setting of standards or in the issuance of abatement orders.

The regulation of thermal pollution will have important implications both for the future qualities of surface waters and for the cost of thermal pollution abatement which the electric utility industry will be required to pay. The characteristics of surface water temperature standards which are apt to be of primary significance in the future are: the water use and values which the standards are designed to protect; the allowable temperature increase in light of these uses; the definition and interpretation of mixing zones and zones for the passage of aquatic species; the point where the maximum allowable temperatures will be measured; the proportion of stream flow allowed for cooling; and the degree to which the standards are enforced, interpreted, and applied.

A number of tentative observations can be made concerning aquatic thermal standards according to Cheney, et. al. (1969). The temperature standards have tended to be set upon the basis of protecting aquatic life from thermal damage since the ecological habitat preservation usually implies the more stringent temperature regulation. Also, the allowable maximum temperature increases will vary depending upon the ambient regional conditions, and the local water-use classifications. The maximum allowable temperature set forth in standards has already been reached in some cases under summer

ambient conditions. In the past years, little consideration has generally been given in the setting of standards, to the proportion of total stream flow that may be passed through the condenser. The presence of passage zones for aquatic life, which are related to thermal mixing and heat-plume factors in the water body, may be of significant ecological importance and will require further study to understand their implications and the possibility of dealing with them. This subject is discussed in greater detail in a following section. The concept of mixing zones has not been explicitly defined by the States in many cases and this has caused temperature standards to be ambiguous to the point of being meaningless. Another topic which is notably absent from thermal standards which will require further study in the future is thermal discharge stratification. Also, little comment has been made as to whether standards are meant to apply to existing installations or primarily to future plants. The present legal basis for the control and abatement of thermal pollution had not been clearly defined during recent years due to litigation and legislative proposals, but the implementation of the Federal Water Pollution Control Act of 1972 should resolve this problem. However, at the present time it does not appear possible to establish sound estimates concerning the degree or extent of thermal pollution control which can be expected in the future due to the implementation of standards.

EPA Water Quality Criteria. The Federal guidelines on water quality criteria are currently under revision, and thus, the most recent available information concerning the current trend in water

quality temperature standards would be the report of the National

Technical Advisory Committee (NTAC) entitled Water Quality Criteria

which was published in 1968. The criteria which were established by

this report focus on water quality requirements for five major uses:

public water supply, fish and wildlife, recreation and aesthetics,

agriculture, and industry. The temperature standards were proposed

by the Committee for four of these uses with industrial use not

being included due to the wide variety of requirements. The specific

recommendations of the Committee are included in Appendix I of this

report.

When these recommendations of the NTAC became available, they

frequently were used by the Federal government in its negotiations

with States to seek the refinement and upgrading of standards before

approval was recommended to the Secretary of the Interior. The

recommendations call primarily for adherence to the natural tempera-

tures with only a narrow range of departures allowed. The objective

of limiting this deviation from natural conditions was to preserve

the normal daily seasonal temperature fluctuations which existed

before the addition of waste heat.

The criteria were generally stated for the recreation use with

the maximum temperatures and a desirable range provided. In most

cases, the total recreation values are more likely to be reduced

than enlarged by the elevation of water temperature.

For public water supply use, no fixed criteria were feasible

since the surface waters vary with geographic location and climate

conditions in the States. The Committee did determine, however, a

number of conditions which detract from water quality for public water supply use. The undesirable conditions include: maximum temperature limits; magnitude and rates of increase of temperature; restrictions on temperature changes which adversely affect the biota, taste and odor, or the chemistry of the water; restrictions on temperature changes which decrease acceptance of the water for cooling and drinking purposes; and finally, restrictions on temperature changes which adversely affect the water treatment plant functions.

For the farmstead and livestock uses the water temperature is not an important consideration in most cases. However, where large volumes of water are used for hydrocooling farm products, the natural temperature of the water can be a factor in influencing its acceptability for such use. For irrigation use, it has been found that irrigation water at excessively high temperature may be detrimental to plant growth due to the resultant increase in the temperature of the soil to which the water is applied. The recommendations were stated generally, in this case, and the maximum recommended temperature and a desirable range were provided.

A body of water must be able to maintain a well-rounded population of fresh water organisms (warm-water and cold-water biota) or marine and estuarine organisms. The ambient temperature of the surface waters of the States vary from $32^{o}$ F to $100^{o}$ F as a function of latitude, altitude, season, time of day, duration of flow, depth, and many other variables. The fish and aquatic life occurring naturally in each body of water are competing there with various

degrees of success depending upon the temperature and other conditions of the habitat. The interrelationships of species, number of daylight hours, and water temperature are so intimate that a small temperature change can have drastic effects. Also, the gradual seasonal change in water temperature is important for animal life acclimation to climate and regulation of spawning activities, metamorphosis, and migration. The effects of toxicity on fresh water organisms also increase with temperature.

In arriving at a suitable criteria, a determination must be made about how much the natural temperature may be exceeded without adverse effects. Whatever requirements are determined, a seasonal cycle of gradual temperature changes must be maintained. Rather than an unvarying number to state this criteria, a temperature increment based on the natural water temperature appears to be appropriate. Thus, the recommendations for fish and aquatic life were more specific and more stringent. This was done to prevent the rise of a situation where a desired species would be eliminated and an undesirable species introduced to take its place.

For fresh-water organisms in warm-waters restrictions were placed on the maximum allowable temperature rise for streams and lakes based on the monthly average of the maximum daily temperature; the normal daily and seasonal temperature variations present before the addition of heat had to be maintained; and the recommended maximum temperatures not to be exceeded for certain species of warm-water fish were provided in tabular form. For fresh-water organisms in cold-waters restrictions were placed on discharges of heated

water to inland trout streams, in the vicinity of spawning areas, and headwaters of salmon streams, etc. For other types of cold-water bodies restrictions were placed on the maximum temperature rise for streams, lakes, and reservoirs; the normal daily and seasonal temperature fluctuations which existed before the addition of heat had to be maintained; and the recommended maximum temperatures that are not to be exceeded for various species of fish were again given in tabular form.

The organisms in the intertidal zones vary in their ability to withstand high temperatures. The location of the species within the tidal zones has a direct effect upon the ability of the species to acclimate to the higher temperatures. In general, the temperatures in the marine waters do not change as rapidly nor do they have the overall range as do fresh waters. In attempting to set up permissible levels of temperature increase in receiving waters due to heated waste discharges, precaution must be taken to prevent incremental increases above background values even though such increases lie below maximum limits. Such precautions are necessary to prevent gradual net increases in background temperatures due to the continuously increasing volumes of heated wastes being discharged into the receiving waters. Thus, for marine and estuarine organisms, close management of all discharges was called for by the Committee with restrictions placed on the increase of monthly means of the maximum daily temperatures on a seasonal basis.

Standards Adopted by the States. Certain characteristics may be enumerated concerning the water quality standards containing

temperature criteria adopted by each of the fifty States. The standards vary significantly quantitatively from State to State with most States choosing to use a combination approach including both numerical and narrative approaches. The numerical criteria included in the standards are found to be generally oriented to the type of fishery protected. Also, the numerical limits generally reference a seasonal maximum temperature; an allowable change above ambient conditions; and, in some instances, a rate of change. Reference was usually made to a mixing zone, but frequently in an ambiguous manner.

The diversity of the adopted temperature criteria gives an indication, according to Krenkel (1969), of the type of commitment which will be required to control thermal pollution and the difficulty which States experience in selecting an appropriate numerical limit for temperature. Among the serious problems which arose in attempting to set limits on this complicated water quality parameter were lack of data on existing temperatures and bureaucratic difficulties of data scattered among agencies or lost in the records. Also, data in many cases had not been fully evaluated or verified for its accuracy or applicability to the problem at hand. This knowledge of existing conditions is a fundamental requirement for both the establishment of criteria which are applicable to local conditions and as a basis for the implementation and enforcement of the criteria.

Another difficulty arose in the area of heat loads and their effects on aquatic life where only limited information was available.

The effects of a temperature increases on an entire ecosystem had not been determined in many cases although many sources were available concerning tests done on individual species. However, this data was often scattered in many locations, neglected the interrelationships within an ecosystem, and failed to note changes experienced by certain key species at different stages of life development.

The adopted standards indicate uncertainty as to the best way to administer temperature criteria. Among the difficulties arising in this regard are the definition of natural conditions; treatment of cumulative temperature increases; providing seasonally adjustable criteria; and separating and dealing with the adverse effects of natural and man-made influences.

The standards adopted generally include a narrative statement which limits the temperature increase to a level which will not have an adverse effect on beneficial water uses. Numerical limits were also adopted by all except one State with these numerical criteria containing a maximum temperature limit which varied from $55^{\circ}$ F to $96^{\circ}$ F. For streams with cold-water fisheries, most States have established $68^{\circ}$ F as the maximum allowable temperature, whereas, for warm-water fisheries, a maximum allowable temperature is found to range from $83^{\circ}$ F to $96^{\circ}$ F. Most State standards also include a limit for the allowable temperature change above ambient conditions based on monthly means of the maximum daily temperatures at the site in question before the addition of waste heat. These were found to vary from no increase to $20^{\circ}$ F, with the majority in the

range of $4^o$ F to $10^o$ F. Most States adopted $0^o$ F to $5^o$ F as the maximum allowable temperature change for cold-water fisheries, and for warm-water fisheries the range was usually from $4^o$ F to $5^o$ F. Finally, a number of States chose to adopt a rate-of-change temperature criteria to protect aquatic organisms from a damaging temperature shock, with the value most often selected as $2^o$ F per hour, which should not be exceeded except in the case of natural phenomena.

The responsibility for reviewing and approving the temperature standards submitted by each State rested with the Federal government. In the ensuing negotiations with the States, a firm commitment to both prevent and control thermal pollution was received, but the criteria were not uniform among the States. In response to this problem the government has attempted to insure the continuity of criteria at State borders and that the standards contain the principles of NTAC by being reasonably compatible with its recommendations as well as compatible with existing information on water quality and aquatic life in the area. In most cases the States made changes in their proposed criteria after negotiations, but some States were not willing to adopt criteria consistent with the recommendations of the NTAC. In these cases, exceptions to general approval of the water quality standards for temperature criteria were made and the government then worked with the States to evaluate existing data and to develop criteria more in line with existing water quality and NTAC recommendations. The basic reason usually given for the rejection of State standards has been too lenient limits on allowable changes above ambient conditions.

Standards Adopted by New England States. The State of

Connecticut has adopted fresh water classifications of Class A, public water supply, Class B, recreation, Class C, fish and wildlife, and Class D, navigation and industrial use. Similarly, for salt water, the classifications adopted were Class SA, for shellfish, Class SB, restricted shellfish, Class SC, shellfish habitat, and Class SD, navigational uses. The temperature standards adopted were no increase in temperature other than natural for Class A waters, and for all other classes, the temperature rise is not to exceed $4^{\circ}$ F above ambient or $85^{\circ}$ F, nor shall the increase exceed recommended limits for the most sensitive water use.

The State of Maine distinguishes between freshwater which includes rivers, streams, and lakes and tidal waters. For freshwater, the standards have been set forth as an $84^{\circ}$ F maximum temperature for warm-water fish, and a $68^{\circ}$ F maximum temperature for salmon and trout waters. For streams and rivers, the temperature rise allowable from a heated effluent of artificial origin is $5^{\circ}$ F, and in the case of the epilimnion of lakes, a $3^{\circ}$ F temperature rise is allowed due to heated effluent. For tidal waters, no discharge of heated effluent is allowed that would raise the monthly mean of maximum daily temperatures outside of the mixing zone more than $4^{\circ}$ F, nor more than $1.5^{\circ}$ F during July, August, and September in locations where this is shown to be necessary. Finally, no heated effluent may be discharged in the vicinity of, or so as to affect, waters designated by the State as spawning areas.

Massachusetts classifies its waters as follows: Class A, excellent, Class B, recreation, fish and wildlife, Class C, fish

and wildlife, and Class D, industrial. For Class A waters, no temperature increase is allowed other than natural. For Class B and Class C, the temperature may not exceed the limit for the most sensitive use. Also, in no instance shall the temperature exceed $83^o$ F for warm-water fish and $68^o$ F for cold-water fish, or in any case raise the normal temperature more than $4^o$ F. Class D waters also have a limit on no increase to exceed the limits required for the most sensitive use, and in no case may the temperature exceed $90^o$ F. For all coastal and marine waters, no temperature increase is allowed which would exceed the limits of the most sensitive use.

The State of New Hampshire has adopted the temperature criteria set forth in Section 3 of the NTAC report and in the official standards of the New England Interstate Water Pollution Control Commission. The standards require that heated discharge shall not raise the surface temperature outside the designated mixing zone more than $3^o$ F.

In Rhode Island, the water classifications adopted were Class A, excellent, Class B, recreation, Class C, fish and wildlife and Class D, navigation and industrial. For tidal waters, the classifications adopted were Class SA, shellfish, Class SB, bathing, Class SC, shellfish habitat, and Class SD, navigation. The standards for Class A are no increase other than natural origin, for Class B and Class C, the maximum temperature for warm-water fish would be $83^o$ F and for cold-water fish the maximum temperature would be $68^o$ F. The maximum temperature rise for this classification would be $4^o$ F. For Class D waters, the maximum temperature would be $90^o$ F, and

no increase in temperature would be allowed to exceed the limits on the most sensitive use. For all classifications of tidal waters, no temperature increase over the recommended limits for the most sensitive use will be allowed.

The State of Vermont has a Class A water classification for public water supply and the standard in this case is no change in temperature. Classes B and C include various levels of recreation, fish and wildlife use. In these classes the temperature standards are broken down by "water type". For Type I and Type II which pertain to natural trout and trout respectively, the standard is a $1^\circ$ F maximum temperature rise. For Type III, which pertains to warm-water fish, the breakdown is according to maximum river temperature and varies from a maximum temperature rise of $1^\circ$ F for river temperature in excess of $66^\circ$ F, to a maximum temperature rise of $5^\circ$ F for a river temperature below $55^\circ$ F. Type IV includes trout lakes, and the standard in this case is a $1^\circ$ F maximum temperature rise, with a further restriction of no withdrawl from or discharge to the hypolimnion except for water quality enhancement. Type V includes other lakes, and includes the same provision for the hypolimnion with standards based on maximum lake temperature with a limit of $1^\circ$ F temperature rise for a maximum temperature above $60^\circ$ F and a $3^\circ$ F temperature rise for a maximum lake temperature below $50^\circ$ F.

Administration of Standards. The Federal Water Pollution Control Act of 1972 may have a significant effect on the current administration of water quality standards. However, a brief

review of the development of the present procedures and legal oack-ground is necessary since the role of the Federal Water Pollution Control Act of 1972 will not become clear until it is fully implemented and court decisions are made concerning the provisions of this bill.

The implementation of thermal standards by the States was the first step in a joint effort with the Federal government which now works with the States in the areas of monitoring and evaluating the compliance with these standards and in making appropriate revisions of temperature criteria where necessary. The monitoring of compliance requires recognition that the standards are meant to apply to extreme conditions and that the implementation of standards must be considered in relation to the cumulative effect of all the projected heat inputs. Thus, consideration must be given to the fact that the electric utility systems will continue to grow and may result in changing streamflow patterns which will further complicate the administration of standards.

The Federal Water Pollution Control Act of 1965 recognized the States as having primary responsibility in the prevention and control of pollution. This Act encouraged action both on the State and interstate level which would serve to abate the pollution of interstate or navigable waters. Any discharge of waste heat into interstate waters, or portions thereof, which would reduce the water quality below the approved standards would be subject to abatement in accordance with the Federal procedures outlined in the Act. These procedures include provisions for the Secretary of the Interior

(transferred now to the Administrator of the EPA) to convene abatement conferences, call public hearings, and to take other enforcement actions. If the polluter does not take a positive response to these actions, the Administrator may request the Attorney General to bring suit to secure abatement of the pollution difficulty. According to the Act, the court, "giving due consideration to the practicability and to the physical and economic feasibility of securing abatement of any pollution proved, shall have jurisdiction to enter such judgment, and orders enforcing such judgment as the public interest and the equities of the case may require."

According to Stein (1969), the authority to abate pollution which is endangering the health and welfare of the public may be invoked on the Federal initiative based on reports, surveys, or studies and upon State request. In the case of intrastate pollution of interstate or navigable waters, the request of the Governor is required to initiate enforcement action. On the Federal initiative, the enforcement authority may be invoked to abate both intrastate and interstate pollution which impair the interstate marketing of shellfish.

While no specific provisions relating to water quality standards for licensing or certifying the use of water for cooling water at steam electric plants existed prior to the passage of the Federal Water Pollution Control Act of 1972, some States considered and other States were making plans to consider thermal effects in the granting of certificates for the construction of power plants. The River and Harbors Act of 1899 (Refuse Act), was recently enforced

to ban the discharge of pollutants to navigable waters, with a permit program in which the Corps of Engineers and the Environment Protection Agency process and evaluate applications for permits to discharge pollutants into navigable water bodies. This procedure, however, was tied up due to a court case brought by the Sierra Club to require an environmental impact statement on each application. The case was appealed by the government and legislation was filed in the Congress such that no environmental impact statements will be required for the issuance of discharge permits. The following section on the Federal Water Pollution Control Act of 1972 contains the resolution of the question of jurisdiction and impact statement requirements.

All Federal agencies must now give consideration to the effects of and alternatives to thermal pollution as provided in the National Environmental Policy Act of 1969 (NEPA) which requires that an environmental impact statement be prepared and submitted on major actions planned by Federal agencies. This has become known as a "102 statement" and has been defined to require inclusion of an evaluation of all the environmental effects of a project, irreversible commitments of resources, and alternatives to the proposed action. This Act has thus established a procedure by which thermal pollution and its effects would have to be analyzed, described, and included in the decision-making process at any proposed thermal electric project. The roles of these legal measures are, therefore, still in the development stage and until court decisions and amending legislation serve to stabilize the interpretation of these laws, it

is difficult to clearly define their role with relation to the administrative aspects of thermal pollution management in the future.

Federal Water Pollution Control Act of 1972. The discusion of temperature criteria and standards would not be complete without an extensive discussion of the Federal Water Pollution Control Act of 1972. This comprehensive bill will have a significant effect on the thermal pollution problem since the Act deals with temperature standards, temperature criteria, effluent limitations, requirements for applying technology to move towards the goal of zero discharge, transferring of the permit program of the Rivers and Harbors Act, redefining of the requirements for impact statements under NEPA from the EPA, a redefinition of State control over water quality, estab- lishing discharge criteria for ocean sites, etc. The discussion of the bill is limited to only those aspects which could be directly related to the thermal pollution problem and, therefore, the requirements enumerated are not intended to be complete in all cases.

It should also be noted that some of the information in the preceding sections may become superceded as this Act is implemented. An attempt was made to bring these sections up to date as they would be revised as the new procedures and regulations are set forth by the Administrator of EPA.

The Act is cited as "Federal Water Pollution Control Act Amendments of 1972" and was passed on October 18, 1972 over the veto of President Nixon. The Act has as its objective the restoration and maintenance of the chemical, physical, and biological integrity of the Nation's waters. In order to achieve this objective the

following was set forth:

1.  national goal that discharge of all pollutants into
    navigable waters be eliminated by 1985;

2.  wherever attainable, interim national goal of water
    quality to provide for protection and propogation of fish,
    shellfish, and wildlife, and recreation in and on water by
    July 1, 1983;

3.  national policy that areawide waste treatment management
    planning processes be developed and implemented;

4.  national policy that major research and demonstration
    effort be made to develop technology necessary to eliminate
    discharge of pollutants into navigable waters, waters of the
    contiguous zone, and the oceans.

It was also declared that the policy of the Congress is to recognize,
reduce, and eliminate pollution, and to plan the development and use
of land and water resources.  It was further stated that Congres-
sional policy was to support and aid research relating to the
prevention, reduction, and elimination of pollution, and to provide
technical services and financial aid to State and interstate agencies
and municipalities in connection with the prevention of pollution.
Public participation in the development, revision, and enforcement
of any regulation, standard, effluent limitation, plan, or program
established by the Administrator or a State shall be provided for,
encouraged, and assisted.  Finally, it was set forth as national
policy that procedures utilized for administering the Act shall
encourage minimization of paperwork and interagency decision-

making procedures, and the best use of manpower and funds to prevent needless duplication and unnecessary delays.

The Act encourages the States to engage in cooperative activity to enact improved and uniform State laws, and to develop compacts between the States to prevent and control pollution.

The Administrator of the EPA has been granted the authority, under this Act, in cooperation with Federal and State agencies, and public and private organizations, to conduct comprehensive studies on the effects and methods of control of thermal discharges. In evaluating the alternative methods, consideration will be given to: data on the latest available technology; the economic feasibility including cost effectiveness; and the total impact on the environment, considering, in addition to water quality, air quality, land use, utilization and conservation of fresh water and other natural resources. These results shall be available to the public and the States, and considered by the Administrator in carrying out the section of the Act dealing with thermal discharge and by the States in proposing thermal water quality standards.

The Act also establishes the concept of effluent limitations. Except in compliance with the provisions of the Act, the discharge of any pollutant by any person is declared unlawful. Also, in order to carry out the objectives of the Act, the following requirements should be achieved:

1.  not later than July 1, 1977, effluent limitations for point sources which require application of best practicable control technology currently available; and compliance with

any more stringent limitation established pursuant to a State law or regulation, or required to implement any applicable water quality standard established pursuant to this Act.

2. not later than July 1, 1983, effluent limitations for point sources which require application of the best available technology economically achievable for such category that will result in further progress towards the national goal of eliminating the discharge of all pollutants; and these effluent limitations shall require eliminating of the discharge of all pollutants if the Administrator finds such elimination is technologically and economically achievable for a category or class of point sources.

The requirements of the best available technology requirement of July 1, 1983 may be modified for any point source for which a permit application is filed after July 1, 1977, if the owner or operator can satisfy the Administrator that the modified requirements will: represent the maximum use of technology within the economic capability of owner and will result in reasonable further progress toward the elimination of the discharge of pollutants. Effluent limitations as to the best available technology shall be reviewed at least every five years, and revised according to the procedure set forth in the Act. These effluent limitations established in this section will be applied to all point sources of discharge of pollutants.

The Administrator may establish more restrictive effluent

limitations including alternative effluent control strategies for a point source which can be expected to contribute to the attainment or maintenance of a water quality when the discharge of pollutants with the application of the best available technology would interfere with this goal in a specific portion of navigable waters. This water quality would assure protection of public water supplies, agricultural and industrial uses, protection and propagation of a balanced population of shellfish, fish, and wildlife, and allow recreational activities on and in the water However, notice of intent of this further effluent limitation must be given and public hearings held concerning the economic and social costs and benefits of any such limitation. A determination must also be made if the effluent limitations can be implemented with available technology or other alternative control strategies. If the person affected can demonstrate no reasonable relationship between the economic and social costs and benefits, the limitation will not become effective.

Water quality standards applicable to interstate waters adopted by any State and submitted to, and approved by, or awaiting approval by the Administrator, immediately prior to the date of enactment of this Act, remain in effect unless he determines that the standard is not consistent with the applicable requirements of this Act. If this determination is made, he will notify the State and specify the changes needed to meet the requirements. If these changes are not made by the State, he will then promulgate such changes. Similarly, in the case of State standards for intrastate waters adopted prior to the Act, the State will also submit these

standards to the Administrator who will follow a review procedure
similar to the one enumerated above for interstate waters. States
which have not adopted standards for intrastate waters prior to
enactment of the bill will adopt and submit such standards to the
Administrator. If the standards are consistent, they will be
approved and if not, he will promulgate appropriate standards.

The Governor or the State water pollution control agency will
at least every three years hold public hearings for the purpose of
reviewing applicable water quality standards and, where appropriate,
modifying and adopting such standards. Revised or new standards will
consist of the designated use of the navigable water involved, and
the water quality criteria for such waters based upon such uses.
These standards shall protect public health or welfare, enhance the
quality of the water, and serve the purposes of this Act. Again if
the Administrator determines that such standards meet the require-
ments of the Act, the standards become the State water quality
standard. If the standard is inconsistent with applicable require-
ments, he must notify the State and specify the needed changes. If
the changes are not adopted by the State he will promptly prepare,
publish, and promulgate regulations setting forth revised or new
water quality standards. A similar procedure will be followed for
revised or new water quality standards for navigable waters.

Each State will identify those waters or parts thereof for
which controls on thermal discharge effluent limitation are not
stringent enough for the protection and propagation of a balanced
population of shellfish, fish and wildlife. The States will then

estimate for these waters the total maximum daily thermal load

required to attain this goal. These estimates will consider normal

water temperatures, flow rates, seasonal variations, existing sources

of heat input, and the dissipative capacity of the identified water

or parts thereof. These estimates will include a calculation of the

maximum heat input that can be made into each such part, and will

include a margin of safety which takes into account any lack of

knowledge concerning the development of thermal water quality

criteria. Each State will submit to the Administrator for his

approval the waters so identified and the loads established. If he

approves identification and load, they will be incorporated into

current plan. If disapproved, he will identify and establish such

loads as he determines necessary to implement the water quality

standards and the State will then incorporate them into its plan.

The State will also identify those waters within its boundaries which

are not identified as above and estimate for such waters the total

maximum daily load and seasonal margins of safety for thermal dis-

charges at the level which would assure protection and propagation

of fish, wildlife, and shellfish.

Each State will have a continuing planning process for navigable

waters which will include: the effluent limitations and schedules of

compliance; the total maximum daily load of pollutants; the proce-

dures for revision; authority for intergovernmental cooperation; and

an adequate implementation plan. The water quality standards

related to heat should be consistent with requirements given in the

section on thermal discharge.

The Administrator will develop and publish, criteria for water quality reflecting the latest scientific knowledge on: the type and extent of effects on health and welfare which may be expected due to the presence of pollutants in any water body; the concentration and dispersion due to biological, physical, and chemical processes; and the effects of pollutants on the biological diversity, productivity, and stability, including studies of eutrophication or sedimentation. He will also develop and publish information on: factors necessary to restore and maintain the chemical, physical, and biological integrity of water bodies; factors necessary for protection and propagation of fish and wildlife and to allow recreation activities in and on the water; the measurement and classification of water quality; and on the identification of pollutants suitable for maximum daily load measurements. The Administrator will publish regulations providing guidelines for effluent limitations that will be revised at least annually if appropriate. The regulations shall: identify, in terms of the amounts of constituents and the physical, chemical, and biological characteristics of pollutants, the degree of effluent reduction possible through the best practicable control technology; specify factors, such as the total cost of application in relation to effluent reduction benefits, age of equipment, the engineering aspects of the application of control techniques, and process changes, relating to the assessment of the best practicable control technology. The same requirements will also be met concerning the application of the best control measures and practices achievable, and the control measures and practices required to eliminate the dis-

charge of pollutants taking the cost of such measures into account.
The Administrator will also issue information on processes, proce-
dures, and operating methods, including technical data and costs,
which result in the elimination or reduction of the discharge of
pollutants to implement standards in connection with the national
standards of performances.

Testing procedures for the analysis of pollutants including
factors required for permits will be promulgated.  Guidelines for
uniform application forms; the minimum requirements for the
acquisition of information from owners and operators of points of
discharge in State permit programs; and the establishment of
minimum procedural and other elements of State permit programs
including:  monitoring requirements, reporting requirements,
enforcement provisions, funding, personnel qualifications, and
manpower requirements will also be issued.  Methods, procedures, and
processes appropriate to restore and enhance the quality of public
owned fresh water lakes will be developed.

A national standard of performance is a standard for the control
of the discharge of pollutants which reflects the greatest degree of
effluent reduction which the Administrator determines to be achiev-
able.  This would require application of the best available demon-
strated control technology, operating methods, process, or other
alternatives, including a standard permitting no discharge of
pollutants where possible.  The Administrator is obligated, by the
provisions of the Act, to publish a list of categories of sources
from which there is or may be a discharge of pollutants, including

steam-electric powerplants. Then he will propose and publish regulations establishing Federal standards of performance for new sources within each category, and after allowing comment on the proposed regulations, he will promulgate such standards as he deems appropriate. As technology and alternatives change, he will revise the standards according to the required procedure. The cost of achieving this effluent reduction, and other non-water quality environmental impact and energy requirements will be considered in establishing or updating these Federal standards. He may distinguish among classes, types, and sizes within categories and consider the type of process used in establishing the standards. The States may also develop and submit to the Administrator procedures under State law for applying and enforcing standards of performance for new sources located in the State. As long as the State procedure and law are at least to the same extent as required by this section, the State is authorized to apply and enforce these standards of performance. Any point source under construction after the date of enactment of the Act, which is constructed to meet applicable standards of performance, cannot be subjected to more stringent standards within ten years beginning on the date of construction completion or during the period of depreciation or amortization of such facility, whichever period ends first. Finally, after the effective date of standards of performance promulgation, it shall be unlawful for an owner or operator of any new source to operate such source in violation of any standard of performance applicable to the source.

The enforcement procedure under this Act begins with a determi-

nation by the Administrator that a person is in violation of the Act, and he then proceeds under his authority to notify the person in alleged violation and the State involved of such finding. If the State does not promptly begin appropriate enforcement action, an order requiring the person to comply with a condition or effluent limitation will be issued by the Administrator or he will bring a civil action. If the violations are so widespread as to indicate a failure of the State to effectively enforce the permit conditions or effluent limitations, he will notify the State, and if failure continues public notice will be given. During the period beginning with public notice and ending when the State satisfies him that it will enforce the conditions and limitations, orders of compliance or bringing of civil action will be initiated by the Administrator to enforce any permit condition or limitation with respect to any person.

A copy of any order issued will be sent to the State where the violation occurs and other affected States, and this order must indicate the nature of the violation and specify a reasonable time for compliance taking into account the seriousness of the violation. Civil action may be initiated to seek appropriate relief, including a permanent or temporary injunction, for any violation for which he is authorized to issue a compliance order. These actions may be brought in the U. S. district court for the district in which the defendant is located, resides, or is doing business, and this court will have jurisdiction to restrain the violation and require compliance. Notice of this action must be immediately given to the appropriate State. Any person (responsible corporate officer)

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convicted of willfully or negligently violating this law may be punished by a fine from $2,500 to $25,000 per day of violation or by imprisonment for less than one year, or both. For a repeat offense conviction, the fine limit increases to $50,000 per day of violation or imprisonment for less than two years or both. False statements, representations, or certification of applications, records, reports, plans, or other documents, or tampering with monitoring devices may be punished with a fine of not more than $10,000 or imprisonment for six months. Anyone who violates an order issued by the Administrator also faces a fine $10,000 per day for such violation.

Provision is made in the bill for relaxing effluent limitations required under the best practicable or the best available technology, or standards of performance when the owner or operator of a source is able to convice the Administrator, after a public hearing, that the effluent limitation proposed for the thermal discharge will require a limitation stricter than necessary to assure the protection and progagation of a balanced, indigenous population of shell-fish, fish, and wildlife in and on the water body. In this case the Administrator may establish an effluent limitation, which takes interaction with other components into account, that will assure the protection and propagation of the ecosystem. All thermal standards will require that the location, design, construction, and capacity of the cooling water intake structures reflect the best technology available to minimize adverse environmental impact. A point source with a thermal discharge modified after enactment of this Act which then meets the required effluent limitations and

assures protection and propagation of the shellfish, fish, and wild-
life will not be subject to any more stringent limitations with
respect to thermal discharge during a ten year period beginning on
the date of such modification or during the period of depreciation
or amortization of such facility, whichever comes first.

The Administrator is further authorized after public hearings,
to permit the discharge of pollutants, including thermal discharge,
under controlled conditions associated with approved aquaculture
projects. He is also required to establish any procedures and
guidelines he deems necessary to carry out this type of program.

In connection with the permit program, the Act requires any
applicant for a Federal license or permit allowing discharge into
the navigable waters (defined as "waters of the United States,
including the territorial seas") to provide the licensing agency
with a certification from the State where the discharge will orginate
that it will comply with the applicable provisions of this bill.
The State or interstate agency will establish procedures for
publication of all applications for certification and for public
hearings concerning specific applications. If the State or agency
fails to act on a request for certification within one year after
receipt of such request, the certification requirements become
waived with respect to the Federal application. Otherwise, no
license will be granted until certification has been obtained or
waived, and no license or permit will be granted if certification is
denied by the State or interstate agency. When the discharge may
affect the quality of water in another State, the Administrator will

notify the other State, the licensing agency, and the applicant. If the other State determines that the discharge will affect the waters so as to violate the water quality requirements in such State, and notifies the Administrator and the licensing agency in writing of its objection, and requests a public hearing, the licensing agency will hold a hearing. Depending on the outcome of this hearing, the agency may condition the license in such a manner as may be necessary to insure compliance with applicable water quality requirements. The agency will not issue a license if the imposition of conditions cannot insure compliance. The certification obtained with respect to construction of a facility will fulfill the requirements with respect to certification for licenses to operate unless the State or interstate agency notifies the licensing agency that there is no longer a reasonable assurance that there will be compliance with the applicable provisions of the Act. This provision will be particularly applicable in the case of construction of nuclear power plants. Also, prior to the initial operation of a Federally licensed facility or activity, which may result in discharge to navigable waters, the license will provide opportunity for the certifying State or agency to review the manner in which the facility will be operated for the purpose of assuring that the applicable effluent limitations will not be violated. Upon notification by the certifying State that operation of facility or activity will violate applicable effluent limitations, or will violate the applicable provisions of the Act, the Federal agency may suspend such license or permit, after a public hearing, until notification is received

from the certifying agency that the facility or activity will no longer violate the applicable provisions of the Act.

The bill does not limit the authority of any department or agency pursuant to any other provision of law to require compliance with any applicable water quality requirements. The certification obtained will set forth effluent limitations, and monitoring requirements necessary to assure that the applicant for a Federal license will comply with effluent limitations, other limitations, standards of performance, prohibition, or effluent standards, and with any other appropriate requirement of State law set forth in such certification.

The Administrator now has permission to issue permits for discharge of any pollutant if the discharge will comply with other requirements of this Act. This permit program of the Administrator and permits issued thereunder will be subject to the same terms, conditions, and requirements as apply to the State permit programs. The permits for discharges to navigable waters issued under Section 13 of the Act of March 3, 1899 (Rivers and Harbors Act) will be deemed permits issued under this title, and permits issued under this title will be permits issued under Section 13 of the Act of 1899. These permits will remain in force for their term unless revoked, modified, or suspended. Thus, a permit for discharge into a navigable water will no longer be issued under Section 13 of the Act of March 3, 1899, and applications pending under the 1899 Act at this time will be deemed an application for a permit under this Act.

Any time after the promulgation of procedural guidelines, the

Governor of a State desiring to administer a permit program may sub-
mit to the Administrator a complete description of the program it
proposes to establish and administer.  A statement from the attorney
general must be included to assure that the laws of the State provide
adequate authority to carry out the program.  The Administrator will
approve such programs unless he shows adequate authority does not
exist to issue permits which: apply and insure compliance with the
requirements of Act; are for fixed terms of less than five years;
can be terminated or modified due to a violation of a condition of
the permit, obtaining a permit by misrepresentation, or due to a
change in any condition requiring temporary or permanent reduction or
elimination of the permitted discharge.  The Act also requires State
programs to provide for the means to:  inspect, monitor, enter, and
require reports; insure that the public, and the other States, the
waters of which may be affected, receive notice of the permit
application; provide an opportunity for a public hearing before
acting on an application; insure the Administrator receives a copy
of all permit applications; insure that the other States whose waters
may be affected by issue of a permit may submit written recommenda-
tions to the permitting State, and if any part of the written explan-
ations are not accepted, that State will notify affected State and
Administrator in writing of its failute to accept the recommendations
with its reasons, and to insure civil and crimial penalties and the
means of enforcement.

After the State has submitted a program, the Administrator will
suspend the issuance of permits by the Federal government to those

navigable waters subject to such program unless he determines that the State permit program does not meet the requirements of the Act. If he so determines, he will notify the State of the modifications or revisions necessary to conform to the requirements of the bill or promulgated guidelines. If it is determined, after public hearing, that the State is not administering the program in accordance with the requirements of the Act the Administrator will notify them, and if appropriate corrective action is not taken he will withdraw approval. However, approval can be withdrawn only if the Administrator first notifies the State and then makes the reasons for withdrawl public and in writing.

Each State will transmit to the Administrator a copy of each permit application and provide notice to him of every action related to the consideration of such permit application. No permit will be issued if he objects in writing to the issuance of such permit as outside guidelines and requirements of this Act. The Administrator may also waive this immediately preceding sentence, or the entire paragraph at the time he approves a State permit program, for any category of point sources within the State submitting such program.

In this case, he will promulgate regulations establishing the categories of point sources which he determines are not subject to the requirements of administrative notification in any State with an approved permit program. He may distinguish among classes, types, and sizes within any category of point sources. A copy of each permit application and permit issued under this section will also be available to the public on request for the purpose of reproduction.

Compliance with a permit issued according to the guidelines of
this section will be considered as compliance with other sections of
the Act. Until December 31, 1974, in any case where a permit has been
applied for, but administrative disposition not completed, the dis-
charge will not be in violation of other sections of this Act, or
section 13 of the Act of March 3, 1899, unless the delay is due to
withholding of information by the applicant.

No permit for a discharge to a territorial sea, the waters of
the contiguous zone, or the oceans will be issued except in compli-
ance with the guidelines described below, after they are promulgated.
Prior to the promulgation of the guidelines the permit may be issued
if the Administrator deems it to be in the public interest. He will
promulgate guidelines for determining the degradation of waters of
the territorial seas, the contiguous zone, and the oceans which
will include the effect of the disposal of pollutants on: human
health or welfare; marine life and changes in the marine ecosystem
diversity, productivity, and stability; and esthetic, recreation, and
economic values. Also, consideration will be given to persistence
and permanence of the effects of disposal, the effect of disposal at
varying rates, of particular volumes and concentration of pollutants;
other locations and available methods of disposal including land-
based alternatives; and the effect of alternate uses of the oceans.
In the event that insufficient information exists on a proposed  dis-
charge to make a reasonable judgment on any of the above guidelines,
no permit will be issued.

In another area of critical concern to power plant siting and

thermal pollution, the Act states that any citizen can commence a
civil action in his own behalf: against any person, including the
United States and any other governmental agency to the extent per-
mitted by the eleventh amendment of the Constitution, who is alleged
in violation of an effluent standard or a limitation or an order
issued by the Administrator; or against the Administrator where there
is a failure to perform any non-discretionary act or duty under this
Act. The district courts have jurisdiction without regard to the
amount in controversy or citizenship of parties to enforce the
effluent standards or limitations. However, no action may be
commenced before the plaintiff has given notice of the alleged vio-
lation to the Administrator, the State where the violation occurs,
and any alleged violator; or if the Administrator or State has
commenced and is diligently prosecuting a civil or criminal action to
require compliance. If the action is against the Administrator,
written notice must be given before action can commence. Action can
be brought immediately after notification, however, respecting a
violation of national standards for new sources. Any action con-
cerning a violation by a discharge source of an effluent standard
may be brought only in the judicial district in which source is
located, and the Administrator may also intervene in such an action
as a matter of right. The court may allocate the costs of litigation
to any party, and if a temporary restraining order or preliminary
injunction is sought, may require the filing of a bond or equivalant
security. The Act does not restrict any right which a person may
have under a statue or common law to seek enforcement of any

effluent standard or limitation or to seek any other relief. The term "citizen" is defined as a person or persons having an interest which is or may be adversely affected. The Governor of a State may also commence a civil action against the Administrator where there is alleged a failure by him to enforce an effluent standard under this Act when the violation is occurring in another State and is causing an adverse effect on the public health or welfare in his State.

No provision of the Act precludes or denies the right of a State or political subdivision thereof or interstate agency to adopt or enforce any standard or limitation respecting the discharge of pollutants, or any requirement concerning control or abatement of pollution. The exception to this is that if an effluent limitation, effluent standard, pretreatment standard, etc. is in effect under this Act, the State or political subdivision may not adopt or enforce any effluent limitation, effluent standard, etc. which is less stringent. Also, nothing in the Act impairs or affects any right or jurisdiction of the States with respect to the waters of such States.

Concerning administrative and judicial procedure, a review is possible of the Administrator's action in: promulgating standards of performance; promulgating an effluent standard, prohibition, or treatment standard; making any determination as to a State permit program; approving or promulgating any effluent limitation; or issuing or denying any permit by an interested person in the Circuit Court of Appeals of the United States for the Federal judicial district in which such person resides or transacts such business,

upon application by such person.  Any application must be made within ninety days from the date of the promulgation, issuance or denial, or after such date only if this application is based solely on grounds which arose after such ninetieth day.  Actions, not spelled out above, by the Administrator are not subject to judicial review.

Finally, the Act will not:  limit the authority of any officer or agency of the United States under any law or regulation not inconsistent with this Act; or affect or impair the authority of the Secretary of the Army under the Act of March 3, 1899 (30 Stat. 1112), except that a permit issued under this Act shall be conclusive as to the effect on water quality of any discharge subject to section 13 of the Act of March 3, 1899.  The discharges of pollutants into navigable waters subject to the Rivers and Harbors Act of 1910 and the Supervisory Harbors Act of 1888 will now be regulated pursuant to this Act, and not subject to the Act of 1910 and the Act of 1888 except as to affect navigation and anchorage.  Except for Federal financial assistance for constructing publicly owned treatment works, and issuance of permits, no action of the Administrator or taken pursuant to the Act will be deemed a major Federal action signifi-cantly affecting the quality of human environment within the meaning of the NEPA of 1969.  This provision sets forth the limits of NEPA with regards to EPA actions.  Nothing in NEPA will be deemed to authorize a Federal agency with the authority to license or permit the conduct of any activity resulting in the discharge of a pollutant into navigable waters to review any effluent limitation or other requirement established pursuant to this Act; or authorize any

agency to impose as a condition precedent to the issuance of a

license or permit any effluent limitation other than the effluent

limitation established pursuant to this Act.

Thus, in summary the provisions of this Act are found to be far-

reaching and comprehensive in the area of water quality control.

This Act will have a dramatic effect on the public policy towards

thermal pollution as its regulations become implemented in the near

future. The definitions of standards of performance, effluent

limitations, and water quality standards and the requirements for

discharge certifications and permits imposed by the Act will evolve

with the executive and judicial decisions of the near future, and

their impact on the current approach to thermal pollution abatement

will be better understood at that time. In the meantime, an accurate

prediction of the effects of bill's enactment is not possible.


II. B. 4. Mixing Zones

Areas which are unavoidably and harmfully polluted to allow for

mixing of discharge waters with receiving waters are known as mixing

zones. These zones have defined limits, established by the proper

administrative authority, and the size of the zones will generally

vary with the physical characteristics of the receiving water body.

Waters outside the zones must meet the standards for the water body.

The NTAC report (1968) specifies that mixing zones should be as

small as possible and provide only that mixing required to preserve

the welfare of aquatic life. This is due to the fact that mixing

zones form barriers which can block a spawning migration of

certain fish and also damage aquatic invertebrates and plankton organisms.

In general, the established temperature standards all permit a "reasonable" but undefined area for mixing beyond the point of discharge to be exempt from the established standards. This condition allows the State regulatory authorities to use their own discretion and it thus prevents the estimation in advance of the amount of heat that could be discharged into a given water body. This provision, however, also requires that an administrative ruling be made at each individual location. It should also be noted that in some cases thermal standards have been established at the point of discharge and in this case the definition of a mixing zone is not required.

The width of a zone of passage for aquatic organisms, and the volume of flow in it are related to the characteristics and size of the stream or estuary. The area, depth, and volume of flow in the zone must be adequate to provide a satisfactory passageway for fish and other aquatic biota. The cross-sectional area and volume of flow in the passageway will therefore largely determine the survival percentage of drift organisms.

No specific mention of mixing zones is made in the Federal Water Pollution Control Act of 1972. However, due to the use of the concept of effluent limitations, standards of performance for new sources, and the permit program, it appears that the concept of a mixing zone may no longer continue to apply for new power plants, but instead an effluent limitation at the point of discharge may apply. On the other hand, the opportunity is provided to demonstrate that

lesser standards, perhaps including mixing zone, will create no

adverse effects on aquatic organisms. Therefore, further inter-

pretation of the Act will be required to determine the answer to

this question.

EPA Water Quality Criteria. The report of the NTAC (1968)

considers the problem of mixing zones and zones of passage. The

specific recommendations of the committee are included in Appendix

II of this report.

Barriers to migration and free movement of aquatic species block

spawning migrations of anadromous and catadromus species. Also, the

natural tidal movement in estuaries, and the downstream movement of

plankton and aquatic invertebrates in flowing fresh waters are

important considerations in the repopulation of areas. A thermal

barrier can destroy this possible source of food and create unfavor-

able conditions above and below it.

With this in mind, it becomes essential to provide adequate

passageway for the movement of biota. Within these passageways,

water quality favorable to the biota should be maintained at all

times. It is understood, however, that certain areas of mixing will

be unavoidable, and since these create harmfully polluted areas, it

is essential that they be limited in length and width and provide

only for mixing, according to the Committee. In addition to

providing favorable conditions, the passage zone must be in a

continuous stretch bordered by the same bank for a considerable

distance to allow for safe and adequate passage up and down stream.

The Committee recommended that the depth, area, and volume of

flow must be adequate to provide a usable passageway for fish and other aquatic organisms. The recommendation is for a passageway containing 75% of the cross-sectional area and/or volume of flow of the stream or estuary. Also, it is apparent that where there are several mixing zones close together, they should all be on the same side of the water body so the passageway is continuous. The concentrations of the waste materials in these passageways should meet the water quality requirements for a water body.

The shape and size of the mixing areas will therefore vary with the location, use, character, and size of the receiving water. The areas should be as small as possible and provide for mixing only to provide for the welfare of the aquatic life resource. Devices which accomplish mixing as quickly as possible should be used to insure that the waste is mixed with the allocated dilution water in the smallest possible area. The water quality must meet the water quality requirements for the area at the border of the mixing zone. If these requirements are not met upon complete mixing with the available dilution water, pretreatment must be used so the requirements will be met. Finally, mixing areas must not be used for or considered as a substitute for waste treatment or as an extension of, or substitute for, a water treatment facility in order to protect aquatic life resources.

Definition Adopted in the 50 States. According to the publication by the EPA, "Mixing Zones", some States have made no reference to mixing zones in their adoption of thermal water quality standards. Other States indicate that in the measurement of temperature to

determine compliance with thermal standards, allowance should be made for a mixing zone with provisions made for adequate dispersion.

Frequent mention is made in the adopted definitions of mixing zones that cognizance must be given both in time and distance to allow for the mixing of the effluent and the water body. Another often mentioned requirement is that the distance and the areas which are allowed for complete mixing must not affect the adopted water use classification. This is the primary concern in many cases. Thus, in these States the discharge must be in such a condition as to not adversely affect the actual use of the water body for beneficial uses.

The sampling procedure used by the States to determine compliance with standards is also frequently mentioned as a consideration for mixing zones. According to most definitions which mention sampling, the required sampling should be done at a point where the standards can be evaluated, except for areas immediately adjacent to a discharge, in which case cognizance should be given both in time and distance to the opportunity for the admixture of the waste effluents with the receiving water, as was previously mentioned. One State specifies that the sampling should be done at the mid-point of the stream flow. According to another, the sampling should be done in such a manner and at such times as to be representative of the receiving waters after a reasonable opportunity for dilution. This question concerning the ability to measure and determine compliance with the standards is also an important consideration. The sampling frequency is also required to provide a sound basis for

computations in some instances.

The reasonableness of the mixing zones may be determined on the basis of the physical characteristics of the receiving waters and the methods in which the discharge is physically made. The boundaries of the mixing zone, when set, are sometimes made to consider the existing physical conditions of the water body, the magnitude and character of the effluent, the size and character of receiving water, and the adequancy of an outfall or diffuser to achieve maximum assimilation and dispersion. Some States are even more specific requiring consideration of the nature and rate of discharge; the nature and rate of existing discharges to the waterway and their effects; the size of the waterway and the rate of flow therein; the seasonal, climatic, tidal, and natural variations in the size, flow, nature and rate of the discharge and the effect of these variables on the ability of the discharge to meet standards; and finally, the uses of the waterway in the vicinity of the discharge.

Also, in many States, restrictions are placed against a thermal barrier to migration and free movement of aquatic biota. A number of States have set forth a minimum of 50% of the stream or estuary cross-section and/or volumetric passageway as a zone of passage, however, this may include the establishment of artificial fishways where necessary. Another State has limited the reduction of a passageway to not less than 75% of the original cross sectional area. Finally, one State requires that not more than 25% of the cross-sectional area and/or volume of the flow of the stream may be affected, similar to the previously mentioned requirement, but in

this case the additional constraint of not including more than one-third of the surface area measured from shore to shore is included.

The authority for designating and controlling mixing zones varies among the States. The agencies which have been delegated this authority include the: State Department of Health, State Department of Environmental Protection, Department of Air and Water Resources, State Water Resources Commission, State Stream Control Board, and the Committee on Water Pollution.

Some States have set forth the approach of determining the mixing zone for each discharge to minimize the deterimental effects, while other States have chosen to adopt standards applicable to all water bodies in the State.

Finally, a number of facts may be pointed out which have occurred usually only in the case of one State. A short transition zone has been allowed in one instance between the adjacent zones of varying water quality. The effluents released to streams or impounded waters must be fully and homogeneously dispersed and mixed with the main flow or water body by appropriate means at the discharge point, and the use of a limited mixing zone is allowed in this case only if necessity can be shown and no objectionable or damaging pollution condition will result. The limiting of the rate of temperature change to prevent mortality of biota is also mentioned in one instance. The area should be used for mixing only and not as a substitute for treatment, resulting in as small an area and length as possible. In this case the pollutant must have already been treated in an approved manner. One State requires that the facilities

adopted at a point of discharge will allow standards to be applied within the zone of mixing in time. Similarly, another State has adopted a mixing zone definition which will decrease with time and improved technology. The criteria of the NTAC (1968) concerning mixing zones and zones of passage has been adopted in entirety by one State. Another State defines its general policy as the use of structures to minimize the extent of the mixing zone. The use of a maximum allowable temperature at a distance of a certain number of feet from the point of discharge has been used in two cases. The establishment of a mixing zone may also provide for variations due to seasonal, climatic, tidal, and natural variations in the size, nature, and flow of the discharge to the water body.

Thus, in summary, the definitions of mixing zones adopted by the States are seen to vary from no mention of mixing areas to very strict requirements. The mixing zone is provided to allow for dilution of the effluent but in such a way as to not adversely affect water use classifications. Sampling to determine compliance with standards should therefore be done in such a manner and at such times as to be representative of the receiving waters after a reasonable opportunity for mixing. Also, in establishing mixing zones consideration should be given to the physical characteristics of the effluent and receiving waters and the methods in which the discharge is physically made. The concept of a zone of passage for aquatic biota in which restrictions are placed against a thermal barrier to the migration and free movement is also an important consideration in the determination of a mixing zone. Finally, the States have either

adopted varying approaches to the consideration of each point of discharge, or a blanket regulation for all water bodies within a State.

Definitions Adopted by New England States. The State of Connecticut has adopted the following definition for mixing zones. The definition indicates that in the case of waste treatment plant effluent or cooling waters discharged to receiving water bodies, cognizance shall be given both in time and distance to allow the discharge to mix with the receiving body. However, the distances required for complete mixing shall not affect the water usage class which has been adopted. Also, the distances shall be defined and controlled by the Water Resources Commission.

The definition for mixing zones applied by the State of Maine are as follows. After any classification by the legislature of surface or tidal waters, it shall be unlawful to dispose of any waste in such a way as to lower the quality of said waters below the minimum requirements of the classification after due consideration for natural variations and after reasonable opportunity for dilution, diffusion, mixture or heat transfer to the atmosphere within mixing zones established by the Environmental Improvement Commission. The Commission may establish a mixing zone with respect to any discharge at the time of application for license for such discharge, and when it is established, it becomes a condition of and forms a part of the license. Mixing zones may also be established by order of the Commission, after thirty days notice and a public hearing, with respect to a discharge for which a license has been

previously issued or for which no license is required. Also, prior to any order or commencement of any enforcement action to abate a classification violation, a mixing zone with respect to the discharge must be established. In determing the extent of the mixing zone, consideration must be given to: the nature and rate of discharge; the nature and rate of existing discharges to the waterway, and their effects on its ability to achieve the classification standards; the size of waterway and the flow rate; and seasonal, tidal, climatic and natural variations in the size, flow, nature and rate of discharge and the effect of this on ability of the waterway to meet its classification standards; the uses of waterways in the vicinity of the discharge; and other evidence which will enable the Commission to establish a reasonable mixing zone. The order establishing the mixing zone may provide that the extent shall vary in order to take account of seasonal, climatic, tidal and natural variations in the size and flow of, and the nature and rate of discharges to, the waterway. Finally, where no mixing zones have been established, it shall be unlawful to discharge any waste into any classified surface waters, or tial flats in such a manner as will lower the quality of any significant segment of the waters, tidal flats, affected by such discharge, below the minimum requirements of such classification after reasonable allowance is made for dilution, diffusion, mixture or heat transfer to the atmosphere.

The mixing zone definition adopted by Massachusetts requires that cognizance be given both in time and distance to allow for mixing of the effluent and stream when an effluent is permitted to be

discharged to receiving waters. Also the distances required shall
not affect the water use classification adopted.

In New Hampshire, the mixing zone requirements established are
the entire criteria pertaining to zones of passage and mixing zones
contained in Section 3 of the NTAC report (1968).

Rhode Island has adopted a definition similar to the one of
Massachusetts. In the discharge of waste to receiving waters, cog-
nizance shall be given both in time and distance to allow for mixing
of effluent and the stream. Also, the distances required for
complete mixing shall not affect the water usage Class adopted but
shall be defined and controlled by the regulatory authority.

The State of Vermont has granted authority to the State Depart-
ment of Water Resources to designate certain lengths or areas of
water bodies as mixing zones subject to the following conditions.
The mixing zones shall be only for the dispersal and dilution of
waters which have been treated in a manner approved by the department.
Also, the zones may be of no greater length or area than is required
for this purpose, and may be allowed only if wastes generally con-
form with technical and other requirements for the receiving waters.
The mixing zone shall not act as a barrier to the passage and
migration of fish or produce adverse effects on a fishery or other
forms of aquatic life. This has been interpreted by the State to
mean that they will not authorize a mixing zone which will reduce
the passageway to less than 75% of the cross sectional area of the
flow volume of a stream.

## II. B. 5. Ecological Aspects of Thermal Pollution

Physical and biological changes will result from all discharges of heated water to another water body. The changes which result can be beneficial, detrimental, or insignificant depending on the ecology of the water body and the desired uses of it.

Among the physical effects of adding waste heat to a water body is that the resulting temperature increase causes the capacity of the water to hold oxygen to decrease. Thus, under fully saturated conditions, the amount of available dissolved oxygen will be less at the elevated temperatures than at the lower temperatures. However, the heating due to thermal discharge will only drive off oxygen when the concentration of dissolved oxygen is in excess of the resultant saturation level. The reaeration rate of water in contact with the air also increases as the temperature rises.

Care must also be taken since the addition of heat to a water body can induce stratification due to the decreased density of the water at increased temperatures. Only a few degrees difference in temperature is sufficient to cause the water to flow in separate and distinct layers. The cooling water withdrawn from the hypolimnion region of a lake may be discharged after use at a temperature lower than that of the surface, and this could result in an interflow developing below the surface layers.

Since the water provides the environment of life for many species of organisms, any changes in temperature, chemical content, and rate of flow may affect the types and numbers of such organisms. Unfortunately, the state of the art is not too well advanced with

most studies confined to the laboratory, and few studies have dealt with natural ecosystems. The transfer of this lab data accurately to other sites is not feasible in most cases. However, the temperature changes frequently play an important and regulatory role in the physiology of fish and other cold-blooded aquatic animals. Among the affected processes are reproductive cycles, digestion rates, and respiration rates.

According to FPC (1969), it has also been determined that temperatures higher than those normally experienced, which are in the sub-lethal range, can be detrimental to organisms in a number of ways, especially during the summer months. Organisms become more susceptible to disease and poison; survival of individuals may be impaired; food supply may diminish; inability to reproduce may result; there may also be difficulty in competing with other organisms; and organisms may have difficulty in catching food. Also, the elimination of one species in the food chain may change the ecological balance and cause significant changes in the species of animals and plant present. The aquatic species all have an optimal temperature range also, and if the environmental temperature varies above or below this range, the species chances for survival decrease drastically. Among the other ecological effects observed in conjunction with the thermal pollution problem are: oxygen consumption in aquatic vertebrates increases with rising water temperature; changes in temperature cause some dissolved gases to change their selective toxicity towards fish; supersaturation of nitrogen may occur as a result of increased water temperature; and overfishing may take place

in areas where thermal discharge has improved the availability of fish.

According to Jensen (1971), this response of a biological organism to a temperature change depends on many factors, both physical and biological. The physical factors include the rate at which the temperature change is applied, the amplitude of the temperature change, the duration of the exposure, whether the organism is expecting such a change, and the background temperature to which the organism was exposed. The biological factors include the species, stage of development, state of stress, and the relative fitness of the individual within the species. Within a large number of specimens, the response would also be influenced by synergistic interactions between temperature and dissolved oxygen, salinity, turbulence, turbidity, toxic chemicals, etc. It is for this reason, that the response of an aquatic organism to a change in temperature is difficult to estimate.

Within an ecosystem, the biota have developed as a result of a long evolutionary process during which balances were established. Man must, therefore, use great care in altering the natural environment due to the possibility of far reaching effects of his actions. Otherwise, the ecology in the vicinity of a heated discharge may be seriously altered by the discharge of waste heat. To prevent this occurrence, temperature criteria were developed with the basic objective of protecting the native aquatic life by limiting the artificial discharges to the environment in such a way as to have optimal conditions prevail.

The temperature effects on other forms of aquatic life which act as food sources, competitors, and predators of the organisms also have an indirect effect on other aquatic organisms which are directly influenced by a change in temperature. This interrelationship must be given careful consideration if the ecosystem is to be maintained.

The ecologists need more information on how each part of the ecosystem compliments the other parts and this type of study at a thermal plant may require three to five years for a before and after study. This would allow the definition of existing organisms and food chains after which work could proceed on attempting to classify organisms as to importance. It should be noted concerning the elimination of a species, however, that the health of the ecosystem is related to the species diversity present, with greater diversity being a sign of increased health. Also, little knowledge is currently available on the effects of temperature increases on future generations.

The operation of the power plant is one key to the success of a well-designed and located plant. This is due to the fact that the avoidance of temperature shock is critical, especially for decreasing temperatures which would result during periods of maintenance. In this case, an attempt should be made to design for lower rates of temperature rise and fall where possible. However, it should also be understood that sudden shutdowns will remain an unavoidable possibility in an electric power plant, and the lethal effects resulting from this action will have to be expected.

According to Jensen (1971), ecological considerations must be

included in power plant siting if a degree of compatibility is to attained between a thermal power station and the aquatic environment. Special attention should be devoted early in the process of site selection to development of temperature criteria based upon the reproductive and development stages of the organisms in the respective area, and an effort should be made to protect these organisms. This could possibly lead to seasonal variations in standards based upon fish migration at certain times of the year. The careful location of discharge structures within a water body could result in benefits from natural turbulence in the water body. The use of the principle of the momentum jet can also be used to induce turbulence and may result in a dual benefit since both heat dissipation would increase and biological protection may increase because aquatic organisms generally tend to avoid areas of excessive velocity gradients. Auxiliary pumping units may also be considered for application at existing plants to lower the temperature in the discharge canal by pumping water past the condenser and merely diluting the cooling water with this additional water prior to discharge. Steps should also be taken to minimize the possibility of biological entrainment in the cooling water intakes although the effects of such passage on organisms are difficult to generalize due to added effects of abrasion,noise, and turbulence. Also recirculation should be avoided when it is demonstrated that repeated entrainment and passage through the condenser system would result in serious consequences for a significant portion of the species.

Thus, in summary, the complex responses of the ecosystem depend

on a large number of factors and are difficult to generalize. The addition of waste heat can cause significant changes to the ecology of the area with little hope of predictability. Therefore, the aquatic biologists must continue in their attempts to define and reconcile the beneficial and detrimental effects of such as to maximize the overall benefits to mankind. In the meantime, the siting and operating considerations mentioned in this section, which would tend to minimize the adverse effects on the ecosystem, should be analyzed and employed in relation to the benefits achieved and the costs of implementation.

II. B. 6. Thermal Pollution Abatement Alternatives

The selection of a thermal pollution abatement program requires consideration of the fullest range of technically feasible possibilities. Since every stage in the generating - disposal system can have a potential environmental impact and external social effects, every element of the system may be regarded as a possible point for thermal control decisions. Thus, the plant location, the waste heat production process, and the waste heat disposal systems must be considered. The opportunities for control are more restricted at existing facilities and the relative costs are also likely to be higher at these locations.

In the year 1970 only a small portion of the total United States electrical plant capacity was equipped with auxiliary cooling devices; less than 8% of the 202,000 Mw thermal capacity used cooling ponds and about 13% used cooling towers, according to Warren (1969).

He reported that a majority of the cooling tower use is found in the South Central and West Regions, with the Southeast, West Central, and Western Regions dominating in the use of cooling ponds.

The four basic supplementary heat rejection units, natural draft cooling towers, mechanical draft cooling towers, open ponds, and spray canals, provide a wide range of alternative systems for handling condenser water discharge. Therefore, it appears likely that at any power plant in the future it will be possible to consider several feasible alternative systems to meet specific temperature standards.

The condenser cooling water systems can generally be classified as three types: open-cycle systems, recycling systems, and combination systems which permit seasonal operation. The cooling water passes directly from the condenser to the receiving water body in the open-cycle system. Generally, with this type of cooling system, the temperature rise is between $10^{\circ}$ and $30^{\circ}$ F. A temperature rise of less than $10^{\circ}$ F is generally impractical since extremely large flows of cooling water would be required and the volume of the condenser apparatus required to handle these flows would block out the space required for supports, piping and control systems. Thus, the only practical means of attaining a temperature rise less than $10^{\circ}$ F would be a dilution with a large quantity of unheated water or by decreasing the power load. Also, for a temperature rise in excess of $30^{\circ}$ F the turbine steam-cycle efficiency begins to deteriorate rapidly, and the flow of cooling water no longer reduces inversely proportional to the increasing temperature rise. Diffuser pipes may

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be used for effluent disposal to minimize adverse effects in the open-cycle cooling system. The coastal sites may result in this technology being a particularly attractive alternative.

Supplementary cooling devices can be added to a once-through system between the condenser and the point of discharge for a combination system if the cooling limit of the heat rejection unit at design conditions is compatible with the water quality standards. Natural draft towers are technically possible, but are not usually economically attractive in this situation. Mechanical draft towers are more suitable due to their flexibility and low capital versus operating and maintenance costs. Where the standards are set forth as a temperature rise and the water supply is adequate in volume a cooling tower system could be installed to provide the required degree of cooling. For unreliable water supplies where temperature limitations are defined in terms of maximum receiving water temperatures during specific time periods, a supplementary tower system could be used where the cooling tower supplies a proportional flow quantity for operation in the combination system. Cooling ponds and spray canals could also be added on and operated in the combination system, but these alternatives are subject to a land area constraint.

Recycling systems are most frequently used on inland and estuarine sites and can employ natural draft towers, mechanical draft towers, cooling ponds, or spray canals. These systems use the off-stream cooling device to reduce the temperature of the condenser discharge prior to recycle back to the plant. Small amounts of make-

up water are required from an outside source in this case, with the quantity depending on evaporative and blowdown losses. The blowdown rate depends on the concentration of solids in the source water. Normally, according to Rainwater (1969), the make-up requirements are approximately 4% of the cooling water flow, evaporation being 1 - 1½% and blowdown from 2 - 3%. Since the heat rejection devices function more effectively at high temperatures, condenser rises often fall between $25^{\circ}$ F and $35^{\circ}$ F in the recycle systems. Dual-pressure double-pass condensers are usually necessary when a large temperature rise and high cooling water temperature exist.

Due to operational experience, EPA studies, and manufacturers data, it has been determined generally that all four supplementary cooling devices are worthy of consideration as a practical solution to the thermal pollution problem anywhere in the United States. The use of cooling ponds as an add-on facility in an open-cycle system, however, is not a practical alternative for meeting standards due to high pond outlet temperatures. Also, other site factors must be considered in the final selection, such as structural requirements, and soil conditions at the particular site, and these may eliminate some choices from practical solutions. The problem of size limitation often arises with the large volumes of water required for some power plants, but the size of the individual cooling units does not have to increase, but rather multiple units can be assembled at each site. Finally, the majority of the evidence available indicates that the probability of induced fog, precipitation, etc. from cooling towers is quite low and that the potential trouble spots can be

identified and the magnitude of the hazard quantified.

Plant Location. The need for additional generating capacity and new plant sites will probably continue unabated for the next twenty years. According to Craig (1972), the average capacity installed on new sites will increase from an average value of 380 Mw in the 1960's to 1,880 Mw in the 1970's, and to 3,900 Mw in the 1980's. In the 1950's, 300 Mw units were considered a maximum size, while at the end of 1968 there were 140 fossil-fueled plants in operation with a capacity in excess of 500 Mw, and 45 of these were over 1,000 Mw in size. The estimates made by the FPC in May 1971 indicate a total of 300 new thermal powerplants over 500 Mw will be required within the next twenty years. These figures indicate an expanding need for plant capacity along with requirements for cooling water and control of air pollution which will necessitate additional large quantities of land. These requirements for cooling water and land area may impose a constraint on the number of thermal pollution abatement alternatives available at a planned site. For the existing plants, the location is predetermined and it is not a relevant alternative.

Before discussing the details of the alternative methods of waste heat disposal available, a few general comments are appropriate concerning the alternate sites available for electric power plant development. Rivers have been used frequently in the past as sources of cooling water. The natural flows of streams have provided a conveyance for the heated discharge. However, in view of the magnitude of flows required for the large steam-electric plants

planned for the future and the thermal limitations imposed by water quality standards, the river sites suitable for once-through cooling have been reduced in number and supplementary cooling devices will have to be employed at this type site more frequently in the future.

In the case where an available lake is used for a cooling water supply, with a once-through cooling system, the thermal stratification during the summer months may provide a large potential source of cooling water. The lakes are usually isothermal in the winter months, that is, they have nearly the same temperatures from the top to the bottom layer. However, with the change of season in the spring, stratification occurs in three layers: the upper layer of epilimmion, which is warmed by the sun and mixed by the wind resulting in relatively constant temperature with depth; the second layer, the thermocline, where temperature drops sharply; and finally, the lower layer, hypolimnion which extends to the bottom of the reservoir with only minor temperature change with depth and with season. In some installations, cooling water has been withdrawn from the hypolimnion and the heated water released to the epilimnion with no increase in reservoir surface temperature. One disadvantage of this scheme is that the hypolimnion water tends to become low in dissolved oxygen during the summer. Thus, care should be used to assure that the discharge of heated water does not lower the dissolved oxygen in the surface layers of the reservoir.

Estuarine water is also used in some cases for cooling purposes in steam-electric plants. The quantity of water is not usually a

limitation in the cases, but there are usually temperature restrictions to limit the number of available sites. There is also increasing public awareness of the ecological significance of estuaries and this may result in increasing legislative protection of these areas.

Another large potential source of cooling water for once-through systems is the ocean. With the proper design of intake and discharge points, the adverse effect on marine life could be minimized in these cases. The outfalls for these sites should be located so as to avoid the estuarine waters and currents which might bring the heated effluent ashore or to spawning and migration areas.

Consideration should be given to the fact that cooling water systems at both estuarine, ocean, and coastal sites must be constructed of corrosion resistant materials. In some cases, it is not advisable to use copper for this purpose due to the possible adverse effects on shellfish or other aquatic organisms. These adverse effects can be avoided by the use of materials such as stainless steel or nickel-base alloys.

Plant Operation. Another alternative for thermal pollution abatement is the actual operation scheme of the steam-electric power plant. The feasible alternatives in this area are of course restricted for existing power plants. Where complete renovation is not a viable alternative, the only major choice remaining would be to change the plant operating rates to adjust the output of waste heat to variations in environmental parameters and social costs. In this case, under conditions of low flow, high ambient temperature,

or during periods of fish migration, thermal pollution effects could be reduced or eliminated by adjustment of the plant operating rate.

The technical operational adjustment possibilities will be more extensive in the case of new plants. These options include the plant size, thermal-efficiency variations in the steam-cycle, or a shift to a non-steam cycle to supply electricity. One promising approach to reducing the thermal pollution load is stepping up the power plant efficiencies by raising the upper temperature in the thermodynamic cycle of the plant. According to Dallaire (1970), with the steam temperature at $1000^{\circ}$ F and the condenser cooling water at $50^{\circ}$ F, for an ideal Carnot cycle the energy-conversion efficiency is 65%. However, in practice today the actual conversions obtained for the most efficient fossil-fueled plants with the steam at $1050^{\circ}$ F are about 40%. The ideal efficiency, on the other hand, could be boosted to 69% by increasing the top temperature to $1200^{\circ}$ F. However, the present temperature limitations of materials in generating equipment will probably rule out stepping up steam temperatures to this level in the short run. The power cycle "top" temperature can be raised, however, by connecting a topping unit to the usual steam cycle. In this process, the combination gases are used at a high temperature to effect some energy conversion and these gases are then passed through the usual steam generator. Substantially improved electric generating efficiency would result from the use of the gas-turbine system for this purpose on a short term basis. The other topping units which have been proposed for combined cycles are thermionic generation and magnetohydrodynamics (MHD). These

systems are currently suffering from materials problems which have no readily apparent solution. Also, since both systems generate direct current, expensive d-c to a-c conversion equipment must be provided.

The light-water nuclear-fueled plants which will account for the vast bulk of nuclear-generated power in the next few decades will be limited to efficiencies of approximately 35% due to the low temperature of the water in the primary flow loop which circulates through the reactor core for heat absorption. On a long term basis, high-temperature gas-cooled reactors could bring significantly higher efficiencies according to Dallaire (1970). The gas within the primary loop is heated to a temperature of over $1,000^{\circ}$ F in this process and one 330 Mw plant of this type has a projected efficiency of 39.2%. The advanced breeder reactors which provide a significantly higher efficiency also offer a chance of making a commercial appearance sometime during the next few decades.

Waste Heat Disposal. Thermal discharge can be shifted from the aquatic to the atmospheric media in whole or in part. The heat given up by steam in the condensers is first absorbed by a flow of cooling water which is used for this purpose due to its high specific heat, general abundance, and its ability to consume heat in the evaporative process. Terrestial heat disposal has been considered, but this could lead to ground-water pollution and may result in a significant disappearance of surface waters. Among the other alternatives available to thermal discharge to an existing water body are air-cooled condenser systems, artificial cooling ponds, some cooling

tower designs, and spray canal systems. The air-cooled systems are a technological possibility, although not yet economically feasible, for even large power plants. It is not certain whether they could be technically possible for use in existing plants. Cooling ponds and towers may be utilized either to recycle water or to partially treat heated effluent prior to disposal. In either mode, they may be designed to direct any portion of the condenser heat rejection to the atmosphere rather than to the water body. Spray canal systems incorporate a combination of artificial cooling and areal redistribution of heat. The accelerated cooling would come in this case from the increased evaporation in this system. The outflow location within the streamflow vertically or horizontally, the dispersion of the outflow at many points, or piping of effluents should be considered with a once-through cooling process. Finally, the storage of heated effluents for programmed discharge could be considered as an alternative to programming plant heat production rates.

Where the cooling water is discharged to a water body the dissipation of waste heat is accomplished by evaporation, radiation, and conduction. If the wet-type cooling tower or spray canal is used for heat dissipation, it is accomplished primarily by the evaporation of water, whereas, in a dry -type cooling tower, the heat dissipation occurs principally due to conduction and convection.

Once-Through Cooling System. A once-through cooling system is currently used at many steam-electric plants to dissipate waste heat. In this type of system, the water is withdrawn for the water body,

passed thru the condenser, and then returned with its increased heat

load and higher temperature to the river, lake, pond, reservoir,

estuary or ocean. The only consumptive use of water with this system

would be from the increase in evaporation from the water body due to

the addition of the heat. The once-through type of cooling system

has the advantages of low cost and a minimum consumption of water

(usually about 1% of the condenser flow) at those sites where the

available water sypply is adequate and State and Federal water

quality standards would not be violated. However, an important

design consideration with this type of system is to locate the

intake and discharge structures in such a way as to avoid recircula-

tion of the water.

In addition to the surface discharge, in which water is dis-

charged from a canal or pipe into the water body, some installations

using once-through cooling use diffuser pipes at the discharge

point to generate mixing within the receiving body of water. This

process limits the temperature rise in the water body but it reduces

the rate of heat dissipation at the atmosphere. The alternate plan,

the surface discharge, takes advantage of the surface phenomenon of

heat dissipation and disperses the water over a wide area where this

is not in violation of water quality standards.

The diffuser provides an effective method of limiting the

surface temperature rise, but it also involves a trade off due to a

much lower rate of heat dissipation and disturbing of the bottom of

the water body and a large portion of river cross-sections. If the

rapid dissipation of heat, which is mainly a surface phenomenon, is

the prime concern, then the heated water should be discharged by the surface method where it would spread out over a wide area.

Also, in a practical application of this type of technology for cooling it may be found that the standards could be met with a high degree of probability with a once-through cooling system. In these cases the design chosen could employ a once-through system assisted by a supplemental cooling tower which could be designed to operate only when the river flow is not sufficient or the natural temperature of the water body is too high.

The increasing flows which are needed for the larger units being constructed today along with stricter water-quality standards which have been adopted for temperature are combining to make the use of this type of cooling system less desirable and in many cases not technically feasible for river locations. The current developments in understanding the ecology of the estuaries and the delicate balance maintained within them gives an indication that the water-quality standards in this region may become very strict in the future. Finally, mention must be given to dilution, which withdraws water in excess of the cooling requirements, by-passes the plant with an auxiliary flow, and then mixes the auxiliary flow and the heated discharge before return to the water body.

The once-through system generally requires the least noticeable changes to the natural environment since the major portion of the required structures can usually be placed underground or underwater.

Cooling Ponds. At some inland locations where adequate water bodies to allow for the once-through cooling system are not available,

cooling ponds may be constructed to provide cooling water needs
where suitable sites can be found. In this system, the water is
continuously recirculated between the condenser of the plant and
the pond with make-up water added to the pond to replace evaporative
losses due to heat addition, seepage, and blowdown losses. This
system is the oldest and simplest type of man-made heat rejection
unit used in this country. The land area requirements for con-
struction of a cooling pond system generally range from 1 to 2
acres of surface area per Mw of generating capacity and are the
major disadvantage. However, in the case where a large reservoir
or lake is already available in the vicinity of the site, this water
body could be used for a cooling-water source if such use did not
interfere with other planned uses. This alternative was considered
as a surface or diffuser discharge to a small lake in this report.
However, this would usually require a much larger surface area than
the man-made cooling pond. The cooling pond type of system would
require essentially the same type of structures as the once-through
system. Where the necessary land is available these new bodies of
water may add to the beauty of the area and provide recreational
opportunities. Other advantages include simplicity, low maintenance
cost, ability to operate for extended periods without make-up
water, low power requirements, and high thermal inertia.

In the cooling pond, the lower limit of cooling is a computed
value which is known as the "equilibrium temperature" which is a
function of meteorological conditions, including solar radiation,
air temperature, wind speed, and others. This is the temperature

that the water would approach if all the influencing parameters were held constant. The cooling pond approaches the equilibrium temperature asymptotically. The cooling ponds may be classified as "well-mixed" with complete mixing with receiving water and uniform temperature throughout except for a small region near the point of discharge or "plug-flow" where there is no mixing with receiving water and exponential decay depending on the hydraulic design parameters. The well-mixed type normally requires a much greater surface area than the plug-flow type for the same temperature, according to Ryan (1972). Another classification is shallow or artificial and deep or natural ponds. The shallow or artificial ponds are generally 8 to 20 feet deep with complete vertical mixing. According to Ryan (1972), this type may be either plug-flow or fully-mixed, with loadings of $\frac{1}{2}$ to 1 Mw per acre. The deep or natural ponds have depths more than 20 to 30 feet, are highly stratified and usually have low loadings of approximately $\frac{1}{4}$ Mw per acre. For considerable entrance mixing this type would be similar to the naturally stratified reservior and for small entrance mixing it would be similar to shallow flow thru pond.

Spray Canals. Another alternative heat dissipation unit available is the spray module system. The system eliminates the structures necessary for a fixed spray pond, and results in an increase in system flexibility. The self-contained spray modules may be installed in a completely closed system with a cooling pond or canal, or in conjunction with a cooling pond or canal as part of a combination system. The current trend is to use the spray modules in a canal which forms a closed cycle system for the cooling water.

The spray canal system operates on the same principle as the cooling pond, but the evaporative losses are enhanced by spraying the warm water from the plant discharge in the air over the canal. This causes the interfacial area and the relative velocity between the water and air to increase and results in an increase of the surface heat exchange coefficient. Thus, the spray canal systems require only 5 to 10% of the surface area of a cooling pond to accomplish the same job, according to Rainwater (1969). Also, approximately the same degree of cooling can be attained with the spray canal as in a cooling tower since the theoretical limit is the wet-bulb temperature.

The typical design results in the spray nozzles being located 5 to 10 feet above the water surface, and the design of these nozzles is a critical factor in effective pond performance. The performance of this type of system is limited by the comparatively short time the water droplet is in contact with the area.

The spray canals require little maintenance other than routine pump maintenance and nozzle and pipe cleaning. In the power plant itself, however, the maintenance requirements may increase due to the possibility of impurities collecting in the canal and being carried into the condenser. Other unfavorable aspects which may arise include poor heat transfer due to climatic conditions and the possibility of freezing. According to Dynatech (1969), undesirable factors to avoid include high power consumption, dead zones, and low heat transfer coefficients.

Unfortunately, although considerable testing of spray modules has been carried out, the material obtained is considered proprietary

and is not available in the open literature. This situation makes a more detailed discussion of this mode of cooling impossible at the present time.

Cooling Towers. Where suitable sites for ponds or reservoirs are not available and either limited flows or water quality standards prevent the use of available streams and lakes, some type of auxiliary cooling device must be provided. In the wet type system, heat is dissipated principally by evaporation since the water is brought into direct contact with a flow of air and its heat is carried away mainly by vaporizing some of the water into the air stream. These systems usually employ cooling towers with the flow of air provided by either mechanical means or natural draft. This type of system usually requires a source of make-up water to be available to replace the evaporative losses and drift and to provide a blow-down effect within the tower to prevent the accumulation of solids on the equipment due to chemicals contained in the source water.

The principle of cooling tower operation is enumerated by Kennedy (1972). The water is cooled by the moving air due to sensible and latent heat transfer, and the air wet-bulb and dry-bulb temperature control the amount of transfer by each process along with the tower characteristics. The process of evaporation accounts for more than 75% of the total heat transfer and the wet-bulb temperature fixes the lower limit of cooling warm water by this evaporative wet cooling tower. The tower size is a function of the approach, that is, the difference between the wet-bulb temperature and the temperature of the cold water leaving the tower. The "range"

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of a tower is defined as the temperature difference between the hot and cold water, and this value generally varies from $14^{\circ}$ F and $34^{\circ}$ F. The wet-bulb, range, and other factors control economical tower designs which generally have approaches of $5^{\circ}$ F to $25^{\circ}$ F.

Within the tower, the warm water is usually allowed to flow onto a lattice network called "fill" which breaks the water into droplets or it is sprayed into the air. These processes facilitate the evaporative heat transfer as the air moves through the tower. The cooled water is then collected in a basin from which it can be pumped back to the condenser in recirculation. In order to reduce "drift", the loss of droplets of cooling water which may contain accumulations of chemicals or salt, the fill may be designed to assure the exposure of a thin film of water. Refinements in this process may make the design of cooling towers to use ocean or brackish water possible in the future. In order to protect spray nozzles from clogging, to protect the fill from deterioration, and the condenser from corrosion, this make-up water must be chemically treated. The solids from these chemicals then may accumulate in the cooling water, and must then be removed by "blowdown". The average amount of make-up water to compensate for evaporative losses, drift, and to provide blowdown generally amounts to some 2% of the cooling water flow, according to FPC (1969).

The mechanical draft type of towers are equipped with motor driven fans designed for either a forced draft, with fans located at intakes, or induced draft with the fans at the air outlets. The induced draft towers may be designed as counterflow with an upward

flow of air meeting a downward flow of water, or cross flow with a downward flow of water meeting a horizontal air flow. According to Kennedy (1972), the counterflow tower is thermodynamically superior since the enthalpy of the air increases as it comes in contact with warmer water, causing the driving potential to remain nearly constant along the air flow path. In the crossflow type, the air moves horizontally through the fill at lower levels and thus is in contact with cooler water than that at higher levels. This limits the air passing through the upper sections of the fill to having an exit temperature approaching the hot-water temperature. Thus, the closer approach temperature is possible with the counterflow tower. However, the crossflow design has a lower head drop in the air flow, and this can affect the large air requirement brought on by the low thermo-dynamic efficiency and result in a reduced fan-power need. The crossflow tower also offers greater add-on flexibility since the air-flow travel distance need not be changed due to adding on, where in the counterflow tower the travel distance varies with the fill height, which would have to be increased in order to add on capacity. The air-flow pattern is simpler in the crossflow configu-ration which is beneficial since one very critical factor to the efficient functioning of the tower is a uniform distribution of the air and water flows throughout the fill. This is very difficult to achieve with a counterflow tower. Localized icing and fogging problems may be caused when this system is used by the release of large volumes of warm and humid air very close to the ground level.

It was reported in Dallaire (1970) that the mechanical
draft type made up all cooling towers constructed in this country
until recently, especially in water-short regions and at minemouth
coal fired plants. Also, since the land requirement for this type
of system is relatively small, they can usually be constructed
wherever sufficient make-up water is available. The use of fans in
the mechanical tower permit good control of the air flow and conse-
quently over the cold water temperature. It should also be noted
that these towers are subject to recirculation of the hot, humid
air they release.

The introduction of the natural draft hyperbolic cooling tower
in this country occurred in 1963 when the first unit was introduced
in Kentucky at the Big Sandy Plant. Since this time approximately
40 towers have either been completed, are under construction, or are
presently being designed. On a world wide basis this type of tower
had had a long and successful background. According to Rogers and
Cohen (1970), the first application of this type of tower was in 1912
in Holland and this unit is still in operation. In this natural
draft type of tower the flow of air results from the chimney effect
of the large hyperbolic structures, which may be up to 400 feet in
height and 400 feet in diameter at the base. The airflow through
the wet packing near the ground results from the difference in
density between the air inside and outside the tower. In this case,
since the warm air is released over 400 feet above ground level,
and there is less likelihood of icing or fogging problems in the
vicinity of the tower, and less likelihood of recirculation problems.

Since the amount of heat dissipated in the natural draft towers depends on the wind velocity, they are usually located in unobstructed areas and care is also taken to avoid mixing of the moist air and stack gasses, according to FPC (1969). Also, since the cooling efficiency of the tower is partially related to the air flow rate, there will be a tendency to increase the tower height within structural limits. The hyperbolic natural draft units in general require smaller amounts of real estate and piping, are relatively free from recirculation and interference, and have none of the noise and vibration associated with mechanical draft units. However, on the negative side, the hazard to airlines, modification of local wind currents, and aesthetic aspects make the natural draft tower less desirable. These trade off's must be considered in making the choice between the two types of towers.

Forcing the electric utilities to construct wet cooling towers at every plant site, thereby providing a safety factor against thermal pollution, may not always be the optimal solution since this frequently results in a consumptive loss of water which may be as much as two and one-half times the loss experienced with a once-through system of cooling. This large loss of water results since these cooling towers dissipate heat almost entirely by evaporation, whereas in a once-through system the natural body of water removes heat by both conduction and back radiation in additional to evaporation. According to Dallaire (1970), the wet cooling tower system, if used in all cases, would forego the assimilative dissipation capacity of the existing water bodies. If the current use of mixing

zones were completely eliminated, the arbitrary application of cooling tower technology could take place and by the year 2020 the additional consumptive use of water may require up to 20 billion gallons per day. Since our future needs for adequate water supply could not tolerate such a loss, natural heat dissipation mechanisms will have to be utilized to their fullest extent.

No wet cooling tower systems have been constructed with sea water supply for electric power plants in the United States. Salt water towers have been constructed for a small generating station in Europe, and towers operating in the Middle East at oil installations use brackish water for make-up. The salt water differs from fresh water only slightly as far as cooling efficiency of a supplemental heat rejection system with a resulting increase in cooling unit size of about 3%. The materials and construction aspect pose no insurmountable barriers to construction and operation of large salt water towers. The principal problem, however, results from the possible discharge of salt particles discharged to the atmosphere by these systems since the towers cause a small portion of the circulating flow to become physically entrained in the air current. This drift has the chemical composition of the circulating flow in contrast to water vapor from evaporation which is pure water. The typical figure of 0.2% of the circulating flow for drift, which is current practice, is far in excess of current engineering capability and practicality, according to Rainwater (1969), He reports this drift can be almost eliminated by control of the air velocity and drift eliminator design. Mechanical draft towers are now available with

drift elimination of 0.02% of the circulating water flow. Very low

drift rates of 0.01% of total circulation water flow can be obtained

with natural draft towers due to slow velocity of air and extreme

vertical distrances which the air travels through, according to

Rainwater (1969). Also the future design improvements may lead to

levels of 0.005 - 0.001% of the cooling water flow for drift losses.

The dry cooling towers may also be used for the disposal of

waste heat. In this type of system, the use of water would be

practically eliminated since the dissipation of heat is accomplished

by conduction and convection through an extended surface heat

exchanger. This type of cooling tower has the limitation of cooling

temperatures being restricted to the dry-bulb temperature of the

atmosphere instead of the wet-bulb as in the evaporative towers, and

this would result in a penalty in the efficiency and capacity of the

power plant. This type of cooling tower is very expensive and no

large scale installations have been put into operation yet in the

United States.

The limitations on thermal discharge to natural waters, the

unavailability of make-up water, and the potential adverse increases

in solids concentration from plant blowdown may make the use of dry

cooling towers a more desirable alternative in the future. According

to Leung and Moore (1971), in one system an extended surface air-

cooled condenser, in which the turbine exhaust steam is discharged

directly, is utilized. Since large ducts are needed in this system

to convey the exhaust steam to the exchanger coils, a design

limitation is placed on the size of the unit to which it can be

applied. The largest system of this particular type to date is 120
Mw. The other dry cooling tower system uses a direct contact or jet
condenser instead of the conventional tubed condenser. The circu-
lating water is then sprayed into the jet condenser where it mixes
with and absorbs heat from the exhaust steam as condensation occurs.
Most of the heated condensate is recycled by large circulating water
pumps to the dry-type cooling tower and then the remaining condensate
is returned to the feedwater cycle. This system can be used with
either the natural draft or induced draft mode.

Beneficial Uses. The final set of technical alternatives
available for controlling direct heat disposal to the aquatic
environment is making use of waste heat in other activities prior to
its dissipation. Due to the large markets for heat currently exist-
ing in the area of household and commerical heating, it would seem
that this method could offer great possibilities. If the markets
could be developed for this rejected heat energy, this could prove an
attractive alternative to utilities, either as a means of minimizing
the cost of thermal pollution abatement or of transforming a private
liability into a profit-earning output.

However, this system is not without its technical problems,
according to Cheney, et. al. (1969). The difficulties stem from the
nature of heat as a form of energy. The heat would be delivered as
heated air or water or as steam via piping systems which would be
expensive to maintain. If the steam were supplied directly from the
turbine exhaust a substantial amount of electrical generating
efficiency would be sacrificed. Even in the case of hot air or water

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systems, electrical output losses would result from the necessity of supplying water to users at a substantially higher temperature than that which is presently discharged from generating stations. Current practice which is governed by the concept of generating efficiency, limits raises of the temperature of condenser cooling water between 10 to 30$^\circ$ F above ambient source temperatures. Another drawback of municipal use of waste heat is the seasonal effect on demand in any power supply area. Also, the colder months during which this demand for heat would occur generally correspond with the seasons when the problem of thermal pollution is less severe. It is, therefore, not clear at this time whether the electric utilities will take it upon themselves to conduct the necessary research and development required to exploit these innovative possibilities.

Dallaire (1970) sets forth the following proposals which have received considerable attention in this area: space heating, industrial processes, agriculture, aquaculture, water treatment, desalinization, de-icing harbors and recreation. It should be emphasized, he states, that even if all the above mentioned schemes were widely implemented, the total amount of heat generated would still be greatly in excess of the requirements and thus some amount of thermal pollution would still have to be considered. Already, the waste heat from power stations provides enough energy to heat every home in America.

The major manufactoring industries using process heat in this country are: food products; paper products; chemical products; petroleum; rubber and plastics; and textile mill products according

Dynatech (1970). The estimated steam consumption by these

industries ranges from 2,000 to 3,000 bkwh which is of the same order

as the 1980 projected electric power production. Thus, a significant

amount of thermal discharge could be used by an urban area's indus-

tries if the area served by the plant included equal fractions of the

nation's steam using industries and population. A comparison was

also provided for the amount of steam consumed by these industries

per kilowatt-hour of electricity used and it was determined that the

pounds of steam per kilowatt-hour of electricity was once about

30 lb/kwh and it has declined to less than 10 lb/kwh in recent years.

This unfortunately is contrary to the desired trend of decreasing

demand for electric power by using heated discharge. Another problem

to be solved is the mismatch between the required temperatures for

industrial process heat and the available temperature of discharges.

Aquaculture would be one potential use of the heated condenser

discharge water. In this case marine and freshwater organisms may

be grown and cultured in water bodies treated with hot water.

Experiments are currently underway using heated effluent to farm

shrimp and to increase oyster production. Studies are also being

made to determine the possibility of using the technique to increase

lobster production, and crab and mussel production. Sport fish

hatcheries to increase growth rates are also being considered,

according to Brown (1970). The task ahead is to design ecosystems

and to make them biologically useful by taking advantage of these

waste calories rather than allowing the thermal waste loads to go

undirected into natural and at times delicately balanced and complex

life systems. New circuits within the environment may be constructed, composed of species which will fit into a new food chain in a positive manner and to convert this waste energy from electric power generation into desirable recreational materials or foodstuffs. Organic wastes from sewage treatment could be used to provide necessary nutrients and the waste heat could be used to provide an optimal temperature range for maximum biological activity and production, according to Mihursky (1967). The scheme of aquaculture, with the proper research, could be advanced to the development stage, but the energy requirements and ecological side effects will require further study. The main drawback of aquaculture, according to Dynatech (1970), are: the water bodies are still involved; heat rejection remains highly concentrated; this application doesn't reduce electric power requirements; and the process is ill-defined technically and economically and far removed for the normal areas of concern of the power company. The problem of radioactive contaminants would also have to be considered and require future research. Thus, the use of aquaculture is not so much regarded as a solution to thermal pollution but rather as a potential resource for increased food production.

The use of heated cooling water for irrigation purposes could result in benefits to the field of agriculture. It could serve to decentralize the heat rejection process and may result in the generation of some revenue. The warm water could prolong the growing season thru a warming of the soil and promote faster seed germination and growth. The problems which would come with this

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system, however, include the ability of the soil to adapt to change, parasites, and crop resistance to heat. Also, the ditch-type methods of irrigation can result in the water being heated by the sun and returned to the river at elevated temperatures. Thus, although the use of the heated discharge for irrigation may eliminate the problem of local high temperature mixing regions in the river, it can cause a significant decrease in streamflow and result in significant physical and thermal changes. Consideration should also be given to the possible contamination due to small amounts of radioactive material in condenser water and this matter will require thorough analysis. There are numerous studies and pilot plant programs currently underway to examine this problem.

The alternative use of cooling ponds for a means of thermal pollution abatement would include the possibility of multi-use development of recreational facilities. In a 1,200 Mw power generation facility in Illinois, the lands adjacent to a 2,600 acre cooling pond are being developed for recreational uses including fishing, swimming, boating, camping, and picnicking. At a similar size facility in Virginia, the cooling pond has been used for both boating and water skiing, according to Brown (1970).

The limited use of the condenser cooling water for the heating of buildings up until the present time has been chiefly due to its relatively low temperature. Only a very small fraction of the waste heat from power plants is currently used for this purpose. However, Dallaire (1970) indicates that at one location the hot water is transported over a distance of ten miles to heat residences in a city

of 60,000 at 60% of the cost of heating using fuel oil. It may become economical in the future to tap off steam at $250^{\circ}$ F from a point before the final turbine passage, and thus provide a high quality steam heat to a community. Heat could also be used during the summer months to provide space cooling by developing refrigeration systems that operate on the input of waste heat from power plants.

The use of waste heat to increase the temperature of sewage might result in a substantial increase in the capacity of municipal sewage-treatment plants. In the activated sludge process of secondary sewage treatment a $10^{\circ}$ C change in temperature would result in a nearly two-fold increase in the rate of decomposition, according to Dynatech (1970). This method, however, would require the solution of the problems of grease and micro-organism build up in the condenser. The negative aspects of this beneficial use include: the temperature levels required are in excess of plant design; only a small percentage of the waste heat discharge would be required; and finally, the thermal pollution load would be transferred from the power plant to the sewage treatment plant with no net benefit to the environment.

These considerations would also be applicable in the case of desalination. In this case, the water requirements would only become compatible if sea water desalination was considered for irrigation. It appears in this case, however, that the new environmental problems created would exceed those resulting from the original thermal pollution.

The use of the waste heat for ice control on highways and water-

ways has also been discussed in Dynatech (1970). In this case, the distribution problems appear to be insurmountable in the case of highways and the heat sink would only be provided for a fraction of the year. In the case of navigable waterways the problems are not so nearly acute for both distribution and construction. However, the ecological effects and a plan to dispose of the heat in the remaining spring and summer months would have to be developed.

There is also a possibility of using the heated water for water treatment since the processes of flocculation and filtration occur more readily at high temperature. The use of municipal water supplies as cooling ponds has also been considered since for the residential market much of the water consumption is for purposes where temperature is not critical or heating would be required. With water entering the home a higher temperature, domestic electric consumption may also decrease. But, since most water is consumed by industry for cooling instead of a residential use, this alternative process appears to be an unfeasible one, according to Dynatech (1970).

Thus, the concept of beneficial use of waste heat as a solution to the overall problem of thermal pollution does not yet appear to be a viable one, with the greatest prospects being heating and air-conditioning of buildings which is currently a technically feasible process. Even in this case, however, distributional problems and seasonal fluctuations in hot water demand create great difficulties. Thus, it appears that heat dissipation equipment or small-total energy systems will be required in the future to control the thermal discharge problems.

<u>Aesthetic Consideration</u>. The aesthetic considerations are now becoming of greater importance in designing and constructing structural improvements. The aesthetic qualities of waste heate abatement alternatives are generally highest for the least expensive systems. The least noticeable changes to the environment are generally with the once-through systems where required structures include an intake with screens, a conduit or canal leading to the condenser, a discharge pipe or canal, and perhaps a diffuser pipe. These structures are usually located at the edge of the river or reservoir with most of the installation underground or underwater. The negative aspects of increased algal growths, and fog due to the heat addition must also be considered.

The requirements for cooling pond structures are similar, and where favorable sites are available, the cooling pond may occassionally add to the beauty of an area and provide recreational opportunities. However, again negative effects of increased water temperature, accelerated evaporation, and fogging due to humidity changes in the local area would have to be considered.

The evaporative cooling towers are the least desirable from an aesthetic viewpoint. Cooling towers require large, unsightly structures in both the mechanical and natural draft mode. They also release large quantities of moisture causing fogging in the warm months and icing in the winter. The mechanical towers require large volume, but less height, and thus are not as objectionable aesthetically. However, since they release moisture at lower elevations, the icing and fogging problems are generally greater.

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Due to the large size and height, the natural draft towers are not pleasing and little can be done to blend them in with the environment.

The dry cooling towers create even greater problems because for both the mechanical and natural draft type they would require either larger size or a greater number of units than the evaporative type. There would be no icing or fogging problems, but the release of large quantities of warm dry air could affect climates.

Decentralized Power Generation Systems. Another possible means of providing equipment to reject heat directly to the atmosphere, according to Dynatech (1970), is to reverse the trend of large central power plants. If one would agree that the total quantity of heat rejected from all thermal power generating stations is small when compared with the earth's total heat balance, then the concentrated nature of the discharge becomes clearly identifiable as the essential aspect of heat rejection leading to its classification as a pollutant. Thus, one means of attacking the thermal pollution problem would be the elimination of large central power stations in favor of small individual generating units such as gas turbines located throughout the community at the individual sites.

The advantages of this type of system, from Dynatech (1970), include: the heat rejected is at a higher temperature and thus more readily available for community use; alleviation of the difficulties due to distribution of work; and operating problems now experienced in large grids could be avoided. The disadvantages would include: the possibility of increased air pollution from a large number of

gas turbines; overall system efficiency may decrease; and maintenance of a large number of complex systems may be more difficult than maintenance at a given single plant.

The concept of a decentralized total energy system includes meeting all the energy input requirements of a plant or dwelling with a single system. The required forms of energy include: electricity, heat, and shaft rotation. The merit of a total energy system may be evaluated based on whether the user requirements of electricity, heat, and shaft power are divided in such a way as to be compatible with the energy system output. Full use will have to be made of the waste heat to take advantage of the high system efficiency potential. In this regard, however, it is fortunate that an additional degree of freedom is available to adjust the thermal output of the system over a wide range of limits.

## II. B. 7. Evaporative Losses

The analysis of heated discharge into the aquatic environment must give careful consideration to the induced evaporative losses which may be considered as a siting constraint. A higher stream temperature than would naturally be present at a given location and under given atmospheric conditions would result from heated discharge being returned to a water body from a power plant, whether it was diluted with the main flow or not. According to Löf and Ward (1970), during most of the year the natural water temperatures are below those of the air in contact with the water, but the water temperature is frequently fairly close to the wet-bulb temperature of the

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atmosphere. Water evaporation will take place when the water sur-
face temperature exceeds the wet-bulb temperature of the atmosphere
and the rate of evaporation is a function of this temperature
difference. For a water temperature above the dry-bulb temperature
of the atmosphere, heat will be transferred by convection in
addition to that lost due to evaporation. The third mechanism for
heat loss from a water body is radiation into the atmosphere which
occurs when the water temperature is above the effective radiation
receiving temperature of the sky. However, evaporation, with its
resulting cooling, is the dominant water body temperature restoring
mechanism. The process, therefore, is effectively the same process
which occurs in a wet cooling tower system. Thus, there is a great
similarity in these processes from the overall water evaporation
standpoint. The loss from once-through cooling is usually somewhat
less since some of the heat transfer is due to radiation, particu-
larly if a large water body with low velocity is exposed.

The factors which control evaporation from streams generally
apply to ponds and lakes also. Due to the higher humidity occurring
near large water surfaces and because of the larger radiation
effects, a slightly smaller portion of the thermal load will be
dissipated by evaporation and convection. Also, if an artificial
pond is constructed to dissipate waste heat, the total evaporation
loss will be greater than that due to cooling towers or for streams
because of the added solar energy load which will contribute to the
water loss.

Thus, thermal discharges may result in diminished downstream

flows and lake volumes.  According to Löf and Ward (1970), in the
most modern fossil fuel-fired plants which generate approximately
4,200 BTU/kwhr-generated of waste heat which must be discarded to
the atmosphere, through the water bodies, the in-plant and off-site
evaporation through the water bodies would total approximately 0.5
gallons per kwhr-generated.  The present evaporation from the
electric power plants and in affected streams in this country results
in approximately 1 billion gallons per day.  When compared against
the evaporation losses in agriculture and the natural losses from
lakes and rivers, this amount is small, but on a micro-scale, for a
given regional location where multi-plants are located on a small
stream, the evaporation loss may be a major portion of the normal
stream volume.  For nuclear plants with water cooled reactors, the
evaporation would be 60 to 70% greater than that experienced in the new
fossil-fueled plants and about 25% above the present average of all
plants, according to Löf and Ward (1970).  Due to the small portion
of the total load demand supplied by nuclear power at this time, the
effect is not yet significant and it is not expected to become so
before 1980.  If nuclear power does develop, however, by the year
2000 significant increases in heat rejection and water evaporation
may be expected to result.  If more efficient nuclear plants
assume larger fractions of the load, these evaporation losses will
be reduced, but evaporation from power plants would still increase
to approximately 10 times the present rate.

Thus, the total consumptive use of the cooling water supplies
depends principally upon the type of cooling system employed.  The

once-through systems located on rivers, lakes, and reservoirs would

generally have losses of 1.0% or less of the condenser water cooling

flow due primarily to induced evaporation in the receiving waters.

The losses with cooling ponds would be on the order of 1.5% of the

condenser flow. Finally, with the evaporative cooling towers, the

losses due to evaporation, drift windage, and blowdown would

probably exceed 2.0% of the condenser flows, according to FPC (1969).

The evaporation also results in a degradation of water quality

since it causes the dissolved solids concentrations to increase. The

economic affects resulting in this instance may include the cost of

necessary desalination or dilution supplies required to restore

water to the original quality. This problem of dissolved solids

would be particularly acute in the western states where annual

average evaporation exceeds precipitation. The resulting evaporation

excess may be as much as 75 inches/year at some locations, with an

average of the excess at 26 inches/year.


II. B. 8.  Effects on Alternate Water Uses

Mention must be made of the uses of water bodies which will be

affected either adversely or beneficially by changes in temperature.

Heat discharged from steam-electric plants in the cooling water will

affect the public water supply and organic waste disposal uses of

water.

Since chemical reactions proceed at a faster rate as water

temperature rises, water treatment processes could experience a

savings in chemical costs, but the increased temperature may make

drinking water less palatable and result in algal growths, according to the FPC (1969). The eutrophication process in lakes may be speeded by the addition of waste heat, and in streams with an enriched nutrient environment, a raise in temperature may result in excessive algal blooms. Water temperature affects organic waste assimilative capacity by affecting the rate of pollutant oxidation, the capacity of water to hold oxygen in solution, and the rate of reaeration of the water. The rate of biochemical stream self-purification can be increased by adding heat up to about $90^{\circ}$ F, and above this point increased temperature appears to reduce BOD utilization. Also, the rate of oxygen absorption from the atmosphere is increased by raising water temperature, the rate of oxygen use by bacteria is increased even more in the temperature range usually considered acceptable for other purposes.

CHAPTER THREE

THERMAL POLLUTION AND POWER PLANT SITING

The problem of thermal pollution has many effects on the siting

of electric power plants.  The economic aspects of the plant location

and operation, and the thermal pollution abatement alternatives will

require definition and careful consideration in decision-making for

site selection and development.  Another siting consideration is the

ability of a plant alternative to comply with the thermal standards

of the available water body, and physical models are necessary to

enable decision-makers to evaluate this question.  Finally, the

evaporative losses due to the forced temperature rise induced by the

introduction of waste heat along with other resource requirements

must be defined and quantified as constraints before a site and plant

alternative can be considered as feasible for development.


## III. A. Economic Theory of Thermal Pollution Management

Unless explicit controls on the disposal of waste to the environ-

ment are provided, an individual firm will produce a waste product

and employ the mode of disposal which is most consistent with the

achievement of profit, earnings, and other objectives of the firm,

such as a larger share of the market.  According to Cheney,et. al.

(1969), the cost or benefit of the resulting waste discharge which

must be borne by both other enterprises and society, in general, will

usually not be considered by the firm in making its production and

waste disposal decisions, except when the firm would receive adverse

public opinion as a result of significant damage to the environment.

Also, since the external effects of the disposal of waste products are usually marginal, they become superimposed on and mixed in with the effects of many other polluters, and therefore, they tend to be borne by a large number of economic units and individuals. Thus, the actual effects of a single waste discharge are usually not known or discernible. Under these circumstances, the incentives for voluntary pollution control by private enterprise tend to be minimal and if they do exist, they are usually outweighed by the cost of the prospective abatement technique.

When an industry fails to consider these external costs, the true costs to society become understated in the private cost-revenue calculations upon which decisions concerning production are based in our market-type economy. Thus, since the product's price fails to reflect the external costs associated with its production, a higher demand and corresponding level of production results than would be justified if the full costs of production, including social costs, had been reflected in the market pricing decisions. At the same time, the individuals or industries upon which the pollution does fall must pay increased costs for consumption or production. Thus, this external cost situation tends to bias the allocation of productive resources toward less socially productive purposes and away from areas of high social value. Where the waste discharge results in external benefits the resource would likewise tend to go in the opposite direction. Also, since the private waste discharger does not collect revenues from the receivers of the benefits, no financial incentive is provided to produce these benefits at the optimal level.

In these cases, the market system fails to provide for the optimal allocation of resources to their most efficient use. The question of the equity concerning the social justice of waste producers imposing damages on others with no compensation must also be considered. The issue which must be faced is the proprietary right to resources such as streams, lakes, and ocean water. Without the establishment of legal measures concerning private property rights to these water bodies, they tend to exist as common property resources which become exploited competitively for their waste disposal value with no equity considerations.

With regards to the specific area of thermal pollution, according to Cheney, et. al. (1969), public policy will have to set forth social rules for exploitation of the aquatic environment for waste heat disposal and the allocation of these rights among dischargers. As related to the economic efficiency in the allocation of scarce water resources among competitive uses, the social objective may be set forth as the maximum net economic benefits from the water resource. This achievement of the social efficiency objective would require the water resource be allocated over all general uses and among all users as that social productivity of the resource is maximized.

Thus, in order to achieve social efficiency the external costs of waste heat disposal will have to be incorporated as a necessary production cost for the electric utilities to consider in making production and disposal decisions. The levy of an effluent charge by a public authority on individual polluters equal to the incre-

mental damage cost imposed on other users by a unit of thermal pollution would be one way to accomplish this. This would induce the waste heat producer to economize on its use of the water resource for waste disposal to the extent that this use precludes other valuable uses or decreases economic productivity in other uses. The economization of the water resource for waste heat disposal implies that a higher cost will be incurred by the electric utility through reducing the cooling water quantities, treating the thermal discharge to reduce damage, altering the characteristics of the disposal mode, or adopting some optimal combination of the pollution abatement measures available. It is also assumed that the various technical abatement alternatives will be available and the cost minimization motive will result in the firm adopting its own most efficient combination. Finally, overall social efficiency dictates that reductions in the external costs should be achieved only to the point where reductions do not involve greater expenditures of other resources on abatement measures than the benefits derived from the abatement.

Thus, an efficient waste heat abatement program would not suggest that environmental waste disposal be entirely prohibited nor would it imply that there will always be an economically justifiable level of thermal pollution reduction in all cases. The whole concept of efficiency in thermal pollution management requires a striking of a balance between social benefits of abatement and its social costs. Also, in those cases where the waste heat discharge results in benefits, the efficiency of social economy dictates that the heat discharge be increased as long as the costs of the increase are less

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than the resulting increase in benefits.

One example of the external costs of thermal pollution is the increased loss of water by evaporation which is not usually considered in decisions regarding the production or disposal mode. The evaporative losses will cause an increase in the dissolved solids concentration and may require desalination or dilution supplies to restore water to the original quality.

Another possible economic cost of thermal pollution is the economic loss experienced at a downstream power plant if it is forced to use cooling water which is warmer than that which would have been naturally available had there been no thermal discharge upstream. A number of factors have to be considered in the analysis of this question. Dilution of the heated discharge takes place with the resulting downstream temperature falling between that of the natural river and heated discharge unless the upstream plant withdraws the entire streamflow. There is also a temperature decrease due to the natural process of heat dissipation in the river prior to the withdrawl of cooling water downstream unless the second plant is only a short distance away. Given a sufficient distance between plants, the river would cool back to ambient conditions. Finally, natural causes may impart heat to the river instead of causing cooling and this would result in the added heat due to thermal discharge being superimposed on natural effects.

A decrease in the total electric generation capability and plant thermal efficiency, resulting in an increase in cost per kwhr of electricity generated, would be the result of a downstream power

plant using warmer condenser water than would naturally be available. Löf and Ward (1970) developed an equation to determine this cost in mills per 1,000 gallons of water used in the condensers. The equation for net additional capital cost considers: the initial capital cost of the plant, the steam-cycle efficiency, the turbine-generator efficiency, the fractional decrease in the plant load factor, the temperature change in water passing through the upstream thermal discharge, the present load factor of the plant, the power plant design life, and the natural temperature of cooling water. For typical values and a $10^{o}$ F increase in the inlet cooling water temperature, the additional capital cost of power generation equipment was about 1.0 mill/1000 gallons of cooling water circulated. This increase in capital cost would be accompanied by an operating cost increase caused by higher fuel use to meet the fixed electrical demand. An equation was also developed for this cost considering: the fuel costs, the boiler efficiency, and the overall efficiency of generation. Again, with substitution of typical values, the additional fuel cost for a $10^{o}$ F rise in cooling water temperature due to an upstream thermal effect would be 1.2 mills/1000 gallons circulated. Thus, the total cost increase for a $10^{o}$ F rise would be 1.0 mill capital cost plus 1.2 mills fuel cost, or about 2.2 mills per 1000 gallons of cooling water flow. For a flow rate of 50 gallons/kwhr of condenser water generated, the increase would, therefore, be 0.1 mills/kwhr. Unless this cost were avoided by means of supplementary cooling devices, there would be an increase of about 1% in total generation costs. These effects could be doubled for river

temperatures artificially raised 20$^o$ F.

Thus, excessive thermal discharge would probably have a small effect on an individual downstream powerplant, but the cumulative effects of successive thermal discharges could be more serious. It has been estimated that if 10% of the total power generation were affected by an average rise in condenser inlet water temperature of 10$^o$ F, the additional cost of generating this 125 billion kwhr would be $12 million dollars, according to Löf and Ward (1970). These figures for the off-site costs of thermal pollution were shown to be considerably less than the on-site costs of preventing thermal pollution, which are discussed in another section of this paper. Thus, the economic damages to subsequent users for cooling purposes in power generation would not be as great as the cost of preventing the discharges in the first place. The comparison included these assumptions: use of recirculation cooling by an upstream plant would be dictated only by regulations; internal economies obtained by once-through cooling would not be enough to equal off-site damages; and other downstream effects of increased thermal discharge were not considered.

Thus, no economic incentive could be shown for the elimination of thermal discharge upstream merely to reduce the temperature of the inlet cooling water supply. However, if regulations were established to levy charges or penalties for thermal discharge, an incentive would be provided for the use of abatement techniques. This assessment of power plants for thermal discharge could be effectively added to the cost of once-through cooling.

It should be noted that in general it is difficult to give a precise evaluation of the additional costs which a given utility will have to bear in the expansion of a given system as a result of the imposition of thermal standards. The additional costs incurred for a new plant may not be simply equal to the actual cost of the abatement alternatives. The operating cost of the plant will also have to be considered due to the losses in plant performance as a result of intake water at elevated temperatures in some cases.

In the more complicated regional case where several new plants are to be built within a design period and where many site and plant alternatives are available, the answer concerning the cost increments and locational effects due to thermal standards is not evident. This fact has necessitated the study of these costs through a systematic approach to a general locational problem relating the direct costs of environmental control to other factors determining plant location such as air pollution, fuel costs, etc.

III. B. Development of Cost Aspects for Abatement Alternatives

If the electric utility management strives to minimize abatement costs, the costs of controlling thermal pollution will become a function of the technical possibilities available to meet the standards, the cost function for undertaking the best available alternative, and the level of abatement which the control objective implies, according to Cheney, et. al. (1969). These factors will vary with plant characteristics and different locational circum-stances. Another difficulty in determining the prospective plant

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abatement costs is that regulatory standards, which determine the required level of abatement, are still in a formative stage and individual situations are, therefore, subject to a substantial degree of discretionary judgement by State regulatory agencies. An effort will be made, nonetheless, to provide a basic perspective on the cost of the individual plant abatement programs where possible.

The cost of thermal pollution control represents the additional net cost incurred by the electric utility over the cost of producing electricity in the absence of control. Since a rational cost-minimizing abatement program for the individual generating plant may involve some combination of measures, such as site reselection and in-plant redesign, it becomes extremely difficult to calculate the addition to the net cost attributable specifically to thermal discharge in a precise manner.

This section will survey the more significant types of private costs together with the important environmental variables that condition the feasibility of alternative waste disposal techniques. The representative cost calculations developed in recent literative will be developed as a guide to these costs.

The FPC has developed some cost data for the various cooling water systems. The installation costs which were developed exclude the cost of condensers and auxiliaries, but include such items as pumps, piping, canals, ducts, intake and discharge structures, dams and dikes, reservoirs, cooling towers, and appurtenent equipment. The following table summarizes these costs:

## Table 3.1

Comparative Costs of Cooling Water Systems for Steam Electric Plants

| Type of System | Investment Cost, ($/kw) | |
| --- | --- | --- |
| | Fossil-fuel plant* | Nuclear plant* |
| Once-through** | 2.0 - 3.0 | 3.0 - 5.0 |
| Cooling ponds*** | 4.0 - 6.0 | 6.0 - 9.0 |
| Wet cooling towers: | | |
| Mechanical draft | 5.0 - 8.0 | 8.0 - 11.0 |
| Natural draft | 6.0 - 9.0 | 9.0 - 13.0 |

*Based on unit sizes of 600 Mw and larger

**Circulation from lake, stream, or sea and involving no investment in pond or reservoir

***Artificial impoundments designed to dissipate the entire heat load to the environment. Cost data are for ponds capable of handling 1,200 to 2,000 Mw of generating capacity.

from: FPC (1969)

In another study, the following FPC data was used in determining the added investment in cooling facilities for the National Power Survey of 1970:

## Table 3.2

### Unit Costs for Various Cooling Facilities ($/Kw)

| Type of System | Fossil-fueled plant | Nuclear plant |
| --- | --- | --- |
| Once-through fresh water | 3.0 | 4.0 |
| Once-through saline water | 4.0 | 5.0 |
| Once-through saline water with outfall | 9.0 | 13.0 |
| Cooling pond | 5.0 | 7.0 |
| Cooling tower | 7.0 | 10.0 |

from: Warren (1969)

The comparison which will be made of thermal pollution abatement alternatives by means of the developed models will consider economics, local climatological conditions, unit size, and the

secondary effects. In a report of this nature, there were certain assumptions which had to be made in order to compare and determine economic costs. In the instances where this was necessary, the assumptions were clearly stated with the possible variations.


III. B. 1. Plant Location

The plant location alternative will involve a cost trade-off. The costs of selecting a site with the minimum thermal pollution which may result in higher generating and transmission costs will have to be compared with a site which would minimize the sum of these three direct costs. The difference could be considered as the cost of thermal pollution abatement.

Also, the extremes in temperature, relative humidity and other climatological conditions may affect cost of the cooling system. According to Dynatech (1969), the plant location can also have a considerable effect on economics in the case of a mine-mouth plant where higher cooling costs are offset by lower fuel costs. The availability of water at a site is another economic consideration along with the water quality which must also be considered since water treatment will increase the cost for the required chemicals and due to the increased maintenance costs. If cooling towers are employed, the topography of the surrounding region may cause the vapor plumes to remain in the vicinity of the plant or poor draft patterns to arise resulting in increased costs due to performance losses. The climatological factors of principal importance in determining the economic aspects of the thermal pollution

alternatives in power plant siting are temperature, wind, and the precipitation amount.

### III. B. 2. Plant Operation

In the waste heat production process alternative for existing plants, the cost of abatement to the utility would be the difference between the higher cost of producing the same amount of electricity elsewhere in the system or purchasing the electricity elsewhere, and the lower cost which would have been incurred at the plant where output is now foregone, according to Cheney, et. al. (1969). In some cases, the recommended generation plan may call for discontinuing operation of an existing plant. This would involve a cost equal to the net loss suffered by the utility over the expected remaining life of the plant.

### III. B. 3. Waste Heat Disposal

The waste heat disposal systems which were considered in the development of the cost aspects were the once-through system with either a surface discharge or a diffuser, cooling ponds, spray canals, and wet mechanical cooling towers. Unfortunately, the time restrictions on the publication of this report prevented detailed development of the economic aspects of wet natural draft cooling towers, and cooling towers and combination systems.

Once-Through System. An operating expense which must be considered in all thermal pollution abatement systems is the cost of the power plant or loss in plant output required to pump the water

through the system. The annual operating and maintenance costs for this once-through type of system would be relatively small except for these pumping costs.

In Dynatech (1969), the equipment cost developed for the once-through system included the cost of the condenser, the associated pumps and piping, the heat rejection unit, and the accessories. The operating costs included the power costs for the pumps and the costs for make-up and treatment water. The power requirements for the pumps were determined and the cost of power was estimated at 4 mills/kwhr. The maintenance costs were set equal to the power cost of the circulating water system, but in Dynatech (1971) this estimate was revised to 0.1% of the total capital cost, 10% of the operating costs, and 1% of the condenser cost. Since nuclear power stations have a different rate of heat rejection due to plant efficiency differences and in-plant losses, calculations were made in the study for both fossil and nuclear plants with temperature rises of $10^{\circ}$ F and $20^{\circ}$ F. The fossil plant was assumed to have a 40% plant efficiency, 15% in-plant loss, and a heat rejection of 3,840 BTU/kwhr, whereas the nuclear plant had a 33% plant efficiency, 5% in-plant loss, and a 6,410 BTU/kwhr heat rejection rate. The results for the once-through cooling were given for both river and estuary sites. (see table 3.3.) The operating cost is made up primarily of pump power costs and it decreases for the larger temperature rise since less water is circulated. Likewise, the maintenance costs are less due to smaller pumps, and less expensive replacement equipment.

## Table 3.3

### Once-Through Cooling System Costs (Dollars)

#### River Site

|  | Fossil-fueled | | Nuclear | |
|---|---|---|---|---|
|  | $\Delta T=10^{\circ}F$ | $\Delta T=20^{\circ}F$ | $\Delta T=10^{\circ}F$ | $\Delta T=20^{\circ}F$ |
| Equipment | 5.30/kw | 5.00/kw | 5.88/kw | 5.24/kw |
| Operating | .59/kw-yr | .30/kw-yr | .99/kw-yr | .50/kw-yr |
| Maintenance | .59/kw-yr | .30/kw-yr | .99/kw-yr | .50/kw-yr |
| Circulating water rate | .76gpm/kw | .38gpm/kw | 1.28gpm/kw | .64gpm/kw |

#### Estuary Site

|  | Fossil-fueled | | Nuclear | |
|---|---|---|---|---|
|  | $\Delta T=10^{\circ}F$ | $\Delta T=20^{\circ}F$ | $\Delta T=10^{\circ}F$ | $\Delta T=20^{\circ}F$ |
| Equipment | 6.30/kw | 6.00/kw | 6.88/kw | 6.24/kw |
| Operating | .59/kw-yr | .30/kw-yr | .99/kw-yr | .50/kw-yr |
| Maintenance | .59/kw-yr | .30/kw-yr | .99/kw-yr | .50/kw-yr |
| Circulating water rate | .76gpm/kw | .38gpm/kw | 1.28gpm/kw | .64gpm/kw |

from:  Dynatech (1969)

The cost figures in table 3.3 were developed as follows. The cost of the fossil-fueled plant with a $20^{\circ}F$ temperature rise was taken from Shade and Smith (1968) who estimated the cost at $5.00/kw for the installed condenser, pumps, and piping. The Dynatech authors developed a figure of $1.32/kw for a condenser for the 1,000 Mw nuclear plant with a $15^{\circ}$ F temperature rise and a 33% efficiency. To this figure was added $0.84/kw for the circulating pumps and the total was doubled to take installation costs into account. For the intake crib an estimate was taken from Steur (1962) at $1.00/kw and then added to the total which resulted in a cost of $5.32/kw. The

pump cost was determined by using a figure of $1.0/gpm with an estimate of 0.84gpm/kw for a typical nuclear plant and 0.42gpm/kw for the fossil plant. The condenser for a marine installation was estimated at 25% more than conventional units as determined by Bauman (1964). Assuming identical installation costs, and $.50/kw for additional piping due to the marine water supply, the cost of the cooling system would rise to $6.15/kw for the 1,000 Mw nuclear plant on an estuary site. Shade and Smith (1968) gave a figure of $6.00/kw for a bay or lake cooling scheme with increase in cost due to longer piping. Finally, in Eicher (1969) an estimate was made of the additional cost of a once-through marine installation at $1.00/kw, and this relationship was used in their study to evaluate the increased cost of development of this technology at an estuary site.

In Inter Technology Corporation (ITC) (1971), detailed cost estimates have also been made for once-through condenser cooling water systems. The land requirements for this system were based on TVA plants, where the land area for the entire site was determined to depend primarily on the site location of the alternate, and thus no universal correlation was attempted. With no technological advancements deemed possible in this area, a nominal value of $400/ acre was assigned for this land cost. The cost data analyzed was found to vary from $200 to $1,400/acre on TVA plants for 750 to 1,750 acre sites. Since the cost of land improvements were also variable a reasonable nominal value was assigned. The cost of land improvements ranged from $7 to $740/acre and were typically $35/

acre. The maximum cost of $740/acre is a lone point and most were under $50/acre.

The pump and motor cost correlations of their study were the least successful. However, the plant data and chemical engineering literature indicated the combined cost of pumps and motors is proportional to the hydraulic power output to the 0.568 power. This relationship was then adjusted by means of a cost coefficient for each application. Cost data for the circulating water system pumps was presented in 1962 dollars for a maximum flow rate of 150,000 gpm. The condenser cooling water intake structure costs were also presented in 1962 dollars. The cost of the intake lines was based on the length of the lines and thus was found to be almost independent of the flow rate and the same could be said of the discharge lines. The cost of the intake lines was in 1962 dollars and most of the data presented for the 10 Tennessee Valley Authority (TVA) plants indicated intake lines of less than 1,000 feet length. The cost of the discharge line, where the length range was from 500 to 2,500 feet in length, were again presented in 1962 dollars  The equations developed for these elements of the once-through system are presented in tabular form. (see table 3.4) The ITC study also presented cost trends for bringing the 1962 costs up to present levels and these figures indicate a factor of approximately 1.50 would be appropriate for the condenser cooling water system, not including the cost of the condenser itself.

The FPC (1969) and Warren (1969) have also presented unit cost data which are given in the following tables. (see table 3.5

## Table 3.4

### Cost Equations from ITC Study

**Land Cost**

| | |
|---|---|
| Land | Cost=$400/acre |
| Land Improvements | Cost=$ 35/acre |

**Circulating Water System**

Pumps and Motors (150,000 gpm max.)
$$Cost=\$100,000 \left(\frac{Power\ Output,\ hp}{700}\right)^{0.58}$$

Intake Structure*  Cost=$100,000 + 1.15 (gpm to condenser)

Intake Line*  Cost=$ 90,000 + $630 (length, ft)

Discharge Line*  Cost=$760 (length, ft)

Other (controls and equipment)
$$Cost=\$1.75 \times 10^6 \left(\frac{gpm\ to\ condenser}{10^6}\right)^{1.72}$$

*Costs in 1962 dollars

from: ITC (1971)

and table 3.6) The data indicate that the cost for a once-through cooling system will generally range from $2.0/kw for a fossil plant with fresh water to $13.0/kw for a nuclear plant with saline water and a diffuser.

## Table 3.5

### Once-Through System

**FPC Investment Cost Data, ($/kw)**

| Fossil-fuel | 2.0 -3.0 | Nuclear | 3.0 - 5.0 |
|---|---|---|---|

Note: excludes condenser cost and auxiliaries, but includes such items as pumps, piping, canals, ducts, intake, and discharge structures

from: FPC (1969)

Table 3.6

## Once-Through System

FPC Investment Cost Data, ($/kw)

|                          | Fossil-fuel | Nuclear |
|--------------------------|-------------|---------|
| Fresh water              | 3.0         | 4.0     |
| Saline water             | 4.0         | 5.0     |
| Saline water with outfall | 9.0        | 13.0    |

from: Warren (1969)

In Bayer (1969), a study was made of the cost of pumps for a water pumping system. The costs considered were the fixed costs of capital cost and operating, maintenance, and repair and the variable costs of the energy associated with the pumping.

The capital cost developed included the investment cost of all parts of the pumping installation: pumps and pump drives (including standby equipment), the water pipes, power transmission and control facilities, valves and performance instrumentation, the pump house, surge prevention or protection devices, etc. The report assumed there is no significant correlation between unit cost and pumping head and this led to using the installed horsepower as the only variable in the cost equation. This practice has been generally accepted in preliminary evaluations. The relation given between installed horsepower and installation cost was

$$C = 367 \ (HP)^{0.90} \quad \text{for } 100 \leq HP \leq 100,000 \qquad (3\text{-}1)$$

$$C = 1307 \ (HP)^{0.66} \quad \text{for } 30 \leq HP \leq 400 \qquad (3\text{-}2)$$

where

$C$ = pump station cost in 1967 dollars

$HP$ = total installed horsepower

The annual operating, maintenance, and repair cost was also

given for pump staticns. The relation developed was

$$OMR=24 \ (HP)^{0.94} \ \text{for} \ 100\underline{<} \ HP \ \underline{<}100,000 \tag{3-3}$$

where

OMR=operating, maintenance, and repair cost in 1967 dollars

These annual costs for operating, maintenance, and repair amount to

approximately 8 - 10% of the total investment cost. The Engineering

News Record Construction Cost Index was recommended to bring these

costs up to present levels with the applicable factors as 1807./

1070. which is equal to approximately 1.70. This results in a

discrepancy between the ITC factor of 1.50 for 1962 to 1973, and the

ENR factor of 1.70 for 1967 to 1973. The author has chosen to use a

value of 1.60 for the 1962 to 1973 period and 1.50 for the 1967 to

1973 period since a majority of the inflationary increases in cost

have occurred in the second-half of the past decade.

The cost aspects of the once-through system with a surface dis-

charge were determined in the following manner for use in this

study. In order to make the cost model consistent with the analysis

of other abatement technologies a land cost of $400/acre and a land

improvement cost of $35/acre were included. The cost of the pumps,

motors, and the pumping station were estimated to be equal to:

$$CAPCO3=367 \ COSFA1 \ (HORPOW)^{.90} \tag{3-4}$$

where

CAPCO3=capital cost of pumps, motors, and pumping station, 1973

dollars

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COSFA1=cost factor to 1973 level=1.50

HORPOW=total installed horsepower for circulating water system

The intake structure was evaluated as follows:

$$CAPCO4=(100,000 + (1.15 \text{ GPM})) \text{ COSFA2} \qquad (3-5)$$

where

CAPCO4=capital cost of intake structure, 1973 dollars

GPM=total circulating water flow, gallons/minute

COSFA2=cost factor to 1973 level=1.60

The intake line was costed according to the following equation:

$$CAPCO5=(90,000 + (630 \text{ LENGT1})) \text{ COSFA2} \qquad (3-6)$$

where

CAPCO5=capital cost of intake line, 1973 dollars

LENGT1=length of intake line, feet

Due to the lack of information in the literature on cost data for surface discharge canals, a 1973 dollar level of $800/foot of length was assumed. The resulting equation is:

$$CAPCO6=800 \text{ LENGT2} \qquad (3-7)$$

where

CAPCO6=capital cost of discharge canal, 1973 dollars

An item was also included for controls and connections according to the following formula:

$$CAPCO7=1.75 \; 10^6 \left(\frac{\text{GPM}}{10^6}\right)^{1.72} \qquad (3-8)$$

where

CAPCO7=capital cost of other equipment, 1973 dollars

In order to differentiate among the various site type alterna-

tives, the following typical lengths were chosen for the intake pipe

and surface discharge canal. (see table 3.7) These values were

obtained from a survey of current plants on this type site and the

TVA data given in the ITC (1971).

## Table 3.7

### Intake and Discharge Length Data

| Site Type | Intake Line, (ft.) | Discharge Canal, (ft.) |
|-----------|--------------------|------------------------|
| River | 1,100 | 900 |
| Great Lake | 1,900 | 1,000 |
| Coastal | 1,900 | 1,000 |
| Offshore Ocean | 300 | 300 |
| Estuary | 1,100 | 900 |
| Small Lake | 1,100 | 900 |
| Water Poor | — | — |

The operating, maintenance and repair costs may be considered

as either fixed or variable over the design life of the facilities.

The fixed operating costs will generally apply to equipment which

will be constantly in use, whereas the variable operating costs

would depend upon the capacity factor of the power plant. The

variable operating costs are frequently made up of the cost of power

to run the pumps but since this study considers this power as a

deduction from total plant output, the variable operating, main-

tenance, and repair costs were assumed equal to zero. The model

does have the capability of incorporating this type of cost, how-

ever, if necessary in future work. The fixed operating, maintenance,

and repair costs were estimated for the pumps, motors, and pumping

station according to the following relation:

$$FOCTA = 24.0 \ COSFA1 \ (HORPOW)^{.94} \tag{3-9}$$

where

FOCTA=fixed operating costs of thermal pollution abatement

equipment, dollars/year

The diffuser alternative of the once-through discharge system

used the same cost equations for capital and operating costs as the

surface discharge alternative with the following exceptions. A dis-

charge line from the plant was used instead of the discharge canal

and it estimated according to the following relation:

$$CAPCO8=760 \ LENGT3 \ COSFA2 \qquad (3-10)$$

where

CAPCO8=capital cost of discharge line, 1973 dollars

LENGT3=length of discharge line, feet

Also, the diffuser pipe was computed by the following equation:

$$CAPCO9=760 \ LENDI \ COSFA2 \qquad (3-11)$$

where

CAPCO9=capital cost of diffuser, 1973 dollars

LENDI=computed length of diffuser, feet

The intake lines were assumed to be the same for the diffuser

alternative as the values given in table 3.7 for the surface dis-

charge, but the length of the discharge pipe was assumed to have the

lengths given in the following table. (see table 3.8) The diffuser

length is computed for each plant alternative by the appropriate

subroutine and thus it becomes a calculated value.

The coastal, estuary, and offshore ocean marine sites required

salt water to be passed through the circulating water system.

Upon a review of the results presented in this section the author

## Table 3.8

### Discharge Pipe Length Data

| Site Type | Discharge Pipe, (ft.) |
|---|---|
| River | 1,400 |
| Great Lake | 2,000 |
| Coastal | 2,000 |
| Offshore Ocean | 300 |
| Estuary | 1,400 |
| Small Lake | 2,000 |
| Water Poor | — |

has determined that a capital cost increase of 20% for the pumps, motors, and pumping station and a fixed operating, maintenance, and repair cost increase of 10% would be reasonable estimates of this additional cost for the once-through system.

Finally, the total capital cost of thermal pollution abatement equipment was computed by summing the individual components. The capital cost of the abatement alternative per installed kw was also calculated and presented in the output for a comparison with the currently available values.

Cooling Ponds. The use of artificial cooling ponds is costly in terms of land purchase and development since one surface acre plus the shoreline area is generally required per megawatt of generating capacity. According to Cheney, et. al., (1969), the costs will depend on land values, topography, soil type and other geophysical factors which affect construction and maintenance outlays. Since these factors vary considerably with location, the costs of cooling ponds can be expected to vary over a wide range, and generalizations will be difficult. The water loss due to evaporation can be somewhat higher in cooling ponds than for

alternative systems since a differential increase in natural evaporation will occur, even at zero heat load, over the entire surface area of the pond and this loss could be charged to the plant. No attempt was made to cost the consumptive use of water in this study, but the consumptive use was considered as a resource for the siting constraints. The use of the cooling pond method will also usually involve the same plant intake structure and pumping costs as the once-through system.

Over nineteen steam-electric plants accounting for approximately 3% of the thermal generating capacity use artificial cooling ponds, according to Cheney, et. al., (1969), and this indicates that this method can be the least-cost alternative where locational factors are favorable. The engineering cost calculations of Steur (1962) indicate that where land cost is reasonable and make-up water is available, cooling ponds can be provided at a lower cost than cooling towers. It should be noted, however, that the costs assumed by Steur were very favorable and it is not likely that many plant sites could be found with such favorable land and development costs. Therefore, the cooling pond alternative can be expected to provide a least-cost solution only at a small minority of the available power plants.

The construction of a cooling pond requires creation of an artificial lake by damming and/or excavating. Hydrological studies are required to assure sufficient rainfall or runoff is available to make up losses, and a pumping system may be required to provide this make-up supply. It should be noted at this point, however,

that the cooling pond considered in this study was assumed to be used only in closed cycle operations and due to the thermal standards imposed on existing classified water bodies, the cooling pond on a natural water body was considered as a surface discharge on an existing small lake or reservoir. Thus, the cost alternatives developed for this technology are only applicable to a completely constructed cooling pond with dikes, excavation, etc. where no natural body of water existed previously. The cost of the pond, according to ITC (1971), can be estimated on the basis of the cost of land plus $400/acre for improvements and alterations required to form the cooling pond. The other elements considered in that study for the total capital cost of the cooling pond system were the intake line, discharge line, pumps, and other equipment.

The FPC (1969) and Warren (1969) have presented unit cost data which are given in the following tables. (see table 3.9 and table 3.10) The data indicate a range in investment cost of cooling ponds from $4.0/kw for a fossil-fueled plant to $9.0/kw for a nuclear unit.

Table 3.9

Cooling Pond System

FPC Investment Cost Data, ($/kw)

Fossil-fuel    4.0 - 6.0    Nuclear    6.0 - 9.0

Note: excludes condenser cost and auxiliaries, but includes such items as pumps, piping, canals, ducts, intake and discharge structures, dams and dikes, and reservoirs.

from: FPC (1969)

Table 3.10

Cooling Pond System

FPC Investment Cost Data, ($/kw)

| Fossil-fuel | Nuclear |
|-------------|---------|
| 5.0 | 7.0 |

from: Warren (1969)

Thus, the cost of a cooling pond itself will be mainly a function of the land requirements. The work of Shade and Smith (1968) used a land cost at $1,000/acre, including the required modifications. This compares well with the ITC (1971) total cost of $800/acre. The estimate of Kolfat (1968), Steur (1962), and Eicher (1969) were for an additional cost of a cooling pond as $2.50/kw over the cost of a once-through system. This figure was developed by an estimate of a 2.0 acre/Mw pond, and with $1,000/ acre for land and excavation, and the remaining $0.5/kw for piping, dams, etc.

The cooling pond cost developed in Dynatech (1969) was $6.50/ kw for fossil plants and $7.50/kw for nuclear plants in order to account for the greater amount of land required with a nuclear plant. However, this cost included the condenser, the associated piping and pumps, the heat rejection units, and the accessories. Since different condenser arrangements were possible, the equipment cost was not given as an increase over the once-through system. The cost of power for the pumps, and for make-up and treatment water are included in the operating cost. The power requirements were determined for the pumps and converted to cost at 4 mills/kwhr.

The maintenance cost was estimated as equal to the power costs for

the pumps of this cooling system alternative for the study, but

revised in Dynatech (1971) as was noted in the once-through system.

The water loss, determined as a percentage of the flow rate, was

used to determine the power requirements for the make-up water

pumps in their study. Since both fossil and nuclear plants have

different heat rejection rates, separate calcuations were made for

each plant type. The same typical plants were used as those

described in the section on once-through cooling systems. The

results for the cooling pond were as follows:

Table 3.11

Cooling Pond System Costs (Dollars)

| | Fossil-fueled | | Nuclear | |
|---|---|---|---|---|
| | $\Delta T = 10^\circ$ F | $\Delta T = 20^\circ$ F | $\Delta T = 10^\circ$F | $\Delta T = 20^\circ$ F |
| Equipment | 6.50/kw | 6.50/kw | 7.50/kw | 7.50/kw |
| Operating | .74/kw-yr | .38/kw-yr | 1.24/kw-yr | .62/kw-yr |
| Maintenance | .74/kw-yr | .38/kw-yr | 1.24/kw-yr | .62/kw-yr |
| Circulating Water Rate | .76gpm/kw | .38gpm/kw | 1.28gpm/kw | .64gpm/kw |

form: Dynatech (1969)

The cooling pond cost model used in this report was developed

in the following manner. The land cost was computed at $400/acre

and the cost of land improvements, including the construction of

the cooling pond, was also assumed to be $800/acre. The cost

equations used for the pumps, motors, and pumping station; the

intake structure; a discharge canal; and the other equipment were

the same as the ones developed in the once-through system. No

intake line was required for this abatement alternative. The

typical lengths were revised, however, and for the discharge canal

a length of 500' was assumed as typical for all sites.

The make-up water system must also be considered in the cost

analysis of the cooling pond. In this case the cost of pumping was

estimated according to the following relation:

$$CAPCOA=1307 \ (HORPWR)^{.66} \ COSFA1 \qquad (3\text{-}12)$$

where

CAPCOA=capital cost of pumps, motors, and pumping station, 1973

dollars

HORPWR=total installed horsepower in make-up water system

No estimate was made for an intake structure in the make-up system

due to the relatively small quantities of water required for this

purpose. An estimate was made, however, for an intake make-up pipe

to convey the water from the source to the cooling pond. The length

of this line was assumed equal to 1,000 feet for all site types and

the following cost relation was developed. A unit cost of \$300/foot

was assumed for the cost of this pipe.

$$CAPCOB=LENGT4 \ COSMAK \qquad (3\text{-}13)$$

where

CAPCOB=capital cost of make-up water pipe, 1973 dollars

LENGT4=length of make-up water pipe, feet

COSMAK=unit cost of make-up pipe, dollars/foot

A blowdown line will be required to carry off blowdown water from

the cooling pond. This pipe size will normally be significantly

smaller than the make-up line due to the evaporative losses from the

pond, and thus the cost relation developed used a unit cost of

$200/foot for this pipe.The length of this line was also assumed

equal to 1,000 feet for all site types.

$$CAPCOC=LENGT5 \ COSBLD \tag{3-14}$$

where

LENGT5=length of blowdown pipe, feet

COSBLD=unit cost of blowdown pipe, dollars/foot

The fixed annual operating, maintenance, and repair costs for this

make-up system were computed in this estimate according to the

following relation:

$$FOCTM=24 \ (HORPWR)^{.94} \ COSFA1 \tag{3-15}$$

where

FOCTM=fixed operating costs of make-up water system, dollars/

year

The fixed and variable operating, maintenance, and repair costs

were estimated according to the cost relationships developed for the

once-through system with the addition of a fixed operating cost for

the make-up water system, FOCTM.  The total fixed operating cost was

the sum of two components, FOCTC and FOCTM.  The total capital cost

of the cooling pond was computed as the sum of the capital costs of

the individual components and a capital cost per kw was also cal-

culated for this abatement technology.

The coastal and estuary marine site types which

would result in the closed cooling pond system using salt water in

the cooling pond systems were subjected to an increase in capital

cost of 20% for pumps, motors, and pumping station and an increase

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of 10% was placed on the fixed operating, maintenance, and repair costs. These figures are in addition to the extra make-up water pumping costs caused by the build-up of the salt concentration in the circulating water.

Spray Canals. The sizing and capital costs for a spray pond alternative would be approximately 0.1 acres/Mw and $1,000/acre of land requirement, according to Dynatech (1969). The spray pond system capital cost would therefore be about $2.50/kw in addition to the base cost and this includes piping, nozzles, pumps, and installation along with a simple single-pass condenser, a circulating water pump, a screen house, and the piping.

The spray pond cost used in their study was $8.10/kw for a nuclear plant since large pumps are required. It should be noted that this cost includes the price of condenser, the associated pumps and piping, the heat rejection unit, and the accessories. Also, the total equipment cost was not given as an increase over the cost of a once-through system since some schemes may require different condenser arrangements. The operating costs were made up of the power costs for the pumps and the costs for make-up and treatment water. The power requirements were determined for the pumps and converted to dollars at a rate of 4 mill/kwhr. The water loss was determined as a percentage of the flow rate and used to determine the power requirements for the make-up water pumps. Calculations were made for both fossil and nuclear plants since nuclear have a significantly different rate of heat rejection due to different efficiencies and in-plant losses. The assumptions made for the typical plants

were the same as those used in the section on once-through cooling

systems. The results for the spray pond were as follows:

Table 3.12

Spray Pond System Costs (Dollars)

|  | Fossil-fueled | | Nuclear | |
|---|---|---|---|---|
|  | $\Delta T=10^\circ$ F | $\Delta T=20^\circ$ F | $\Delta T=10^\circ$ F | $\Delta T=20^\circ$ F |
| Equipment | 7.60/kw | 7.60/kw | 8.10/kw | 8.10/kw |
| Operating | 1.18/kw-yr | .60/kw-yr | 1.98/kw-yr | 1.00/kw-yr |
| Maintenance | .59/kw-yr | .30/kw-yr | .99/kw-yr | .50/kw-yr |
| Circulating Water Rate | .76gpm/kw | .38gpm/kw | 1.28gpm/kw | .64gpm/kw |

form: Dynatech (1969)

The operating costs decrease for the larger temperature rise since

less water is circulated. Maintenance, which was not estimated to

be equal to the pump power costs in this case since it was felt that

this yielded an excessive cost for this alternative, are lower due

to the smaller pumps, and less expensive replacement parts. It

should be noted that the costs developed in the Dynatech study were

for the spray pond alternative, not the spray canal alternative

evaluated in this study.

In the ITC (1971) report the capital cost of the spray pond

itself was evaluated in the same manner as the cooling pond. This

method of evaluation was discussed in the previous section on

cooling ponds and are briefly repeated at $800/acre including both

the land and preparation cost.

Discussions with Mr. Patrick Ryan, a Research Assistant and

doctoral candidate at M.I.T. in the Water Resources and Hydrodynamics

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Division, who has presented numerous works referenced in this report for surface heat exchange and cooling ponds (see Ryan (1972) and Ryan Stolzenbach (1972)), provided the author with a cost estimate of $17,000/spray module at present price levels with significant increase in this capital cost for use in a saline water environment.

The development of the spray canal model closely followed the procedure for the cooling pond alternative. The total land cost was calculated at $400/acre required for the construction of the spray canal. The construction costs were estimated by dividing the total water surface area requirement AREAAC, in square feet by the assumed canal width of 160 feet to determine the total length of the canal, CANLEN. The cost was then estimated according to the following relation:

$$CAPCOD=800 \ CANLEN \tag{3-16}$$

where

CAPCOD=capital cost of spray canal, 1973 dollars

CANLEN=length of spray canal, feet

The cost equations used for: the pumps, motors, and the pumping station; the intake structure; the make-up water system; and the other equipment were the same as the ones developed in the cooling pond system. Again, no intake line was required for this abatement alternative. However, in this alternative no discharge canal was included, and a cost of spray modules was included for the canal system, at $17,000/spray module. The fixed and variable operating, maintenance, and repair costs were also estimated according to the cost relationships developed for the cooling pond system. The total

capital cost was computed as the sum of the component capital costs
and the capital cost per kw was again computed. Finally, the
cost increases due to the use of saline water at the coastal
and estuary sites was estimated in the same manner as was followed
for the cooling pond with a 20% increase in capital cost and
a 10% increase in the fixed operating, maintenance, and repair
costs.

Cooling Towers. Both the capital and operating costs of mechani-
cal draft wet cooling towers are sensitive to plant operating condi-
tions which determine the water temperature reduction range required
by the cooling process, according to Cheney, et. al. (1969). The
ambient atmospheric temperature and relative humidity conditions are
also important since they determine the evaporation rate and technical
cooling efficiency of the tower. It has been determined that the
costs of the tower cooling vary in a positive exponential manner as
the tower exit temperatures are required to approach the ambient
wet-bulb temperature since the evaporation rate and technical
efficiency of the tower decrease progressively as the water tempera-
ture approaches that of the air. The most economical manner of
operation is generally to sacrifice some thermal efficiency by
operating the condensers at higher steam cycle exit temperatures in
order to save on the cooling costs. Also, for a given cooling tower
approach temperature, capital and operating costs of towers per unit
of heat removal have been found to vary inversely within the
required temperature cooling range. This is related to the fact

that tower costs are primarily dependent on the flow of cooling water, and since hotter intake water transfers more heat per unit flow, the lower flow rate of hot water would reduce the investment and operating costs of cooling towers for generating plants of a given size. These technical characteristics of the tower cooling process mean that overall design efficiency will usually require a trade off between reduced circulation costs and increased condenser investment costs in order to minimize their combined cost per kwhr.

This section will present a brief summary of the cost of preventing thermal discharge by means of cooling towers and the development of the model used to cost the wet mechanical draft cooling tower. The capital costs of the towers are a function of the water flow required, the prevailing wet-bulb temperature of the air, the water temperature change through the tower, and the temperature of the water delivered from the cooling tower to the stream. The total capital cost of a forced draft type cooling tower may be taken as approximately $8.00/gpm times a relative rating factor K for the cooling tower according to Löf and Ward (1970). The value of K for the forced draft type of tower varies from 0.4 to 3.0 and indicates the relative size of the tower compared to one for the same flow at standard conditions. This factor is a function of the condenser inlet temperature, the cooling range, which represents the difference between the temperature of the water from the condenser before cooling and the desired final discharge temperature. It should be noted that this cost figure is based on the water circulation rate through the plant, and not on the power capacity.

These bases, however, are related to each other with their ratio depending on power plant efficiency and the cooling range. Löf and Ward also provided an example of 38% efficiency, $15^{\circ}$ F cooling range, with inlet temperature $10^{\circ}$ F above wet-bulb and determined the capital cost for a conventional wet mechanical cooling tower would be approximately 3 mills per 1,000 gallons of cooling water circulated. They also developed relations for the costs of operation in mills per 1,000 gallons circulated. However, in this case the costs of operating the towers in a recirculating mode was included in the cost equation making it impossible to separate out the cost of operating the tower as a treatment alternative rather than as a closed system. The figures developed can, however, be applied as an upper limit of the operating cost for the operation in a combination system since it would be more expensive to operate the towers in a recirculating mode. The equation developed considered the cooling range, cycles of concentration, alkalinity, cost of make-up water, the relative rating factor for the cooling tower, and the cost of electric power. Under typical conditions the cost was determined as approximately 5.0 mills per 1,000 gallons. Thus, the total cost of cooling tower operation as a waste heat treatment alternative would be 8.0 mills per 1,000 gallons of water circulated in a closed cycle system, and somewhat less if operated in a combination system. For a water temperature increase of $15^{\circ}$ F through the condensers at an average plant efficiency of 35%, 43 gallons/kwhr of cooling water would have to be circulated. In this case the total cost of cooling tower operation for recirculation would be

about 0.3 to 0.4 mills/kwhr generated above the cost of once-through cooling. This amount represents 5 to 7% of the generation cost, and 2 to 3% of the combined generation and distribution costs. Thus, for a 1000 Mw plant, 0.3 mills/kwhr with the plant operated 80% of the time, would result in a total additional annual generating cost of $2.1 million.

According to Dynatech (1969), the initial costs of the wet mechanical draft cooling tower system would be a strong function of plant location which affects land costs, installation and accessory costs, and the design ambient conditions. The costs presented in their study were for the complete cooling tower system including the tower, the plant condenser, piping, etc. The initial tower costs were defined to include the capital cost, the installation cost, and the accessory capital costs and the annual operating costs were stated to encompass the costs of power for pumps, fans, etc., maintenance, water treatment, make-up water, and sewer charges. Kolfat (1968) estimated the cost of an induced draft mechanical tower would add $6/kw to the plant cost, but this value is highly dependent upon the desired approach and difficult to generalize.

In the Dynatech (1969) study the wet mechanical draft cooling tower cost presented was $7.20/kw for a fossil-fueled plant. This cost included the condenser, its associated pumps and piping, the wet cooling tower, and its required accessories. The cooling system cost was not given as an increase over the once-through cooling system since some of the technological alternatives considered required different condenser arrangements. The costs developed were

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for both a fossil-fuel and a nuclear plant and are given below. (see table 3.13) The typical plants described in the section on once-through cooling were used in the computations. The calculations were again performed for condenser temperature rises of $10^\circ$ F and $20^\circ$ F.

Table 3.13

Wet Mechanical Draft Cooling Tower System Costs (Dollars)

| | Fossil-fueled | | Nuclear | |
|---|---|---|---|---|
| | $\Delta T=10^\circ$ F | $\Delta T=20^\circ$ F | $\Delta T=10^\circ$ F | $\Delta T=20^\circ$ F |
| Equipment | 7.20/kw | 7.20/kw | 9.40/kw | 9.40/kw |
| Operating | 1.54/kw-yr | .94/kw-yr | 2.34/kw-yr | 1.33/kw-yr |
| Maintenance | 1.54/kw-yr | .94/kw-yr | 2.34/kw-yr | 1.33/kw-yr |
| Circulating Water Rate | .76gpm/kw | .38gpm/kw | 1.28gpm/kw | .64gpm/kw |

form: Dynatech (1969)

The operating costs decrease for a larger temperature rise since they are based upon the power required to pump circulating water and for the fans and a smaller amount of water would be circulated in this instance causing a decrease in the power requirements. Also, the maintenance costs, which are also based on pump and fan power requirements for this study, would decrease due to the smaller pumps required and the less expensive cost of replacement parts. This type of maintenance cost estimate was revised in Dynatech (1971) to a percentage of the total capital, operating, and plant condenser costs.

In Warren (1969) and FPC (1969) unit cost data was presented which is given in the following tables. (see table 3.14 and table 3.15) The data indicate a range in the unit investment cost

from $5.0/kw for a fossil-fueled plant to $11.0/kw for a nuclear

plant.

Table 3.14

Wet Mechanical Draft Cooling Tower System

FPC Investment Cost Data, ($/kw)

Fossil-fuel  5.0 - 8.0      Nuclear fuel  8.0 - 11.0

Note: excludes condenser and auxiliaries cost, but includes cost
of pumps, piping, canals, ducts, intake and discharge
structure, cooling towers, and appurtenant equipment.

from FPC (1969)

Table 3.15

Wet Mechanical Draft Cooling Tower System

FPC Investment Cost Data, ($/kw)

| Fossil-fuel | Nuclear |
|---|---|
| 7.0 | 10.0 |

from: Warren (1969)

In ITC (1971) a methodology was also developed for the costs

of a wet mechanical draft cooling tower system. The cost of the

cooling tower was correlated on the basis of the number of tower

units. The relative rating  factor for a cooling tower is a

function of the approach temperature, the range, and the wet- bulb

temperature. The relative rating factor times the flow rate of

water through the tower in gallons/minute is defined as a tower

unit. The cost estimate was then developed as approximately

$5.0/tower unit. The total cost was made up of the tower cost,

other equipment, pumps, the intake line, and the discharge line.

The wet mechanical draft cooling tower cost model used in this

study was developed as follows. The land cost was included in order to make this model consistent with the other abatement technologies at a cost of $400/acre and a land improvement cost of $35/acre was also included. The cost equations used for the pumps, motors, and the pumping station; the intake structure; the make-up water system; and the other equipment were the same as used for the cooling pond system. No intake line or discharge canal were required for this closed cycle abatement alternative, but the cost of the wet mechanical draft tower was included according to the following relation:

$$TOUT = TEWEBU + APPROACH \tag{3-17}$$

where

TOUT=temperature of water leaving tower, $^\circ$F

TEWEBU=wet-bulb temperature, $^\circ$F

APPROACH=temperature of cold water leaving the tower minus
    wet-bulb temperature, $^\circ$F

$$RANGE = (TIN + TERIPL) - TOUT \tag{3-18}$$

where

RANGE=temperature of hot water entering tower minus the tempera-
    ture of the cold water leaving the tower, $^\circ$F

TIN=plant intake temperature, $^\circ$F

TERIPL=condenser temperature rise, $^\circ$F

$$K = 6.04 - 1.59 \left( \frac{80 - TEWEBU}{10} \right) + 0.16 \left( \frac{80 - TEWEBU}{10} \right)^2 \tag{3-19}$$

$$RRF = \frac{RANGE}{\left[\dfrac{K \ (APPROACH + 0.3 \ RANGE + 17)}{20}\right]^{2.5} - 1} \qquad (3\text{-}20)$$

where

RRF = tower relative rating factor

$$TU = RRF \ GPM \qquad (3\text{-}21)$$

where

TU = tower units

GPM = flow rate through tower, gallons per minute

$$TWRCST = 5.0 \ TU \qquad (3\text{-}22)$$

where

TWRCST = capital cost of tower, 1973 dollars

The wet mechanical cooling tower system would also require large diameter piping to circulate the water between the plant and the cooling towers. The following equations were developed to estimate this cost. A length of 1,000 feet was estimated for both the discharge and return line.

$$CAPCOE = (90,000 + (630 \ LENGT5)) \ COSFA2 \qquad (3\text{-}23)$$

where

CAPCOE = capital cost of return line , 1973 dollars

LENGT5 = length of return line, feet

$$CAPCOF = (760 \ LENGT6) \ COSFA2 \qquad (3\text{-}24)$$

where

CAPCOF=capital cost of discharge line , 1973 dollars

LENGT6=length of discharge line, feet

The fixed and variable operating, maintenance, and repair costs were estimated in accordance with the cost relationships developed for the cooling pond system. The total cooling system capital cost was calculated as the sum of the component costs and the capital cost per kw was also computed again. Finally, the cost increase as a result of saline water at the estuary and coastal site alternative was estimated in the same manner as was followed in the cooling pond system, that is, a 20% increase in capital cost and a 10% increase in fixed operating, maintenance, and repair costs.

According to FPC (1969) cooling towers would have pumping heads of 35 to 55 feet in excess of the head required with a once-through system. This added pumping power for the evaporative cooling towers would be equivalent to 0.5% or more of the output of the power plant. For the mechanical draft wet cooling towers, the power required to drive the fans would be equivalent to approximately 1% of the plant output. The annual operating and maintenance costs for the cooling tower systems, exclusive of the costs of power for pumping and to drive the fans, are found to be 1 to 2% more of the investment costs of the cooling systems. Thus, the use of evaporative type cooling towers instead of once-through systems could result in a cost increase for the generation of power of as much as 5%. Also, in the recirculation mode, the higher intake water temperature which would normally result from cooling towers would result in a

lower turbine efficiency. Most estimates for plants using wet cooling towers indicate a capacity penalty of 1%.

While it was not possible to develop the coding required for the natural draft wet tower and the dry tower, the background material developed will be reported. There were no natural draft wet cooling towers in the United States prior to 1962, principally due to the fact that atmospheric conditions, cooling loads, and the costs of construction labor favored the forced draft type, as reported by Cheney, et. al. (1969). The natural draft towers were generally considered to be more costly than the mechanical draft type. Since they depend on natural air currents to ventilate the cooling surfaces, they require more tower volume per unit of heat removal and thus greater initial capital costs. However, other costs are avoided since the capital installation, operating, and maintenance costs of fans are not required. The result, however, has been a net disadvantage for traditional cross-flow designs of these towers due to increased capital costs, variable performance efficiency, water loss from drift, and propensity to ice up during cold weather. The innovation of hyperbolic design and other structural and component advantages, however, has created a change in this disadvantage since the mid 1960's. The latest figures now indicate that natural draft hyperbolic cooling towers are closely competitive with mechanical draft installations for the larger base load units (in excess of 1,000 Mw). This is due to the fact that for high load factor conditions the capital cost disadvantage is reduced and their operating cost advantage is more fully exploited.

According to Kennedy (1972) the intial cost of a natural draft wet cooling tower is generally greater than the cost of a mechanical tower by 50 to 80%. On the other hand, the operating costs are larger with the mechanical units as are the maintenance costs of the fan drive and the usuable life is shorter. But these additional costs are generally offset by the large interest payments on the larger initial cost of the natural draft units.

A similar conclusion has been derived from another source. Although the capital cost of the hyperbolic natural draft type of tower would be $7 to $10/kw as compared to $5 to $8/kw for forced draft type towers, according to Löf and Ward (1970), the overall costs of the natural draft towers for large base load plants may be less since fan power and maintenance is not required. In the case of nuclear plants, the costs would be increased by approximately 50% in both cases due to the waste heat differential.

Löf (1966), suggested that the total cost figure for dry cooling towers would be two to three times that of mechancial wet sytems, with a maximum total cost for tower operation of 1.0 mill/ kwhr for efficient plants with high load factors. This estimate was for the dry cooling tower mode in which the steam leaving the condenser is condensed by a direct contact cold water spray in a jet condenser. However, engineering cost calculations based on semi-arid atmospheric design conditions, by Ritchings and Lotz (1963) yielded only an 8 to 12 percent cost disadvantage for three alternative closed-system designs in comparison with a mechanical draft wet tower optimally designed for the same conditions. Thus ,

according to Cheney, et. al. (1969), although it remains clear that the dry-cooling tower would only provide a minimum cost solution in the case of extremely high water cost, the magnitude of the cost involved has not yet been clearly defined.

The dry cooling tower-jet condenser system for power plant application would have a unit cost within a range of $25/kw and $35/kw for a fossil-fueled plant and between $35/kw and $45/kw for a nuclear plant, according to Leung and Moore (1971). These dry cooling tower system costs reach the same magnitude as the turbine-generator and steam-generator costs in a power plant. In addition, however, this type of system would significantly affect the plant kilowatt capability and thermal efficiency because of operation at higher back pressures and over a wider range of back-pressures than other systems would allow.

Therefore, Leung and Moore (1971) indicated that in comparing the overall economics of a dry tower, equipment capital costs, fuel costs and demand charges must be considered. They determined that if an increase of 0.3 mills/kwhr is included as an operating and maintenance cost for the dry tower system, a total differential generating cost of 1.14 mills/kwhr would be obtained. This would result in an 8% increase in total power cost to the customer of the utility when transmission and distribution costs are considered, but a 16.3% increase in the cost of generation. These figures were determined for a 1,000 Mw fossil-fueled plant using $0.30/million BTU fuel cost and with an assumed capacity factor of 70%.

In FPC (1969), figures close to these for the dry cooling

towers are repeated, but the report admits that the figures are largely conjectural due to limited experience with them. Including the condenser installation in their estimate, the range for mechanical draft dry cooling towers was $25 to $28/kilowatt and the natural draft dry cooling tower was estimated to range from $27 to $30/kilowatt. Thus, where adequate water supply is available, the dry-type cooling tower would not compare favorably with others. The efficiency penalty due to air cooling only being able to approach the dry-bulb temperature instead of the wet-bulb temperature may also result in plant output being 6 to 8% lower.

### III. B. 4. Summary

An attempt was made within this section to review and analyze the data on the costs of thermal pollution abatement alternatives which was available in the literature then to incorporate this data into the cost models required for this study on electrical energy systems. The work was complicated by the different definitions of cost which were used in the many works (some capital costs include the condenser cost, others do not) and the different times at which the cost was determined. The current rates of inflation make the extrapolation of these costs a difficult task. The operating costs were frequently defined in terms of pump power costs, and for this study the pump power was analyzed as a loss in plant output necessitating a different approach. Although all the feasible alternatives were not carried through to the development of the economic model, all the information which was evaluated on these

alternatives was presented in this section. Finally, the work was carefully documented so that a continuation of the study may be smoothly carried out, and secondly, as more substantial data becomes available on these costs, the model framework will allow for easy replacement of the existing relationships with the more accurate data.

Cost models, equations, or estimates which are formulated upon assumptions require an analysis to determine the sensitivity of the output or results of the model to the stated assumptions. The assumptions which are found to demonstrate a critical impact on the results should be considered as a factor which contributes to the uncertainty of the result. These assumptions should then be subjected to future analysis. The models should also be adjusted by examining the ramifications of relaxing constraints and modifying key variable values. Unfortunately, due to the time restrictions and the amount of work necessary to develop the models this sensitivity analysis was not completed. This matter should be considered in any work continuing the aims of this study. Many of the cost relations used in this report were adapted from ITC (1971), where the cost estimates were generated from elementary cost-estimating relationships as well as point estimates and simple cost factors obtained from historical cost data and industry data. The cost-estimating relationships and cost factors which were developed in this way estimate the cost of a system component as a function of a component's operating characteristics, physical performance, and properties.

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The substantial cost variances that plague system cost estimates
are also mentioned in ITC (1971) where data collected from two sources
illustrated the large cost variances attributable to the geographical
location of construction projects. These data sources were based on
identical type construction projects located in 20 major United
States cities. The sources both were based on a total construction
cost index which was derived by averaging several common major
appraisal and construction indices which would reflect a national
average construction cost. The data gave an indication of how much
the power plant and other construction cost variance may be explained
on the basis of a geographical distribution. The data was obtained
from "Building Construction Cost Data" 1968 by R. S. Means and
Company and the F. W. Dodge figures from the July 17, 1969 ENR. The
Means figures are based on a 1967 average of 100, and the Dodge
figures are based on a 1913 average of 100. This problem would have
a smaller adverse effect on the model when used on a small regional
basis but could lead to difficulties in the case of the model being
used on a national basis. The data used in ITC (1971) was obtained
from TVA from 10 of its power stations and in most cases the equip-
ment and facilities costs were correlated against the equipment's
physical characteristics. The correlation was, therefore, not based
on the performance requirements of the system but instead on the
physical design.

In summary, the following general statements may be made
concerning the cost relations developed. The once-through and
cooling pond systems showed the widest variations in costs over the

range of possible site conditions, and were the most difficult to model for this reason. The once-through system was most sensitive to water supply conditions, and the cooling pond costs were most sensitive to the land prices and the capital costs of developing alternative sites and, to a lesser degree to the variations in make-up water supply. The range of costs for cooling towers will be less since these systems are more capital intensive and they are not subject to high sensitivity with regard to the land acquisition or water supply conditions.

Considering all the alternative cooling system possibilities, therefore, the net cost of cooling at any given location can never be less than the minimum cost of a once-through system under optimum conditions and it should never be more than the maximum cost of a dry cooling tower under the worst conditions. Finally, according to Cheney, et. al. (1969), for a given average United States location, the rank ordering of optimal technologies would probably be: once-through least costly; wet cooling towers; and cooling ponds. This conclusion will be studied further in Chapter 6 under the case study analysis.

### III. C. Physical Modeling

### III. C. 1. Physical Aspects

The temperature distribution which results from the discharge of waste heat to the aquatic environment is a function of the characteristics of the effluent water, the receiving water body,

and local climatological conditions. The distribution of excess heat is accomplished by various physical mechanisms which carry the effluent through the receiving water and eventually to the atmosphere. Among these physical mechanisms are: diffusion and dispersion due to ambient turbulence in the water body; evaporative cooling, also known as latent heat transfer; advective mass transport due to ambient currents; buoyant rise of a heated jet with mixing at the plume boundary; and convective spreading of the effluent over the surface of the water body due to density differences between the heated discharge and the ambient water.

The heat rejection systems considered in this study transfer the heat from the condensing steam to water which is eventually cooled in the atmosphere. The heat may be transferred by the latent and sensible modes. The latent transfer of heat takes place at a constant temperature and involves the amount of heat energy used in the transforming of water from a liquid to the vapor state. This amount of heat, known as the latent heat of vaporization, is taken from the remaining water causing a decrease in temperature. The driving force for this process is the difference between the saturation vapor pressure of the water at the surface temperature and the partial vapor pressure of the air. The sensible heat loss takes place due to the difference in the air dry-bulb temperature and the water temperature. The air heats up due to the transfer of sensible heat and the water surface cools down. The modes of sensible and latent heat transfer frequently take place at the same time, with the amount of heat transferred through each mode a

function of the waste heat rejection unit in use.

In the description of the behavior of fluids of different density in a system governed by buoyant and inertial forces the densimetric Froude number may be defined as:

$$F = \frac{U}{\sqrt{\frac{\Delta \rho}{\rho} gh}} \qquad (3\text{-}25)$$

F=densimetric Froude number

U=characteristic velocity or velocity difference, feet/second

g=acceleration due to gravity=32.2 feet/second$^2$

$\Delta \rho / \rho$=relative density difference

h=characteristic length, feet

If the value of F rises above a certain critical value, $F_c$, then entrainment will occur at the interface with the plume, while for F less than $F_c$ the interface will remain in a stable state. According to Harleman and Stolzenbach (1967), for the turbulent range this value is approximately equal to unity.


III. C. 2. State of the Art in Physical Modeling

Due to the current concern in environmental affairs, the adoption of thermal water quality standards by all fifty States, and the passage of the Federal Water Pollution Control Act of 1972 and the National Environmental Policy Act of 1969, the problems of temperature prediction and heat within a water body have received a great deal of attention in recent years. Considerable research has been undertaken and results are now becoming available for use. In

some cases predictive models are available, while in other cases the
applicability of the established techniques is limited to simple or
approximated conditions. The models of temperature prediction and
heat loss can be divided into simple analytical models, hydraulic
scale models, and numerical mathematical models requiring the use of
computers.

Analytical Models. For the case of a high-velocity jet dis-
charging into a quiescent fluid, previous boundary-layer solutions
were extended by Albertson, et. al. (1950) who formulated the effects
of the initial dimensions of a jet on the velocity distribution. It
was determined that the flow field can be divided into two zones:
the zone of flow establishment near the source, where the source
size is of importance and the zone of established flow where only the
momentum flux of the source is important. In the zone of established
flow, the velocity distributions were found to have a shape well-
approximated by a Gaussian profile. Analytical expressions for the
distribution of velocity, energy flux, and volume flux were developed
for the patterns of mean flow within submerged jets from both
orifices and slots. The resultant distribution of temperature
increase over the ambient can be expressed in a similar manner of
the dilution of the heated water is considered and buoyant forces
are neglected.

A mass-momentum flux diagram was used by Morton (1961) to relate
jets, plumes, and wakes. A simple model was developed based on the
concept of entrainment, and the relation was determined from the
solution of a single differential equation based on a common set of

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assumptions applied to jets, plumes, and wakes. These assumptions included: negligible longitudinal dispersion compared to lateral dispersion; flow was affected only by density differences in the form of buoyancy forces; and mean cross-sectional velocity profiles were similar along the axis. An inflow velocity across the boundary of the jet was used to represent entrainment. Solutions were developed for a simple jet, buoyant jet, a jet in a uniform current, a simple plume in a stratified environment, a buoyant jet projected along a uniform stream, simple wake, a forced wake, and a buoyant forced wake.

Wada (1966) and Hayashi and Shuto (1967) considered the low velocity flow of heated water emanating from a point at the surface from the potential flow theory with consideration given to heat emission to the atmosphere. Their theoretical investigation was of the temperature distribution resulting from the discharge of warm water from a rectangular outlet at the surface into a stagnant fluid. The inertia of the fluid was ignored in their studies and the temperature pattern was the result of dispersion and advection. The flow pattern was determined by ignoring the density differences due to the heated discharge and the temperature distribution was then obtained from the known flow pattern. This limited the application of their work to small temperature differentials. Their approximate solution was presented for the case of no vertical entrainment with all convective terms in the governing equations negligible. In the laboratory experiments performed by Hayashi and Shuto, the experimentally determined temperature was found to be

consistently lower than predicted values indicating the effects of entrainment and initial mixing near the discharge point.

Experiments studying the different aspect ratios of the discharge channel from which a heated discharge issues were conducted by Jen, Wiegel, and Mobarek (1966) for the three-dimensional surface jet. They performed laboratory studies on the mixing of heated buoyant jets discharging horizontally at the surface of a large body of initially stagnant receiving water. They determined that the jet excess temperature decreased first due to jet mixing and was then followed by a region where it decreased at a faster rate. An empirical equation for the temperature along the jet axis was presented for Froude numbers in the range of $18 < F < 180$, which is generally outside the values encountered in field operations of surface discharges. A relation was also determined for the mean values of temperature concentration at the surface.

A similar study was made by Tamai, Wiegel, and Tornberg (1969). This study presented data from a number of sources on the cooling water capacities of thermal power plants, together with the flow characteristics; compared the results of a number of studies of the mixing of buoyant flows discharged horizontally at the surface of a water body; and presented the results of new studies on such flows. The experimental measurements made in this study were for densimetric Froude numbers in the range of 2.4 to 11.3. The results indicate that a narrow stream of warm water flowed along the surface with very little mixing or spreading for low value of F (=2.6). The empirically determined curves for describing the surface spread of

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warm water jets were little different from the previously reported

curves  for values of $3 < F < 11$.

In Motz and Benedict (1971), the work of Morton (1961) and Fan

(1967), was used as a basis for the development of a more refined

model of surface jets which can describe certain cases of heated

power plant discharge.  It was concluded that the two-dimensional

surface jet model is dependent on the velocity ratio and the initial

angle of discharge.  Field and laboratory data were used in the

verification of the model which was developed.  The laboratory data

also supplied drag coefficients, entrainment coefficients, a length

of zone of flow establishment, and the angle at the end of the zone.

Analytical and experimental investigations of the surface dis-

charge of heated water were made by Stolzenbach and Harleman (1971).

Analytical procedures were developed for the prediction of the three-

dimensional distribution of temperature in the near-field region.

The theory considered the parameters of:  aspect ratio of the dis-

charge channel; the bottom slope of the receiving water; the initial

densimetric Froude number; the current in the receiving water

parallel to the shoreline; and the dissipation of heat from the water

surface.  The discharge is considered only to the point where jet-

like behavior ceases, and natural turbulence and convection dominate

temperature and velocity distributions.  The discharge was from a

horizontal, rectangular open  channel at the surface of a large

ambient body of water which may have a bottom slope or a cross

flow at right angles to the discharge.  The theoretical development

assumed the discharge was a three-dimensional turbulent jet in which

the velocity and temperature distributions were related to the centerline values by similarity functions. The vertical and horizontal entrainment of ambient water to the jet were related to the jet centerline velocity by an entrainment coefficient. The cross flow deflects the jet by entrainment of lateral momentum, and the bottom slope inhibits vertical entrainment and buoyant lateral spreading. The lab experiments conducted verified that the theoretical model could predict the behavior of heated discharges. The cross flow was found to deflect the jet, but not greatly affect the resulting temperature distribution. The heat loss also did not significantly affect the temperature distribution of the heated discharge in the near-field.

The theory is applicable to the prediction of temperatures in actual discharges if the temperatures, discharge geometry, and velocities may be schematized by steady state temperatures and velocities and an equivalent rectangular channel. The model may be extended by treating a stratified ambient condition, by considering recirculation of the heated jet in a finite enclosure, and by development of a theory for the transition of the heated discharge into a buoyant plume.

Stolzenbach (1972) discussed the characteristics of the surface discharge of heated water and the resulting stratified conditions in the receiving body of water. The theoretical approach to surface discharges which considers the discharge as a turbulent jet was developed and the effects of buoyancy and surface heat loss were then incorporated into the three-dimensional temperature prediction

model as previously reported by Stolzenbach and Harleman (1971).
This report gave a summary of the developed theoretical approach in
which the temperature and velocity distributions were assumed to
remain structured as a turbulent jet and the analytical results.
A discussion of the structure of a heated surface jet was also
included and the theory of stratified flow was reviewed. An analysis
was also made of the density changes due to temperature and salinity
and their relation to sinking plumes.

In Stolzenbach, Adams, and Harleman (1972), a review of the
three-dimensional temperature prediction model reported in
Stolzenbach and Harleman (1971) was presented, along with a detailed
discussion of the revised computer program and a case study which
illustrates the procedure for optimizing the design of a surface
discharge channel. Subsequent work in using the computer program of
the original report for the calculation of temperature distributions
resulted in modifications and improvements of the original program.
One significant difference presented in this report was the inclusion
of the assumption that the bottom of the receiving water does not
interfere with the surface jet development. The original program
contained the means of considering a sloping bottom in the
receiving water, but since this model did not adequately predict the
point of separation or lateral spreading when the jet was in contact
with the bottom, and the increasing desire to accept the depth of
the receiving water as a limit, the new assumption on bottom slope
was required. Since most operating plants have not been designed to
minimize bottom impact, the comparison of the revised model with

field data was a difficult process.

The mixing phenomenon in submerged buoyant jets have been studied by many investigators. In Brooks and Koh (1965) an analysis was made of the two-dimensional buoyant jet plume problem with application to a submerged ocean outfall diffuser. The more general case was examined by Fan (1967) where the angle of discharge was arbitrary and a round buoyant jet in a uniform cross stream of homogeneous density was studied. He extended the integral technique of analysis and presented empirical relationships for the zone of flow establishment. Fan also presented a literature review of turbulent jets discharged into a crossflow in that study.

A study by Harleman, Stolzenbach, and Jirka (1971) on the use of diffusers in shallow water considered the combined effect of the dilution of a current in a receiving water body and the jet-induced entrainment. A relation was developed for determining the maximum temperature rise at the water surface for a diffuser pipe with an axis at $90^o$ to the direction of the current velocity. The jets discharge horizontally and the relation developed can consider discharge with or against the current as well as discharge in alternating directions. It was determined in this study that in the case of a shallow water diffuser, there is almost no temperature variation from the surface to the bottom outside a relatively small mixing zone.

Ditmars (1972-1) provided a discussion of buoyant jet mixing in various receiving water body environments and its application to choices of diffusion structures. The mechanics and solutions to the governing equations were presented for both an inclined round

buoyant single jet  and a two-dimensional slot buoyant jet discharge
into both uniform density and density stratified stagnant water
environments.   The method of analysis used followed the integral
approach of Morton, Taylor, and Turner (1956) for the simple
buoyant plumes, and the analysis by Morton (1959) for buoyant jets.
The analyses and results were from the works on Fan (1967) and Fan
and Brooks (1969).   A discussion was also included of both round
buoyant jets and slot buoyant jets discharged into a flowing
environment of uniform density, but no analysis was found available
to predict behavior of the round jet in a flowing environment
although much experimental data was available.   For the slot jet,
little analysis and data were found available.   A discussion of
interference between individual jets when multiple port diffusers
are used was also included, along with comments on the surface
spreading of buoyant jets.   For the multi-port diffusers in shallow
receiving water environment reference is made to the experimental
and analytical studies carried out here at M.I.T. by Harleman,
Stolzenbach and Jirka (1971) and Adams (1972).

Adams (1972) presented an analysis of heated water discharge
through multi-port diffusers in shallow water bodies for diffuser
flow.   The downstream dilution in a current was studied under the
assumptions of no stratification, no bottom friction, and the
boundaries at infinity.   The dilution was predicted for the case of
nozzles aligned with the current, nozzles aligned against the
current, and nozzles in alternating directions by means of momentum
and energy equations.   The results were verified by an experimental

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model study. This report indicated that the dilution depends on the induced flow momentum and the crossflow momentum. The dilution will be maximized when these two act together and minimized when they are opposed.

The emission of heat across the interface of the air and water to the atmosphere has undergone a considerable amount of study. Among the more widely used equations is the formula of Edinger and Geyer (1965) which relates the average heat emission to the climatological conditions and the surface water temperature. Brady (1969) also gave a comprehensive review of the surface heat exchange process and the predictive equations. The equilibrium temperature may be defined as the steady state natural water temperature for fixed heat inputs. According to Brady, the forced temperature rise induced by the addition of waste heat from a power plant may be calculated by assuming the excess surface heat flux is proportional to the difference between the water surface temperature and the equilibrium temperatures.

Ryan and Stolzenbach (1972) provided an introduction into heat transfer theory and a detailed treatment of the process of surface heat exchange. The basic parameters describing the thermal behavior of water; convective, radiative and diffusive heat fluxes; and the heat conservation law expressed in control volume and differential form were presented. The physical processes of surface heat exchange were reviewed with a comprehensive analysis of the literature available in this area, and the analytical and empirical methods for estimating the heat transfer components were reviewed, with parti-

cular attention devoted to the surface heat loss due to evaporation.
The concepts of the surface heat exchange coefficient and the
equilibruim temperature were developed to make the surface heat
exchange computations more manageable in the area of heated dis-
charges and temperature prediction problems.

Mathematical treatment of river flow and estuaries has been
restricted to complete vertical mixing or fully stratified cases.
One study of this type was made by Harleman and Stolzenbach (1967) in
which a two-dimensional constant width solution was developed for the
stratified flow of heated discharges.

The longitudinal temperature profile in a river may be
determined, when assuming one-dimensional completely mixed
conditions, by means of an exponential decay curve which treats the
excess heat as a non-conservative substance. Harleman (1972)
provided one-dimensional computational techniques for the prediction
of longitudinal temperature distributions as a result of the dis-
charge of waste heat to a river. Analytical methods were developed
for rivers, and illustrated by means of a case study.

For a completely mixed estuary an approximation can be made of a
homogeneously oscillating one-dimensional flow in which the longitu-
dinal dispersion acts as a mechanism to smooth out the differences
in concentration. Harleman (1972) briefly discussed this problem,
including the effect of salinity on the longitudinal dispersion
coefficient and a numerical example.

The concentration distribution of a conservative substance may
be expressed as an integral equation according to Harleman, Holley,

and Huber (1966). The concentration distribution for excess heat
can be computed in a similar manner by introduction of an appropriate
decay coefficient into the equation using the solution of Huber
(1965). The concentration distribution for a continuous injection
of a non-conservative substance was developed by Harleman (1971-1)
with relation to the one-dimensional modeling of the mass transfer
process of a uniform estuary.

Estuarine temperature distributions were discussed by Edinger
(1971). This work presented the semi-emperical basis for
analytically describing the temperature distribution due to large
heat sources in the near-field, the intermediate region, and the
far-field region. An analytical description of the estuarine
temperature structure was also provided for the vertically mixed
case, two-layered segmented models, and continuous vertical
temperature structure.

The diffusion of the diluted effluent in the far-field in a
prevailing current due to the turbulence of discharge jets and
natural oceanic turbulence was studied by Brooks (1960) for the case
of vertical uniformity and constant velocity. In this case, the
lateral dispersion was determined by a power function of the plume
width. The study attempted to develop a rational method for the
determination of turbulent diffusion in an ocean current. The
results were presented in terms of the rate of which a sewage field
grows, and the rate at which the concentration decreases along the
axis of the sewage field.

A similar study was made by Edinger and Polk (1969) whose

analysis included vertical variations, but all dispersion coefficients were assumed constant. The heated discharge was assumed as a point source of heat at the water surface on the boundary of a uniform stream. The temperature distribution was determined by vertical and lateral eddy diffusivities and by convection in the direction of the stream flow. Buoyant effects were not considered in the model developed, and treatment was limited to the region dominated by ambient turbulence.

Ditmars (1972-2) discussed the passive turbulent diffusion process and its relation to far-field mixing. The governing equations were first developed and then the literature in the field of lateral eddy diffusion coefficients was reviewed. Recommended values for the coefficients were given after discussing the effect of density differences and vertical stratification on lateral spreading. A similar review was made for the vertical eddy diffusion coefficient. The analytical solutions to the governing equations for idealized situations were then presented as a tool for understanding the importance of the independent variables. Solutions were presented for steady, continuous sources discharging to a uniform current, including a point source in a flow with constant eddy diffusion coefficients, and a temperature source of finite extent in large flow environments which was based on the work of Brooks (1960) for sewage effluent fields.

Ryan (1972) presented a comprehensive review of existing models of cooling ponds which will not be repeated here. His report also presented simple analytical models for the case where

lateral mixing dominates, that is, a shallow pond, and the case
where the vertical mixing dominates, that is, a deep and narrow pond.
The report also included a review of the observed physical behavior
of cooling ponds and important design parameters.

Physical Models. The technique of physical scale-models can be
used to determine temperature predictions for complex geometric and
hydraulic conditions, where analytical models would not suffice, with
certain limitations.

Each stage of heat dispersion implies certain scale relation-
ships according to Ackers (1969) who presented an outline of the
principles of modeling. In many cases, similitude of the gravita-
tional, frictional and surface heat loss forces is required simul-
taneously where the given situation is influenced by several
mechanisms.

These incompatibilities could be overcome in some cases,
according to Ackers, by use of a near-field model where inertia
and buoyancy are important. Boundary conditions from this first
model could then be used as input to a far-field model to study
heat transfer processes.

Stolzenbach and Harleman (1971) included a procedure for and
analyses of the modeling of heated discharges for those cases where
the determination of temperatures in the vicinity of the heated
discharge of the prototype is beyond the capability of analytical
techniques. One conclusion was that it is impossible to build a
distorted scale model which reproduces correctly the minimum
required characteristics of the near-field region of a surface

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discharge.

A section by Harleman (1971-2) discussed physical hydraulic

models of estuaries and the use of these models for water quality

studies. The similitude of momentum transfer processes in advective

tidal motion were developed from the principles of inspectional

analysis. This resulted in the Froudian scale ratios for velocity,

discharge, and time. The boundary conditions and roughness relations

were also discussed, and then the similitude of the mass transfer

process was developed by means of the principles of inspectional

analysis. Finally, model verification was considered since the only

precise scale ratios for a distorted model are velocity, discharge,

and time. The model verification was illustrated by showing com-

parisons of the model-prototype data in certain studies.

Stolzenbach and Harleman (1972) also presented a summary of

physical modeling criteria for heated discharge where the situation

under consideration is beyond the capabilities of the analytical

methods. When the physical processes determining the temperature

distribution are well-known, model-prototype similitude relation-

ships can be developed and laboratory scale models may be designed

to yield temperature predictions. In the report, thermal model

laws were derived and the application of thermal model laws was

then discussed for two-layer flow, surface discharge, and multi-

port diffisuers. These models will continue to be necessary when a

detailed temperature prediction is necessary for a complex physical

situation.

Numerical Models. In recent years the use of this tool has

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become increasingly important in the analysis of heated discharge from electric power plants. This technique allows the governing physical equations to be solved at discrete times and locations which satisfy the boundary conditions. In this way the prediction of the distribution of the released heated discharge can be given. The problem formulation and solution in this case is complicated by the fact that the thermal and dynamic characteristics are inter-dependent. Most of the models developed and available in the literature are limited to the solution of the heat budget, continuity, and motion.

Thermal modeling of lakes or reservoirs was presented under simplified inflow conditions by Huber and Harleman (1968) and Orlob and Selna (1968).

For the case where the initial conditions provide complete mixing of the heated water with a river or estuary so that no more influence on the dynamic behavior results, the models of concentration prediction for non-conservative substances can be used.

Numerical models for heated water outfalls were developed by Tetra Tech (1970) for three flow regions. In the near-field, the subsurface discharge into a stratified ambient water issuing from a row of buoyant jets was solved. The jet interference effects were included in this analysis. For two-dimensional and axisymmetric cases, an analysis was made of the flow zone close to and at inter-mediate distances from a surface buoyant jet. In the far-field a passive dispersion model was solved for a two-dimensional situation taking into account the effects of shear current and vertical changes

in diffusivity. The excess temperature distributions were computed in normalized form for two possible vertical distributions of the eddy diffusion coefficient and two possible velocity profiles. The velocity was constant with depth or had a constant gradient while the eddy diffusion coefficient was constant with depth or varied with depth in a manner similar to that which would be experienced due to stratification.

Stolzenbach (1972) developed a temperature prediction model for estimates of temperature rises for a wide range of possible configurations and natural conditions. A simple heat budget model was developed which estimates near-field, far-field, and intake temperatures. The results of this model provide a first estimate and analysis of a given discharge situation. This parameterized model yields accurate information for a simple type model by drawing on the most recent understanding of heated discharge processes. A model of this type may always be formulated to incorporate new knowledge about the physical processes determining the temperature distribution in the vicinity of power plant discharges. Application of the model to two proposed power plant discharges was provided in the study to illustrate the flexibility and utility of the model.

A comprehensive review of the numerical models proposed to evaluate cooling pond behavior was presented by Ryan (1972). The models which currently exist are either one or two-dimensional and are generally of limited value. The one-dimensional model may be used when the mixing of the heated water with the reservoir is large

enough so that the surface heat loss may be evaluated at one surface temperature. The two-dimensional models are usually applied to shallow bays with tidal motion involved. The problems involved in developing a three-dimensional model were also enumerated. A numerical model of a cooling pond divided into the near-field and far-field regions using a modified form of the model of Stozenbach and Harleman (1971) for the near-field area, simple analytical models to describe the surface layer, and vertical heat transport of the reservoir model for the far-field was presented. This proposed numerical model will include all the effects deemed significant in predicting cooling pond behavior, including entrance mixing, wind induced currents, selective withdrawl, density currents, pond geometry and surface heat flux.

### III.  C. 3.  Models Selected for Study

In order to describe the physical and economic aspects, and the resource requirements for the thermal pollution abatement alternatives, models of varying degrees of complexity were required. This work unfortunately was limited in scope due to the time requirements for publication of this report, and thus only the alternatives of surface discharge, diffuser, cooling pond, spray canal, and wet mechanical draft cooling towers were considered. A thorough literature search was made of available models, both analytical and numerical, which would provide a reliable prediction of the physical and economic aspects for use in an electric energy regional planning study.

In as much as the major part of the effort involved adapting
existing work to the needs of this study, the author has made every
effort to give the proper credit to those who have originally
developed these works. Considerable attention was given in the model
formulation to the development of the interactive framework for the
abatement technologies such that additional information may be
easily incorporated into the model in the future. Finally, where
the necessary information was not available in the literature, the
author made the required assumptions to yield the solutions and these
were carefully documented such that more refined data can be used in
their place as it becomes available.

Surface Discharge. The discharge of heated water horizontally
at the water surface is commonly done by means of either a large
diameter pipe or an open canal which terminates near the shore. The
exposure of the heated water to the atmosphere in this manner allows
temperature reduction by heat loss in addition to the effects of
mixing. The resulting temperature distribution in the ambient water
is determined by mixing between the discharged and ambient water and
the rate of heat transfer to atmosphere, which is controlled by the
surface heat exchange coefficient, KOEFF2, according to Harleman and
Stolzenbach (1972). Also, the temperature decrease has been
determined to be a function of the discharge densimetric Froude
number, FROUDE, the discharge channel aspect ratio, ASPECT, a sur-
face heat loss parameter, the bottom slope, and a cross flow
parameter.

In Stolzenbach and Harleman (1972), one of the models selected

for adaptation to the case of surface discharge, the temperature and velocity distributions assumed were those of a classical turbulent jet, and the analytical model was a set of steady, time averaged equations including momentum, continuity, and conservation of heat energy. The theoretical model has a structure which was synthesized from previous knowledge, and thus, no new "adjustable" coefficients were introduced that have to be fitted against experimental data. The method was also verified by a series of laboratory experiments designed to determine the effects of the parameters presented in the dimensionless formulation of the heated discharge. The output from this model was used as the basis for the check of thermal standards and the computation of the abatement characteristics of a surface discharge.

The typical surface discharge alternative modeled for this study considers the discharge of  heated water at the surface of an ambient body of water from a rectangular open channel. The rate of heat transfer to the atmosphere at the water surface and the mixing of the discharge with the ambient will control the resulting three-dimensional temperature distribution. The work of Stolzenbach, Adams, and Harleman (1972) which considers this distribution was used extensively in this report for the analysis of the surface discharge alternative.

The surface jet was considered as a buoyant discharge, and thus characterized by a reduction in vertical entrainment and lateral gravitational spreading. This results in a velocity and temperature distribution which is much wider than deep with increased surface

area which may lead to significant surface heat loss. The model selected gives consideration to the roles of buoyancy, the initial channel shape, turbulent entrainment, and surface heat loss upon the temperature distribution. The discharge is assumed to be a free turbulent jet with a well defined turbulent region where velocity and temperature are related to centerline values by similarity functions.

The site alternatives where the surface discharge was considered a feasible alternative were river, great lake, coastal, offshore ocean, estuary, and small lake. The characteristics of these sites will be further explained in Chapter Four on the thermal pollution abatement model.

In the river site, the surface temperature rise and the maximum temperature at the limit of the mixing zone are computed in the following manner. For a given plant flow, plant temperature rise, and specified constraint of maximum canal velocity, maximum vertical penetration of discharge equal to river depth, the method of Stolzenbach, Adams, and Harleman (1972) was used to determine the resulting temperature prediction and design parameters. This theory may be used for a Froude number,

$$F' = F \text{ ASPECT}^{\frac{1}{4}} \tag{3-26}$$

where

    $F'$=Froude number with characteristic length based on scaling

        factor

    ASPECT=aspect ratio=$h_o/b_o$, where $h_o$ is canal depth and $b_o$ is

        canal half-width

whose characteristic length is equal to the scaling factor, SCALFA,

that is $ASPECT^{\frac{1}{2}}$, when the value of F' is greater than 3. Since the

aspect ratio was assumed equal to 0.5 for the model in this study,

the limiting value of the densimetric Froude number may be determined

$$F = \frac{F'}{ASPECT^{\frac{1}{4}}} = \frac{3.0}{(0.5)^{\frac{1}{4}}} = 3.57$$

The maximum depth of penetration of the heated plume was assumed

equal to the river depth in order to provide a mixing zone, since it

was assumed if discharge just touched the bottom it will move back

up and generally provide an area of one-half the cross section of the

river undisturbed. The maximum canal velocity was assumed equal to

10 fps and included in this model as MAVELO. The limiting value of

the Froude number, FRNUDE, whose characteristic value is based on

the scaling factor length, for the case of maximum depth of penetra-

tion was

$$FRNUHE = \frac{6.8 \; SITTY3^{1.67} \; DELDEN^{0.33}}{FLOPLA^{0.67}} \tag{3-27}$$

where

    FRNUHE=limiting value of FRNUDE based on maximum depth, SITTY3

    SITTY3=depth of river, feet

    DELDEN=density change=32.2 BETTA TERIPL

    BETTA=coefficient of thermal expansion of water, ${}^{\circ}F^{-1}$

    TERIPL=temperature rise at abatement devise, ${}^{\circ}F$

    FLOPLA=total cooling water flow discharge through the abatement

        device, cfs

The limiting value of FRNUDE based on the maximum canal velocity, MAVELO, was

$$FRNUVE= \frac{1.19 \ MAVELO^{1.25}}{DELDEN^{0.5} \ FLOPLA^{0.25}} \tag{3-28}$$

where

FRNUVE=limiting value of FRNUDE based on maximum velocity, MAVELO

The channel should be designed with FRNUDE equal to the smaller of these two expressions since ultimate dilution increases monotonicly with FRNUDE.

The value of HOBO, the product of discharge channel depth, DEPTH, and the initial channel half-width, WIDT2, was then computed as follows:

$$HOBO= \frac{FLOPLA^{0.8}}{2.0^{0.8} \ FRNUDE^{0.8} \ DELDEN^{0.4}} \tag{3-29}$$

The scaling factor, SCALFA, may then be determined as the square root of this value:

$$SCALFA=HOBO^{0.5} \tag{3-30}$$

The velocity in the canal may now be computed:

$$VELCAN= \frac{FLOPLA}{2. \ HOBO} \tag{3-31}$$

where

VELCAN=design velocity in canal, feet/second

Since ASPECT was assumed equal to 0.5

$$ASPECT= \frac{DEPTH}{WIDT2} =0.5$$

this allowed the substitution of

WIDT2=2.0 DEPTH, and calculation of the area of the canal,

Area, as

$$AREA = DEPTH \cdot 2 \cdot WIDT2$$

$$= DEPTH \cdot 2 \cdot 2 \cdot DEPTH$$

$$= 4 \cdot DEPTH^2$$

The depth in the canal was estimated as follows:

$$DEPTH = \left( \frac{FLOPLA}{4.0 \ VELCAN} \right)^{0.5} \qquad (3-32)$$

The initial densimetric Froude number FROUDE was defined as:

$$FROUDE = \frac{VELCAN}{(DELDEN \ DEPTH)^{0.5}} \qquad (3-33)$$

The width of the canal for an aspect ratio, ASPECT, equal to 0.5 was computed by:

$$WIDT1 = (2.0 \ DEPTH) \ 2.0 \qquad (3-34)$$

where

WIDT1=width of canal, feet

The half-width of the canal, WIDT2, can then also be calculated.

The model then searches the densimetric Froude numbers and chooses the Froude number corresponding to the three-dimensional model solution most closely related to the Froude number computed, in order to determine the temperature rise at distances from the point of discharge by means of the dimensionless results from the model.

It should also be noted that the crossflow was neglected in all the models developed in this study for the surface discharge since

while the cross flow does deflect the plume, there is no signifi-
cant effect on the dilution process, according to Stolzenbach (1972).
Thus, the model results used for this model were those with no cross
flow.

The work of checking the thermal standards and determining
the design parameters was carried out in subroutine FROUD of the
surface discharge models. This subroutine, in modified forms, was
used for all the site alternatives with the surface discharge.

For the area mixing zone definition, a computational scheme
developed by Mr. Eric Adams in conjunction with the work reported
in Stolzenbach, Adams, and Harleman (1972) was used to check the area
within the mixing zone. This simple computer program performs a
numerical integration to calculate the area within the specified
isotherm. These calculations were performed in subroutine AREA
which was used for all the site types considered. The point of
maximum decrease in concentration was checked first to see if the
temperature standard can be met even at the point of maximum
dilution, and the area calculations were performed. A detailed
description of this procedure was given in Stolzenbach, Adams, and
Harleman (1972), and will not be repeated here. The model provided
for a correction to the last segment where the temperature limit
was passed due to the iterative process. The solution then back-
tracked to the previous segment and then added the correct propor-
tional part of the last segment. Since the computations were
carried out in dimensionless quantities, the area in square feet was

then obtained by multiplying by the SCALFA$^2$, and then the area was converted to acres.

The ability to handle a distance from the point of discharge definition for the mixing zone was also included by means of the subroutine DIST which computed the temperature rise at a distance, XDISTA, away from the point of discharge and checks them against the allowable values to see if the standard requirements can be met.

If the standards could not be met, the possibility of flow dilution was then examined for both the area and distance mixing zones. The flow dilution was evaluated in 50 c's increments up to a certain maximum limit, and new values of the total cooling water flow, FLOPLA, which now includes the dilution flow, FLODIL, and a new temperature rise, TERIPL, at the end of the canal were computed. A new check was then made of the ratio of the flow of the plant to the river flow, with a maximum percentage of the river flow allowed for cooling use.

The evaporative loss calculations are explained in section C. 4. of this chapter. The heated surface area with a temperature rise in excess of $0.5^\circ$ F was computed by means of assuming a stratified condition with the temperature rise limited to the top-half of the cross sectional area of the river. The segments of analysis were in one-mile increments and it was assumed that the entire surface area of the stream was heated. The surface heat exchange coefficient, KOEFF2, was computed for the heated water surface temperature at the point of discharge and the existing meteorological conditions. The computations for the surface heat

exchange coefficient calculations will be explained in greater detail
in the section on evaporation. The one-dimensional temperature
decay equation with the depth equal to one-half the river depth due
to the stratified conditions was used to compute the temperatures
downstream, and the areas in the one-mile segments were summed until
the $0.5^{\circ}$ F level was reached.

The new intake temperature in this case was set equal to the
ambient water temperature assuming the recirculation would be equal
to zero with the intake located at a sufficient distance upstream.

The land surface area was computed according to subroutine
LANS1. These computations assumed an intake pipe, a discharge canal
with a discharge channel length of LENCAN, which is given in cost
sections as LENGT2, and a rectangular cross section canal. The
land area was calculated by assuming a 25% area requirement in
addition to the water surface area

$$ALAND = (WIDT1 \ LENCAN) \ 1.25 \tag{3-35}$$

where

   ALAND = area of land required for discharge canal, feet$^2$

   WIDT1 = width of discharge canal, feet

   LENCAN = length of canal, feet

and the land area requirement RRT (3) was then computed in acres.

The power requirements were then computed by subroutine POWS1.
The pump efficiency, EFFICI, was assumed equal to 75%. The horse-
power requirement used was

$$HORPOW = \left[ \frac{62.4 \ FLOPAL \ HEAD}{550 \ EFFICI} + \frac{62.4 \ FLODIL \ 5.0}{550 \ EFFICI} \right] \tag{3-36}$$

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where

HORPOW=total pumping horsepower requirements, $h_p$

FLOPAL=original plant flow, cfs

EFFICI=pump efficiency, %/100

HEAD=pumping head through the plant, feet

FLODIL=flow of dilution water, cfs

It should be noted that a separate calculation was made for the
dilution flow since it would not pass through the plant and thus
would not be subjected to plant losses. Th· pumping head assumed
for the dilution flow was equal to 5 feet. The pump power require-
ments were then computed

$$\text{POWRTA}= \frac{0.746 \ \text{HORPOW} \ 24 \ 365}{0.95} \tag{3-37}$$

where

POWRTA=power requirement, kilowatts/year

The physical characteristics of the great lake and coastal sites
were computed in one subroutine. The surface temperature rise or
maximum temperature at the edge of the mixing zone was computed by
means of the subroutines FROUD, AREA, and DIST, and dilution flow
was also provided for in these computations. The evaporative loss
computations will be explained in section C. 4. of this chapter.

The heated surface area was computed in subroutine HAREA. In
this case the near-field boundary conditions were used as the far-
field starting point for calculations. The lateral spreading was
considered as a power function of the initial plume width

$$\text{KZO}=0.01 \ (\text{WIDTH})^{1.33} \tag{3-38}$$

where

KZO=lateral eddy diffusion coefficient based on initial plume

width, $cm^2/sec$

WIDTH=initial plume width, cm

The surface heat exchange coefficient KOEFF2, was calculated and the

centerline temperature decay computed until it reached the specified

limit of $0.5^o$ F, incrementing the areas as it went along. Longi-

tudinal segments of 528 feet were chosen for these calculations.

The following temperature decay equation was used. It should be

noted that the depth assumed in the calculations was only one-half

of the water body depth due to the buoyant surface jet discharge.

$$TEMFED = TEMCEN \cdot EXP \left( - \frac{1.0 \; XDIST \; KOEFF2}{62.4 \; (SITTY3/2 \;) \; SITTY4 \; 24 \; 3600} \right) \cdot$$

$$ERF \left( \frac{1.5}{\left[ \left( 1 + \frac{8 \; KZO \; XDIST}{SITTY4 \; WIDTH^2} \right)^3 - 1 \right]} \right)^{0.5} \tag{3-39}$$

where

TEMFED=centerline temperature rise above ambient, $^o$ F

TEMCEN=centerline temperature rise above ambient at X=0, $^o$ F

XDIST=longitudinal distance from start of far-field, feet

KOEFF2=surface heat exchange coefficient, $BTU/ft^2$-day-$^o$ F

SITTY3=water body depth, feet

SITTY4=water body velocity, feet/second

KZO=lateral eddy diffusion coefficient based on initial plume

width, $feet^2/second$

WIDTH=plume width at start of far-field, feet

ERF=standard error function defined as erf $\phi \dfrac{2}{\sqrt{\pi}} \displaystyle\int_0^\phi e^{-w^2} dw$

The width at each section, WIDTH2, was estimated according to the following relation:

$$\text{WIDTH2=WIDTH} \left( 1 + \frac{8 \text{ KZO XDIST}}{\text{SITTY4 WIDTH}^2} \right)^{1.5} \tag{3-40}$$

The area in acres was then computed by a trapezoidal approximation for each segment where TEMCEN was greater than 0.5 and summated.

The intake temperature for these two sites was also assumed to be equal to the ambient water temperature due to the ability to select an appropriate location for the intake pipe which would result in the recirculation being equal to zero. The pump power requirements were computed in the same manner as was done in the river site by means of the subroutine POWS1. The land surface area computations were also performed in the same manner, but a different length of discharge and LENGT2 was assumed for these site types. (see table 3.7)

The third sub-program considered the offshore ocean site type. The ocean site depth of 100.0 feet, was reduced to a maximum depth of 30 feet for the calculations on the limiting depth of the plume in subroutine FROUD, and for the heated layer depth in EVAS2, and HAREA. The subroutines AREA and DIST were again employed to check the thermal standards and calculate the abatement type characteristics, including consideration of the alternative of dilution flow.

The evaporative loss computations will be explained in a following section, and the heated surface area was computed by

subroutine HAREA. The new intake temperature was taken as equal to the ambient water temperature, due to the flexibility in locating the intake pipe to prevent recirculation for this site type. The land surface area required for the discharge canal, which will have to be constructed in this alternative, was computed by subroutine LANS1 with the canal length, LENGT2, given in table 3.7 and the canal width, WIDT1, computed in subroutine FROUD. The pump power requirements were calculated by means of subroutine POWS1, as was done in the river site alternative.

The estuary site type was also analyzed by a separate sub-program. The procedures used to analyze the abatement characteristics and to check the ability of the plant alternative to comply with thermal standards are contained in the previously described subroutines FROUD, AREA, and DIST. The subroutine for the evaporative loss will be explained in a following section.

The heated surface area computations to $0.5^\circ$ F were partially carried out in the evaporation subroutine where the distance upstream and downstream to the temperature limit was computed. The entire width of the estuary was assumed to be uniformly heated, and with the total affected distance upstream and downstream known, the area in acres, RRT (1), may then be computed.

The new intake temperature for the estuary was set equal to the ambient water temperature. Since the buoyant surface jet will induce a stratified flow upsteam of the plant, the use of a skimmer wall will be required, but it has been assumed for this study that this will be a feasible alternative to prevent recirculation.

The pump power requirements were computed by means of POWS1.
The land area requirements were computed by means of LANS1 with
adjustments made in the discharge canal lengths.  (see table 3.7)

Finally, the small lake alternative was considered with a sur-
face discharge.  This site was selected as a 2000 acre existing
natural water body, or one constructed on a natural water body.  It
would be used as a "cooling pond", but since there will be a dis-
charge of heated water to an existing water body, the standards will
have to be complied with and the physical aspects of the problem will
be different than a closed cycle cooling pond.  The abatement
technology characteristics and the check for compliance with thermal
standards was made by means of subroutines FROUD, AREA, and DIST.

The heated surface area calculations assumed that due to the
limited size of the lake, the entire surface area would be heated
above $0.5^{\circ}$ F.

The new intake temperature was computed in the following manner,
assuming a high degree of initial mixing which results in a fully
mixed water body.  These computations also assume that the lake will
approach the equilibrium temperature.  The details of the procedure
used for the calculation of the equilibrium temperature will be
explained in a following section on the modelling of cooling ponds.
An iterative  process was used to solve for TIN, TOUTLT, and
KOEFF2 assuming the pond was at a temperature, TINTAK, of TEQUIL
plus 0.1 to start the process.  The outlet temperature, TOUTLT,
was equal to TIN plus the plant temperature rise TERIPL.  The
important equations in this process are:

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$$\text{TEMFOR} = \left[\frac{\text{TINTAK} + \text{TOUTLT}}{2.0}\right] 0.5 + \left(\text{TEQUIL}\right) 0.5 \qquad (3\text{-}41)$$

where

TEMFOR=representative surface temperature of pond, $^{\circ}$ F

TINTAK=assumed plant intake temperature, $^{\circ}$ F

TOUTLT=plant outlet temperature, $^{\circ}$ F

TEQUIL=equilibrium temperature, $^{\circ}$ F

The surface heat exchange coefficient calculations will be explained
in the section on evaporation. The actual intake temperature, TIN,
was then computed according to the following equation and compared
against the assumed value TINTAK until the difference was less than
0.1.

$$\text{TIN=TEQUIL} + (\text{TOUTLT} - \text{TEQUIL}) \left(\frac{1}{1 + \dfrac{\text{KOEFF2 AREAFT}}{62.4 \text{ FLOPLA } 3600 \text{ } 24}}\right) \qquad (3\text{-}42)$$

where

TIN=actual value of intake temperature, $^{\circ}$ F

KOEFF2=surface heat exchange coefficient, BTU/ft$^{2}$-day-$^{\circ}$ F

FLOPLA=plant cooling water flow, cfs

The evaporative loss calculations were explained in the follow-
ing section on evaporative losses. The pump power requirements
were computed according to subroutine POWS1. The land requirements
were computed by subroutine LANS1 with revised values of the length
of the discharge canal, LENGT2, as given in table 3.7.

Diffuser. The dilution obtained with a single buoyant jet is
generally small, and thus this method is generally not practical for
water heat discharge from large power plants. A multiport diffuser,

which is made up of many small single jets, yields dilution and temperature reduction several times greater than that of a single jet. This type of diffuser also produces an effective line or slot source a short distance away. Also, the diffuser can be designed for slot discharge which results in the formation of a line source.

The jet dilution and trajectory are strongly influenced by the water environment into which the discharges take place, according to Harleman and Stolzenbach (1972). Currents in the receiving water may also affect the trajectory and dilution of the jet. If the receiving body of water is not density stratified due to ambient temperature differences, for a positive buoyant discharge the water will rise to the surface and spread laterally. However, when the receiving water body is stratified and non-uniform with respect to density the possibility exists that the jet will not reach the surface. This type of behavior is applicable in the case of jets discharged into water bodies of infinite size, and the behavior also holds for large finite bodies. However, for bodies of water which are shallow with respects to the vertical dimension of the discharge, the limited distance for rise available to the jet and the effect of bottom friction can alter the jet behavior.

When the buoyant jet reaches the free surface, the buoyancy and horizontal momentum may cause surface spreading relative to the receiving water in the near-field region, according to Harleman and Stolzenbach (1972). This may result in altering the width and depth of the plume distribution even though little entrainment and mixing takes place. These conditions become important due to their

use as input into far-field mixing studies, and limited studies have shown the thickness of the surface field as approximately one-twelfth of the trajectory length for a round jet in uniform environment. This surface spreading process is difficult to study since different flow regimes are encountered, and was not considered in the model developed for this study.

For receiving water bodies which are shallow relative to the characteristic size of the jet opening, such an near-shore areas, the analysis of jets is difficult due to the interactions of the jet with the bottom and the free surface. However, experimental and analytical studies of this problem of multiport diffusers in shallow receiving waters have been made by Harleman, Stolzenbach, and Jirka (1971) and Adams (1972). The studies involved prediction of temperature downstream of the diffuser in a shallow water body with a cross current. The receiving body was uniform in temperature and shallow enough so that the temperature rise downstream was uniform with depth.

The diffuser abatement technology was considered a feasible alternative at the river, great lake, coastal, offshore ocean, estuary, and small lake sites for this study.

The river site alternative was modeled in the following manner. The abatement characteristics were analyzed with these assumptions. The port diameter, DIAMPO, was assumed equal to 2 feet, and the flow velocity through the port, VELPOR, was assumed equal to 15 feet/second. The flow through each port, FLOPOR, was then computed, along with the total number of ports required to handle the plant flow, NUMPOR. The port spacing, PORSPA, was assumed equal to the river

depth, SITTY3, and the length of the diffuser was equal to the number of ports times the port spacing.

The relations developed by Adams (1972) were used to analyze the temperature rise in the near-field area with the use of diffusers for this shallow water body. Unfortunately, the state of the art is not such that a simple means is available to calculate the area within a particular temperature isotherm as was in the case of the surface discharge, and thus the general question of meeting thermal standards in the near-field was addressed, but in distinction was provided for the area and distance type of mixing zone.

The mixed temperature for the near-field region was computed according to the following relations and the temperature standards were compared with this temperature rise or the actual mixed temperature itself, depending on the limiting value. For the case of ports directed in the direction of or against the cross current, the following relation was used to determine the surface water temperature:

$$
\text{TEMFOR} = \text{TEWAAM} + \left( \text{TOUTLT} - \text{TEWAAM} \right) \Big/ \left\{ \frac{1}{2} \left( \frac{\text{SITTY4 LENDI SITTY3}}{\text{VELPOR ARPORT NUMPOR}} \right) \right.
$$

$$
\left. + \frac{1}{2} \left[ \left( \frac{\text{SITTY4 LENDI SITTY3}}{\text{VELPOR ARPORT NUMPOR}} \right)^2 + \text{PORTDI} \frac{2 \text{ LENDI SITTY3}}{\text{ARPORT NUMPOR}} \right]^{\frac{1}{2}} \right\}
$$

(3-43)

where

TEMFOR=mixed water body temperature in near-field, $^{\circ}$F

VELPOR=flow velocity through the diffuser ports, ft/sec

ARPORT=cross sectional area of jet discharge, ft$^2$

NUMPOR=number of ports in diffuser

PORTDI=direction of port discharge; +1 with current, -1 against

   current

For this study, the direction of the port discharge was assumed to
be with the current. The temperature rise in the near-field region
was then computed as:

$$TERISE=TEMFOR-TEWAAM \tag{3-44}$$

where

  TERISE=temperature rise in near-field region

For the case of alternating directions of the ports the mixed water
temperature was calculated according to the following equation,
with the temperature rise then determined by Equation 3-44.

$$TEMFOR=TEWAAM + \cfrac{TOUTLT-TEWAAM}{\frac{1}{2}\left[\cfrac{SITTY4\ \ LENDI\ \ SITTY3}{VELPOR\ \ ARPORT\ \ NUMPOR}\right]} \tag{3-45}$$

The possibility of flow dilution was also included in the model for
this alternative in checking the thermal standards for the ability
of a plant alternative to comply with the requirements.

The evaporative loss calculations are explained in the following
section of this chapter on evaporative losses. The new intake tem-
perature in this case of a river site was set equal to the ambient
water temperature assuming the recirculation equal to zero with the
intake pipe located a sufficient distance upstream.

The land surface area requirement, RRT (3), was calculated as
equal to zero since the diffuser scheme will involve both an intake
pipe and discharge lines buried underground or underwater, and the
other land requirements were assumed to be negligible.

The heated surface area, RRT (1), was computed in this case by assuming a fully mixed condition due to the shallow depth with complete mixing with the entire river flow. The entire surface area of the river was again assumed to be heated, and the remainder of the procedure followed the process enumerated in the previous section on surface discharges.

The power requirements were computed according to subroutine POWD1 in a manner similar to that described in the previous section on surface discharge. However, in this case the total head, HEAD, was set equal to a head of 20 ft for plant loss s plus SITTY3, the water body depth, plus 20 ft of head due to loss s in discharge pipe and the diffuser for the circulating water flow, and a head of SITTY3 plus 20 ft for the dilution flow.

The great lake and coastal sites were also modeled together in one subroutine in the diffuser alternative. The abatement Technology characteristics and the check of the ability of the site to meet thermal standards was performed in the same manner as the river site. The evaporative loss calculations will be explained in a later section of this study.

The new intake temperature was assumed to be equal to the ambient water temperature for these two sites due to the flexibility in location of the intake pipe, and the relatively large distance offshore where the diffuser pipe would be located.

The power requirements were calculated according to subroutine POWD1 with the total pumping heat, HEAD, determined in the manner described for the river site. The land surface are required for

this technology was computed by means of subroutine LAND1.

The heated surface area was computed in subroutine HAREAD for these alternatives in a similar manner to the procedure outlined for the surface discharge alternative, but the entire depth of the water body was involved in the mixing process for this alternative. Also, the diffuser was assumed to generate fully mixed conditions in the near-field, and thus the input boundary conditions were modified. The lateral eddy diffusion was again computed by means of the 4/3 law based on the initial plume width. The depth used to estimate the temperature decay was also set equal to the entire depth of the water body, SITTY3.

The estuary site alternative with the diffuser pipe was analyzed by another subprogram. The abatement characteristics and the ability of the site to comply with standards were accomplished in the manner described for the river site. However, in this case the diffuser analysis will not yield as reliable a solution due to the changes in the direction of the tidal current during the tidal cycle. The alternative was analyzed by assuming that the diffuser ports were in alternating directions due to the varying direction of the current.

The evaporative loss computations will be developed in a following section. The calculations for the heated surface area to $0.5^{o}$ F were carried out in the evaporation subroutine where the distances downstream and upstream to the specified temperature limit are computed. Assuming the entire width of the estuary was uniformly heated, and knowing the total longitudinal distance affected, the heated surface area in acres, RRT (2), may then be computed.

The temperature rise at a distance of 1,000 feet upstream from the point of discharge was also computed in the evaporation subroutine to estimate the new plant intake temperature since complete mixing over the entire cross-section was assumed at this point.

The land area requirements were computed by means of subroutine LAND1. The power requirements were computed by means of subroutine POWD1 with a total head equal to the estuary depth plus 20 ft in addition to the plant loss of 20 ft.

Due to the large depth of water availab'e at the site, the shallow-water model could not be used to analyzc the ocean alternative. The offshore ocean site was therefore eva uated for the abatement characteristics and the check for thermal standards as two large diameter single port jets separated by a sufficient distance to eliminate intereference. The procedure used is outlined as follows.

The analysis of Fan and Brooks (1969), as reported in Ditmars (1972-1), presented graphical data of the dilution for a single submerged circular jet. The dilution is a function of the densimetric Froude number and the submergence of the discharge, SITTY3/DIAMPO, where DIAMPO is the jet diameter. The model developed for this study assumed there would be two single submerged circuler jets discharging horizontally separated by a sufficient distance to avoid interference and to allow analysis as a single jet. Thus, the plant flow was divided in half, and the analysis carried out for one single jet. The discharge velocity, VELPOR, was assumed equal to 15.0 ft/sec. The diameter of the submerged jet was calculated as:

$$DIAMPO = \left( \frac{4 \ FLOPLA}{2 \ VELPOR \ 3.1416} \right)^{0.5} \qquad (3\text{-}46)$$

where

FLOPLA=total cooling water flow, cfs

VELPOR=flow velocity through diffuser ports, fps

The initial Froude number, FROUDE, was computed according to the

following relation:

$$FROUDE = \frac{VELPOR}{(DELDEN \ DIAMPO)^{0.5}} \qquad (3\text{-}47)$$

Then YD, which is the ratio of the depth SITTY3 to the jet diameter

DIAMPO was computed

$$YD = \frac{SITTY3}{DIAMPO} \qquad (3\text{-}48)$$

The graphical solution was then searched numerically to determine

the appropriate dilution factor, DIL, and then the surface tempera-

ture rise was computed as:

$$TERISE = \frac{TERIPL}{DIL} \qquad (3\text{-}49)$$

where

TERISE=temperature rise in near-field region, $^{\circ}$ F

TERIPL=plant temperature rise, $^{\circ}$ F

DIL=dilution=$C_o/C$

The opportunity for flow dilution was also provided in the analysis

of this alternative.

The evaporation loss computations are outlined in a following

section. The heated surface area computations were carried out

assuming that the heated layer was equal to approximately 1/12 of

the trajectory length. For a horizontal discharge, assuming a 45° trajectory to the surface, the surface heated layer was assumed to be equal to a redefined depth, SITTY3, according to the following relation:

$$\text{SITTY3} = \frac{\sqrt{2} \, \text{SITTY3}}{12} \tag{3-50}$$

Having defined this layer thickness, the computations can then be completed in the manner described for the great lake and coastal sites by the use of subroutine HAREAD.

The new intake temperature was taken as equal to the ambient water temperature due to the flexibility of locating the intake pipe on this island type site. The land area requirements were computed by means of subroutine LAND1. The power requirements were calculated by subroutine POWD1, but in this case the head was set equal to the plant loss plus losses for the diffuser and discharge line equal to the water body depth plus 20 ft.

The small lake alternative was also considered with a diffuser due to the applicability of the thermal standards at this site type. The abatement characteristics and check for thermal standards were made by means of the shallow multi port diffuser calculations enumerated under the river site alternative.

The heated surface area calculations assumed that the entire lake surface area will be heated above 0.5° F. The new intake temperature was computed in the same manner as in the surface discharge computations assuming a high degree of initial mixing and a resulting classification of the water body as fully mixed. The

evaporative loss calculations will be explained in a following section. The power requirements were computed according to subroutine POWD1 with the total head equal to the plant loss plus an allowance for the discharge line and diffuser pipe.

Cooling Pond. The dominating factor in cooling pond performance is density induced currents for ponds not vertically mixed and as the depths are reduced, the density currents become less important and wind induced currents dominate according to Ryan (1972). The wind effects increase the surface heat transfer coefficient and can even cause mixing of surface layers if the velocity is in excess of 15 MPH. The amount of entrance mixing in a cooling pond is a function of the design of discharge structure, the densimetric Froude number of discharge, and the topography of outlet. Increased entrace mixing leads to a decrease in pond performance, an increase in surface layer thickness, a decrease in pond response time, and eddies may be induced in the vicinity of discharge. These characteristics should be avoided by careful design in the shallow closed cycle plug flow cooling pond analyzed in this study.

The cooling ponds have a large thermal inertia and thus intake temperatures do not reflect short term meteorological functuations and respond slowly to loading changes. The time scale, t, for a cooling pond is (V/Q) where V is the volume of the pond and Q is the condenser flow rate. As indicated by Ryan (1972), time scales are frequently in the order of a week or more.

Thus a well designed pond should have a low discharge Froude number, a low intake, and a reasonable depth (generally less than

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15 ft). The more efficient pond will also have the smaller entrance mixing.

The surface area of a cooling pond must be sufficient to cool the water to a temperature that will allow satisfactory operation of the power plant. According to Dynatech (1969), a pond of reasonable size can be designed in order to attain a 2-3$^\circ$ F approach temperature. Another approach to sizing is to allow 1 acre of surface area/ Mw for fossil-fueled plants plus 20% for surrounding land with a 2 acre/Mw plus 20% requirement for the alternat've of nuclear plants. It should be noted that the pond surface area wi.1 be independent of the pond depth for all intents and purposes. The conduction of heat to the earth surrounding the pond is generally ne ected in design but it has been estimated from 12 BTU/ft$^2$-day-$^\circ$ F to as much as 60 BTU/ft$^2$-day-$^\circ$ F, but this assumption has the desirable effect of providing a safety factory in pond design.

In the design of a cooling pond, consideration must be given to the power plant intake temperature, the limit to which the heated water can be cooled, the effect of the weather conditions, the power plant outlet temperature, and the necessary pond area required in order to result in a certain degree of cooling, according to Thackston and Parker (1972). The considerations can be effectively dealt-with by the computation of the equilibrium temperature, the surface heat exchange coefficient, and the plant effluent temperature.

The surface heat exchange coefficient (BTU/ft$^2$-day-$^\circ$ F) is

used to express the rate at which a body of water not at equilibrium
would approach equilibrium. This rate is a function of the dif-
ference between the actual water surface temperature and the
equilibrium temperature and to a rate constant which is a function
of meteorological conditions.

In the work of Thackston and Parker (1972), on the geographical
influence of cooling ponds, the meteorological data was obtained from
the U. S. Weather Bureau's "Local Climatological Data". The high
value of the equilibrium temperature was found to occur in mid-July,
and this temperature is a function of the latitude which controls the
solar radiation. The heat exchange coefficient exhibited the same
pattern as the temperature with heat exchange maximum when tempera-
ture is highest. However, topographic conditions influence the wind
speed and wet-bulb temperature and thus have a strong influence on
the surface heat exchange coefficient. The cause for an increase in
the coefficient is an increase in evaporation and back radiation
due to the higher water temperature, but this may be slightly
offset in the case of lower wind speeds.

The net surface heat exchange coefficient is the sum of the net
solar radiation, the net atmospheric radiation, the back radiation,
the evaporation, and the conduction with the negative terms
indicating a heat loss. The equilibrium temperature may be calcu-
lated by determining the net heat exchange coefficient for an
assumed value of the equilibrium temperature, and making iterations
until the temperature where the net heat flux is equal to zero is
located. This method is more accurate since it does not involve

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approximations beyond the equations used to determine the radiation, evaporation, and conduction terms.

In this study the value of the equilibrium temperature, TEQUIL, was computed in the following manner, with the necessary equations taken from Ryan (1972).

Set PHINET=net heat flux=0

$$PHINET=(PHISN + PHIAN) - (PHIBR + PHIEV + PHIC) \qquad (3-51)$$

where

PHINET=net heat flux for a water body, $BTU/ft^2$-day

PHISN=net solar radiation, $BTU/ft^2$-day

PHIAN=net atmospheric radiation, $BTU, ft^2$-day

PHIBR=longwave radiation from water surface, $BTU/ft^2$-day

PHIEV=evaporative heat loss, $BTU/ft^2$-day

PHIC=heat loss by convection, $BTU/ft^2$-day

Substitute the following for these variables:

$$PHISN=PHISI -PHISR \qquad (3-52)$$

where

PHISI=incoming solar radiation, $BTU/ft^2$-day=2,000 BTU/ $ft^2$-day

PHISR=reflected solar radiation=0.06 PHISI

$$PHIAN=800 + 28\ TEDRBU \qquad (3-53)$$

$$PHIBR=1600 + 23\ TEMSUR \qquad (3-54)$$

where

TEMSUR=assumed temperature of water surface, $^\circ$F

$$PHIEV = 17.2 \ WINVEL \ (PRSAWA - PRPAVA) \qquad (3-55)$$

where

PRSAWA=saturation vapor pressure at water surface tempera-

ture, mm Hg

PRPAVA=partial vapor pressure of the air, mm hg

$$PHIC = .255 \ \left( \frac{TEMSUR - TEDRBU}{PRSAWA - PRPAVA} \right) \ PHIEV \qquad (3-56)$$

Substituting for the variables, the equation was solved for
the water surface temperature at which PHINET=0. The initial value
of TEMSUR was set equal to TEMDEW plus 0.1, and this variable was
iterated at 0.1 increments until PHINET became equal to zero, and
then TEQUIL was set equal to TEMSUR. It should be noted, however,
that evaporative and convection heat loss will take place only if
PRSAWA is greated than PRPAVA and a check should be placed in the
iteration process to account for this. If (PRSAWA -PRPAVA) is less
than 0, then PHIEV and PHIC should be set equal to zero.

The question of thermal standards and the ability of a plant
alternative to be constructed and operated on a given site alterna-
tive in compliance with these regulations was not addressed in the
model for the cooling pond in a closed cycle system. Since no natural
water body would be subjected to an increased temperature it was
assumed that no thermal standards would be applicable in this case.

The abatement characteristics of the cooling pond were
developed in the following manner. The pond depth, DEPTHP, was
assumed to be equal to 15 feet. The minimum pond volume, VOLUM, was

defined as the cooling water flow from the plant, FLOPLA, for a 96 hour period. For these conditions the following variables were evaluated:

HOURS=time for which the pond provides volume to contain the plant flow, hours

DAYS=time for which the pond provides volume to contain the plant flow, days

$$VOLUM=FLOPLA\ 3600.\ HOURS \qquad (3-57)$$

where

VOLUM=volume of cooling pond, $ft^3$

$$AREA1=VOLUM/DEPTH \qquad (3-58)$$

where

AREA1=surface area of pond, $ft^2$

$$AREA2=AREA1/43560 \qquad (3-59)$$

where

AREA2=surface area of pond, acres

A check was then made of the loading of the cooling pond for this particular design.

$$LOAD=AREA2/PLASIZ \qquad (3-60)$$

where,

LOAD=pond loading in acres/Mw

PLASIZ=plant size, Mw

If the loading was determined to be less than 1.0 acre/Mw, LOAD was set equal to 1.0 acres/Mw and new values of AREA2, VOLUM, HOURS, and

DAYS were calculated. If the loading was greater than 2.0 acres/Mw, LOAD was set equal to 2.0 acres/Mw and revised values of AREA2, VOLUM, HOURS, and DAYS were computed.

A simple analytical model as given by Ryan (1972) was used to compute the plant intake temperature for the closed cycle shallow cooling pond. The lateral mixing dominated the vertical mixing in this case. The pond was schematized such that the mixed flow DFLOPLA (where FLOPLA is pumping rate) goes through pond as plug flow, and that a mixing flow (D-1) FLOPLA returns to the discharge end also as a plug flow. Areas of the mixed flow and the return flow were assumed proportional to the flow rate. The total surface area of the pond was assumed active in heat dissipation but only depth d of total depth, DEPTHP, was affected, with complete vertical mixing assumed over the depth d.

The model developed for a shallow pond results in the following equation:

$$\frac{TIN - TEQUIL}{TOUTLT - TEQUIL} = \frac{\exp^{-\frac{r}{2D-1}}}{D - (D-1) \exp^{-\frac{2r}{2D-1}}} \tag{3-61}$$

where

$r = \dfrac{KOEFF2 \ AREAFT}{\rho c \ FLOPLA}$

AREAFT = total surface area of pond, $ft^2$

TOUTLT = discharge temperature from plant, $^\circ F$

D = dilution due to lateral mixing (1 to 5, with 1 indicating no

     mixing)

Since the pond was designed in this alternative, the plug flow case was assumed to exist with its higher design efficiency. Therefore, setting D=1, and rearranging Equation 3-61 reduces to

$$TIN = TEQUIL + (TOUTLT - TEQUIL) \exp^{-r} \qquad (3-62)$$

The intake temperature, TIN, was determined by setting:

$$TINTAK = TEQUIL + 0.1 \qquad (3-63)$$

where

TINTAK=assumed intake temperature

$$TOUTLT = TIN + TERIPL \qquad (3-64)$$

and calculating the surface. heat exchange coeff. ient KOEFF2 for the following surface water temperature TEMFOR

$$TEMFOR = \frac{1}{2} \left( \frac{TINTAK + TOUTLT}{2.0} \right) + \frac{1}{2} \left( TEQUIL \right) \qquad (3-65)$$

and solving Equation 3-62. The equation was solved in an iterative fashion, recomputing TINTAK, TEMFOR, and KOEFF2 until the value determined by Equation 3-62 is approximately equal to the assumed intake temperature, TINTAK.

Blowdown is defined as the quantity of water which must be added to a closed cycle cooling system in order to prevent a build-up in the concentration of solids. This requirement, in addition to the evaporative losses, would make up the consumptive water use needs RRT (2) for this abatement alternative.

The procedure used for determining the evaporative losses is explained in the following section on the subject of evaporation. The blowdown requirements, BLOWDN, were estimated at 1% of the

circulating water flow for fresh water sites, and 5% of the cooling water flow for salt water sites due to the increased concentrations of chemicals and solids. The total consumptive use was simply the sum of the total evaporative losses and the blowdown requirements.

The heated surface area, resource requirement RRT (1) was set equal to zero for all site alternatives for the cooling pond technology. This was done since the ponds will be artificially created water bodies and thus no existing water surface area will be affected significantly by the heated discharge. The only heated discharge to an existing water body may be a relatively small amount of blowdown water.

The land area, resource requirement RRT (3), was estimated at 20% greater than the calculated pond water surface area, AREA2.

The annual power consumption for this alternative was estimated by calculating the horsepower, HORPOC, for the circulating water system and the make-up water system, HORPWR. The total horsepower required, HORPOW, was simply the sum of the two components.

The electric power required by the pumps per year was also computed in three similar steps, with the total electric power requirement per year labeled POWRTA. For the circulting water system, the following relationships were used:

$$HORPOC = \frac{62.4 \ FLOPLA \ HEAD}{550 \ EFFICI} \tag{3-66}$$

where

HORPOC=horsepower requirement for circulting water system

HEAD=pumping head, ft

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EFFICI=pump efficiency, %/100

$$PCWRTC= \frac{0.746 \ HORPOC \ 24 \ 365}{0.95} \qquad (3\text{-}67)$$

where

POWRTC=power requirements for circulating water system, kw/yr

Similarly, for the make-up water system, where the head, HEADM, was

assumed equal to the 20 ft for all sites, the equations developed

were:

$$HORPWR=\frac{62.4 \ RTT \ (2) \ HEADM}{550 \ EFFICI} \qquad (3\text{-}68)$$

where

HORPWR=horsepower requirements for make-up water system

HEADM=pumping head for make-up water system, ft

RRT (2)=make-up water requirement, cfs

$$POWRTM= \frac{0.746 \ HORPWR \ 24 \ 365}{0.95} \qquad (3\text{-}69)$$

where

POWRTM=power requirements for make up water system, kw/yr

The total requirements for horsepower, HORPOW, were the sum of

Equations 3-66 and 3-68, and the total requirements for power,

POWRTA, were the sum of Equations 3-67 and 3-69.

Spray Canal. Since the concept of the use of spray modules in a

circulating water canal is a recent one, very little information was

available in the literature on the physical aspects of this system.

Therefore, the works of Berman (1961) and Dynatech (1969) were

reviewed for the physical aspects of fixed spray ponds, and discussions were held with Mr. Patrick Ryan, Research Assistant at the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics at M.I.T. In conjunction with his doctoral research, he has developed a tentative design curve for the heat dissipated by spray modules per unit as a function of the plant intake and outlet temperature, and the equivalent wet-bulb temperature. This curve was used by the author as the foundation for the development of the spray canal physical model. Ryan (1972) also contains a brief summary of the state of the art in the area of spray modules.

According to Dynatech (1969), spray ponds have been designed to handle cooling water flows as high as 120,000 gpm. The pumping costs for this type system are generally computed for heads ranging from 4 to 30 feet. Also, due to the greatly increased heat exchange coefficient, the area requirements for a spray pond are reduced to approximately 5% of that which would be required for a cooling pond. The detailed design data on the spray pond system was generally not available in the open literature, and that information which was available was frequently not up to date.

The spray module concept used in the spray canal involves re-spraying the same water many times, with droplet sizes of approximately ½ inch, as it passes through the spray canal. According to Ryan (1972), the wind has an important effect on the performance of the spray module, such that a 60% increase in wind speed may lead to a 15 to 20% increase in performance.

One of the principal advantages of this type of system would be the reduction of salt water drift at coastal and estuary sites, according to Brodfeld (1972). He reports that the spray cooling systems were initially used as add-on provisions to existing cooling systems, but that in the future they may become a feasible alternative as an independent system, especially on coastal sites where once-through systems have been proven impractical. The system is not without its difficulties, however, and the problems of large land area requirements, control of seepage fr r canals, and the potential interference due to a large number of spray modules will require further consideration.

The spray canal technology in a closed cycle system will not require analysis of the question of thermal standards and the ability of a plant alternative to be constructed and operated in compliance with them on an available site. This was due to the fact that no natural water body will receive any significant amount of waste heat discharge and thus no thermal water quality standards will be applicable.

The procedure used to develop the spray canal model was as follows. A spray canal width, CANWID, of 160 feet was assumed, and the number of rows NUMROW, was computed at 40 feet per row. The equivalent wet-bulb temperature, TEWEB, was then computed according to the following equation since each row of nozzles perpendicular to the wind direction may increase the effective wet-bulb temperature by $1^\circ$ F.

$$TEWEB = \frac{TEWEBU + (TEWEBU + NUMROW)}{2.0}$$ (3-70)

where

TEWEB=equivalent wet-bulb temperature, $^{\circ}$ F

NUMROW=number of rows

An approach of $10^{\circ}$ F to the equivalent wet-bulb temperature was assumed in the calculation of the plant intake temperature, TIN. The outlet temperature, TOUTLT, was then calculated from the intake temperature plus the plant temperature rise, TERIPL. The characteristic temperature, TEMCHA, will then be computed according to the following relation:

$$TEMCHA = \frac{TOUTLT + TIN}{2.0} - TEWEB$$ (3-71)

where

TEMCHA=characteristic temperature, $^{\circ}$ F

The heat to be dissipated per hour was calculated according to the relation developed by Ryan.

HEET=HEREJC PLASIZ (3-72)

where

HEET=heat to be dissipated per hour, BTU/hr

HEREJC=heat rejection rate, BTU/kwhr

PLASIZ=plant size, kw

The acreage required to dissipate this amount of heat per hour was determined according to a relation developed from the design curve of Ryan.

HETDIS=((1.5 TEMCHA) -10.6) 1000000 (3-73)

where

HETDIS=heat dissipated, BTU/acre-hour

This equation was developed with an assumed area of 40 ft X 160 ft

for each spray module unit, and thus the number of units were

computed as follows:

ACRES=HEET/HETDIS (3-74)

where

ACRES=minimum number of acres required for the spray modules

$$\text{NUMUNI} = \frac{\text{ACRES } 43560}{40 \quad 160} + 1 \qquad (3-75)$$

where

NUMUNI=number of spray module units required

<u>NOTE</u>: +1 was used to compensate for round-off error in
computer program

Finally, the total water surface area of the canal was estimated

based on an assumption of 50% greater than the minimum acreage

requirements for the spray modules.

The new plant intake temperature from the spray canal was

derived from the assumption of a $10^{\circ}$ F approach to the equivalent

wet-bulb temperature. Thus, the intake temperature will be $10^{\circ}$ F

above the equivalent wet-bulb temperature.

The consumptive use of the spray module concept would include

the evaporative loss, the blowdown, and drift loss. The drift is

the amount of water lost from the system due to entrainment of a

portion of the spray in the surrounding air. The evaporative loss

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calculations are explained in the section on evaporative losses.
The drift losses, DRIFT, were computed based upon an assumption of
1% of the cooling water flow. The blowdown losses, BLOWDN, were
assumed at a rate of 1% higher than the values used in the cooling
pond model since the higher rate of evaporation induced by the spray
modules will cause a more rapid build up of chemical concentrations.
Thus, the blowdown was calculated at 2% of the circulating water
flow for fresh water sites, and 6% of the circulating water flow for
the salt water sites due to increased concentrations of chemical and
solids. The summation of the drift, evaporative, and blowdown losses
would equal the total consumptive use, RRT (2).

The spray canal heated surface area resource are requirement,
RRT (1), was set equal to zero for all site alternatives. As in the
cooling pond alternative, no existing water surface area will be
significantly affected by the heated discharge since the spray canal
will be an artificially created water body and only relatively small
amounts of blowdown water may be discharged to an existing water
body.

RRT (3), the land area required for the abatement technology,
was computed based upon an assumption of 20% greater than the
computed water surface area of the canal, AREAAC.

The power requirements for the make-up and circulating water
systems were computed in the same manner as the power requirements
for the cooling pond system, described in a previous section. How-
ever, additional power was required in this system due to the use
of the spray modules. According to Ryan, the horsepower requirement

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for each spray module would be 75 hp. Thus, the total power require-
ment, POWRTA, was the sum of the requirements for the make-up system,
POWRTM, the spray modules, POWRTS, and the circulating water
system POWRTC.

Wet Mechanical Draft Cooling Tower. The model for the wet
mechanical draft cooling tower was developed by Mr. Frederick
Woodruff, Research Assistant at the Ralph M. Parsons Laboratory for
Water Resources and Hydrodynamics at M.I.T. in conjunction with the
work on the Dynamics of Engergy Systems Stuv.

This section will present a brief summary of his work in
developing this model, and its adaptation for t. is study. The
function of the model is to determine the performance characteristics
of a wet mechanical draft cooling tower for a specified plant and
site type. The site alternatives considered feasible for this
alternative were the river, great lake, coastal, estuary, small
lake, and water poor sites.

The flow rate of water through the plant, GPM, was computed in
the following manner:

$$GPM = \frac{QR}{60 \cdot 8.33 \cdot TERIPL} \tag{3-76}$$

where

QR=heat rejection of condenser to cooling water, BTU/hr

TERIPL=plant temperature rise, $^\circ$ F

In the wet mechanical draft cooling tower operated in a closed
cycle mode, the question of thermal stardards and the ability of a
plant alternative to be built and operated in compliance with them on

an available site will not require analysis.  This was due to the

fact that no significant amount of waste heat will be discharged to a

natural water body and thus no thermal standards will be applicable.

The abatement characteristics of the wet mechancial draft

cooling tower were calculated as input to the cost analysis of this

alternative, and were enumerated in the previous section on the

computation of cost for this technology.

The make-up water requirements were calculated according to a

procedure outlined in Dynatech (1971).  The following computations

were performed.  The water temperature into the plant, T2, was set

equal to the wet-bulb temperature TEWEBU plus the approach tempera-

ture, A.  The water temperature into the cooling tower unit, Tl, was

set equal to T2 plus the plant temperature rise, TERIPL.  The average

temperature, TAXT, was defined as the average of Tl and T2.  A sub-

routine AIR, also developed by Woodruff, was then used to compute

the enthalpy of the air at the average temperature, TAXT, and the

wet-bulb temperature, TEWEBU.  The air flow rate was determined as:

$$AFLR = \frac{QR}{(HTAXT - HWB)} \tag{3-77}$$

where

- AFLR=air flow rate through the cooling tower, lb/hr

  HTAXT=enthalpy of the air at average temperature, BTU/lb

  HWB=enthalpy of air mass at wet-bulb temperature, BTU/lb

The subroutine AIR was then used again to compute the relative

humidity, specific humidity, and enthalpy of the corresponding air

mass at the given dry-bulb and wet-bulb temperatures.  The enthalpy

of the air leaving the tower was computed according to the following relation:

$$H2 = H1 + \frac{QR}{AFLR} \qquad (3-78)$$

where

H2=enthalpy of the air leaving the tower, BTU/lb

H1=enthalpy of the air, BTU/lb

The saturation temperature of the air at the outlet of the cooling tower was evaluated according to the following equation:

$$TS2 = 9.9674408 + 2.4105952 \, H2 - 0.02268654 \, H2^2 \qquad (3-79)$$
$$+ 1.0255304 \times 10^{-4} \, H2^3 - 1.4174090 \times 10^{-7} \, H2^4$$

where

TS2=saturation temperature of air at the outlet, $^\circ$F

The latent heat was then computed

$$QLAT = QR - (AFLR \; .24 \; (TS2 - TEDRBU)) \qquad (3-80)$$

where

QLAT=latent heat, BTU/hr

TEDRBU=dry-bulb temperature of air, $^\circ$F

The evaporation ráte of water was calculated as follows

$$WEV = QLAT/LATHET \qquad (3-81)$$

where

WEV=evaporation of water, lb/hr

LATHET=latent heat of vaporization, 1060 BTU/lb

For an assumed concentration, CONC, of 5, where concentration is defined according to the following equation, the total make-up requirements can be calculated:

$$CONC = \frac{EVAP + DRIFT + BLEED}{DRIFT + BLEED} \tag{3-82}$$

where

    EVAP=evaporative losses from cooling water system

    BLEED=continuous removal of circulating water to prevent the

        build up of the concentration of dissolved solids in the

        water

    DRIFT=minute droplets of liquid water entrained in the air as

        it passes through the tower

The flow through the plant in gallons per minute, GPM, was then

converted to a flow rate of lb/hr, FLOW. The drift loss, DRIFT, in

lb/hr was assumed equal to 3% of the plant flow, FLOW. Having

assumed a concentration of 5 the BLEED may now be computed as

follows:

$$BLEED = \frac{WEV + DRIFT - (CONC \; DRIFT)}{CONC - 1} \tag{3-83}$$

where

    BLEED=lb/hr

The total make-up water requirement, RRT (2) may then be calculated.

$$RRT(2) = \frac{WEV + DRIFT + BLEED}{62.4 \;\; 3600} \tag{3-84}$$

where

    RRT (2)=total make-up water requirement, cfs

The heated surface area, RRT(1), was set equal to zero for all

site alternatives. No existing water surface will be significantly

affected by the heated plant discharge since the cooling tower

alternative studied was for a closed cycle system, and the only

discharge will be a small amount of bleed water.

The land surface area requirements, RRT (3), for the wet mechanical cooling tower were computed on the basis of 0.2 ft$^2$ per tower unit, TU. The calculation of the tower units was explained in a previous section on the calculation of the cost of the cooling tower alternative. The area per tower unit was converted to acres and the requirements were then computed as:

$$RRT\ (3)=APTU\ TU \qquad (3-85)$$

where

RRT (3)=land area requirements, acres

APTU=required area per tower unit, acres

TU=number of tower units

The plant intake temperature, TIN, was computed as follows:

$$TIN=TEWEBU + A \qquad (3-86)$$

where

TIN=new plant intake temperature, $^o$ F

A=approach temperature, $^o$ F

The power requirements for the wet mechanical draft cooling tower include both fan power and pump power for the circulating water and make-up water systems. The fan power was computed in the following manner. The water vapor partial pressure was computed as:

$$APSAT=\frac{SH\ 14.696}{.622 + SH} \qquad (3-87)$$

where

APSAT=water vapor partial pressure, psi

SH=specific humidity

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The air density coming into the tower, DIN, in psi was equal to

$$DIN = \frac{144 \ (14.696 - APSAT)}{53.35 \ (TEDRBU + 460)} \qquad (3-88)$$

The water to air flow ratio was defined as

$$WART = \frac{FLOW}{AFLR} \qquad (3-89)$$

The tower characteristic, CHAR, was defined as equal to the relative

rating factor, RRF. A deck spacing, DECKHT, was assumed to be

equal to 2 feet. The packing height was then computed

$$PHT = \frac{DECKHT \ (CHAR - 0.7)}{.103 \ (WART)^{-0.54}} \qquad (3-90)$$

where

PHT=packing height of tower, ft

The water loading of the tower, WLOAD, was assumed equal to 2500 lbm/

hr/ft$^2$. The tower plan area, PLANA, in ft$^2$ was equal to

$$PLANA = \frac{FLOW}{WLOAD} \qquad (3-91)$$

The air loading was determined by

$$ALDG = \frac{AFLR}{PLANA} \qquad (3-92)$$

where

ALDG=air loading, mass velocity, lb/ft$^2$-hr

The equivalent air mass flow rate was then computed as

$$ALDGE = ALDG + 3500 \qquad (3-93)$$

where

ALDGE=equivalent air mass flow rate, lb/hr-ft$^2$

The package pressure drop was equal to

$$DELP = \left[ \frac{\left(\frac{PHT}{DECKHT}\right) .0675}{DIN} \right] \cdot \left[ (4.0 \times 10^{-9} \ ALDG^2) + (1.0 \times 10^{-13} \ 2500 \right.$$

$$\left. ALDGE^2 \ 2.62) \right] \tag{3-94}$$

where

DELP=pressure drop through the cooling tower, inches of water

The air flow rate was evaluated according to

$$ACFM = \frac{AFLR}{60 \ DIN} \tag{3-95}$$

where

ACFM=air flow rate, $ft^3/min$

The fan horsepower was then computed as

$$HPFAN = \frac{ACFM \ DELP \ 5.2}{\left[ 33000 \cdot \frac{FANEF}{100} \right]} \tag{3-96}$$

where

HPFAN=fan horsepower requirement

FANEF=fan efficiency, %

The fan power requirements were computed as

$$POWRTF = \frac{0.746 \ HPFAN \ 24 \ 365}{0.95} \tag{3-97}$$

where

POWRTF=fan power requirements, kw/yr

The necessary pump horsepower and power requirements for the circulating water and make-up water systems were computed according to the procedure enumerated in the section on cooling ponds. The head requirement for the make-up water system, HEADM, was set at 20 feet, and the head requirement for the circulating water system

was determined by:

HEAD=20 + PHT                                                  (3-98)

Evaporative losses. Evaporation is the process by which liquid
water passes directly into the vapor state. The amount of heat
absorbed by a unit mass of water in passing from the liquid to the
vapor state at a constant temperature is the latent heat of vaporiza-
tion, LATHET, which may be computed according to this equation as
given by Ryan and Stolzenbach (1972):

LATHET=1087 -.54 TEMFOR                                        (3-99)

where

LATHET=latent heat of vaporization, BTU/lb

TEMFOR=surface water temperature, $^{\circ}$ F

The LATHET may be assumed at 1060 BTU/lb with a small margin of error.

The partial pressure of vapor in the air, PRPAVA, at which equi-
librium exists between the process of condensation and vaporization
is the saturation vapor pressure PRSAWA, or the vapor pressure of the
liquid, according to Eagleson (1970). When the saturation vapor
pressure is greater than the partial pressure of the vapor in the air,
evaporation losses will take place from the water body due to the
gradient in the vapor pressure. The presence of wind will also have a
major effect on the evaporation rate since it will remove the vapor-
laden air by convection and thus maintain a high transfer rate. This
forced convection resulting from wind forces and the free convection
resulting from buoyancy cause the evaporation to occur from the water
surface. The forced convection normally predominates above a natural
water surface to which no waste heat has been added, while both

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forced and free convection may plan an important role in the

evaporation from a heated water surface according to Ryan and

Stólzenbach (1972)

Both the open and closed loop systems rely primarily on

evaporation to dissipate heat. This evaporative loss is always a

non-beneficial consumptive use of the water resources. It should be

noted that waste heat discharged to a river, lake or existing

reservoir increases the rate of evaporation from the water body.

These losses induced by open-cycle, once-through condensers have

been found to be almost as great as those incurred when supplemental

heat rejection systems are installed in some cases. An accurate

determination of evaporative losses requires a detailed analysis

incorporating meteorological data and other inputs relevant to each

site, according to Rainwater (1969). Once-through open-cycle

systems evaporate approximately 1% of the condenser water flow, and

cooling towers 1.5%. Cooling ponds cannot be generalized since they

must dissipate heat absorbed from solar radiation, which may equal

or exceed plant input in some instances, as well as the waste heat

from the plant itself. On the plus side, cooling ponds collect

precipitation and may reduce runoff. Thus, cooling ponds may lose

a quantity of water less than, equal to, or more than the loss

from cooling towers.

Ryan and Stolzenbach (1972) presented similar data on the

fraction of circulating water flow lost to evaporation for every

degree of condenser temperature rise. This percentage is a

function of the water surface temperature, the wind speed, and the

air temperature. The percentage of the circulating water flow lost

per degree of cooling was determined to vary from .03%/$^\circ$ F to

.07%/$^\circ$ F over the expected range of wind speeds and plant tempera-

ture rises. For totally evaporative losses, as would be the case in

cooling towers, this figure would rise to .1%/$^\circ$ F. These figures

were calculated based upon the assumption that the discharge was

into an existing water body, and that only the forced evaporation

losses were of interest. For the case where a cooling pond is

constructed, the natural as well as the forced evaporation will

require consideration and will in general result in higher water

losses depending on the pond size.

The following table indicates the factors used by the FPC in

the National Power Survey of 1970 to determine the added water

consumption in cfs due to the addition of waste heat.

## Table 3.16

### Added Water Consumption (cfs)

|  | Fossil-fuel | Nuclear |
|---|---|---|
| Once-through system | 5-6 | 11-12 |
| Cooling pond | 7 | 14-15 |
| Cooling tower | 13-14 | 25-27 |

from: Warren (1969)

The evaporative loss for the river site alternative with a

surface discharge was computed in the following manner for this

report. The rate of heat rejection, HEET, in BTU/hr was first

computed. The resulting initial temperature rise, TEMFCD, was then

calculated according to the following equation assuming that the

heated discharge will mix with only one-half of the river flow due to

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the mixing zone requirements and due to the low Froude numbers of

the surface discharge to "float" on top of the river flow and thus

prevent complete mixing. The temperature rise was calculated at

one-mile increments downstream with the area, AREA, equal to one-

mile by the river width, SITTY2.

The evaporation was calculated according to the following

procedure for a surface water temperature, TEMFOR. The partial

vapor pressure of the air and the saturation vapor pressure at the

water surface temperature were then computed

$$PRPAVA = 25.4 \ exp \left( 17.62 - \frac{9500}{TEMDEW + 460} \right) \qquad (3\text{-}100)$$

where

PRPAVA=partial vapor pressure of air, mm. Hg.

TEMDEW=dew-point temperature of air, $^{\circ}$ F

$$PRSAWA = 25.4 \ exp \left( 17.62 - \frac{9500}{TEMFOR + 460} \right) \qquad (3\text{-}101)$$

where

PRSAWA=saturation vapor pressure, mm. Hg.

TEMFOR=surface water temperature, $^{\circ}$ F

The virtual temperatures of the air and water, and the virtual

temperature difference were then determined:

$$TEAIVI = \frac{TEDRBU + 459.69}{\left( 1.0 - 0.378 \ \frac{PRPAVA}{760} \right)} \qquad (3\text{-}102)$$

where

TEAIVI=virtual temperature of air, $^{\circ}$ R

TEDRBU=dry-bulb temperature of air, $^{\circ}$ F

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$$TEWAVI = \frac{TEMFOR + 459.69}{\left[1.0 - 0.378 \frac{PRSAWA}{760}\right]}$$

(3-103)

where

TEWAVI=virtual temperature of water, $^{o}$ R

$$THETA = TEWAVI - TEAIVI$$

(3-104)

where

THETA=virtual temperature difference

The proportionality factor, BETA, the surface heat exchange

coefficient, KOEFF2 and the wind function, WIND, were then computed

$$BETA = \left(\frac{PRSAWA - PRPAVA}{TEMFOR - TEMDEW}\right)$$

(3-105)

and if THETA is greater than 0,

$$KOEFF2 = 23.0 + [14\ WINVEL + 22.4\ (THETA)^{1/3}]\ (BETA + 0.255)$$

$$+ 7.5\ (THETA)^{-2/3}\ [PRSAWA - PRPAVA + 0.255\ (TEMFOR$$

$$-TEDRBU)]$$

(3-106)

where

WINVEL=wind speed at 2 meters elevation, mph

$$WIND = 22.4\ (THETA)^{1/3} + 14\ WINVEL$$

(3-107)

where

WIND=wind function

and if THETA is less than 0,

$$KOEFF2 = 23.0 + (BETA + 0.255)\ 17.2\ WINVEL$$

(3-108)

$$WIND = 17.2\ WINVEL$$

(3-109)

The evaporation due to the addition of waste heat was computed according to the following equation for each one-mile segment

$$EVAP1 = \left[\frac{WIND\ BETA\ TEMFED}{1.94\ 86400\ 32.2\ LATHET}\right] AREA \qquad (3\text{-}110)$$

where

AREA=surface area, $ft^2$

EVAP1=segment evaporative loss, cfs

TEMFED=temperature rise above ambient, $^\circ F$

The computation was cut off at an evaporation limit of $1.25 \times 10^{-8}$ cfs/$ft^2$ which was determined from the evaluation of numerous computations at various levels of cut off. If the segment evaporative loss was in excess of this value, the next segment was analyzed in a similar manner with the temperature decay estimated according to the following procedure.

For a river of constant cross-sectional area in which the discharge is constant both spatially and temporally, the one-dimensional heat conservation equation for a well-mixed river may be written in terms of the heat content per unit volume.

$$\frac{\partial(\rho c\ TEMFOR)}{\partial t} + \frac{SITTY4\ \partial(\rho c\ TEMFOR)}{\partial\ DISTDO} =$$

$$-\rho c\ k_h\ \frac{SITTY2\ \Delta DISTDO\ (TEMFOR\ -TEQUIL)}{SITTT2\ SITTY3\ \Delta DISTDO} \qquad (3\text{-}111)$$

where

$\rho c$=density specific heat, BTU/$ft^3$-$^\circ F$

TEMFOR=surface water temperature, $^\circ F$

t=time

SITTY4=average section velocity, ft/sec

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DISTDO=longitudinal distance downstream, ft

$k_h$=kinematic surface heat exchange coefficient, ft/day

SITTY2=river width, ft

SITTY3=river depth, ft

TEQUIL=equilibrium temperature, $^{o}$F

Heat transfer was considered only across the water surface and the
effects of longitudinal dispersion are neglected.  This heat conser-
vation equation may be simplified by assuming a constant value at $\rho c$
and substituting KOEFF2 for $k_h$.

$$\frac{\partial(TEMFOR)}{\partial t} + \frac{SITTY4 \; \partial(TEMFOR)}{\partial(DISTDO)} = \frac{-KOEFF2}{\rho c \; SITTY3}(TEMFOR - TEQUIL) \qquad (3-112)$$

where

KOEFF2=surface heat exchange coefficient, BTU/$ft^2$-day-$^{o}$F

This concentration equation may also be written in terms of the
ambient water temperature, TEWAAM, as:

$$\frac{\partial(TEWAAM)}{\partial t} + \frac{SITTY4 \; (TEWAAM)}{\partial(DISTDO)} = \frac{-KOEFF2}{\rho c \; SITTY3}(TEWAAM - TEQUIL) \qquad (3-113)$$

By subtracting Equation 3-113 from Equation 3-112 assuming the
magnitude of KOEFF2 remains the same, the heat transport equation
can then be written in terms of the temperature excess, TEMFED.

$$\frac{\partial(TEMFED)}{\partial t} + \frac{SITTY4 \; \partial(TEMFED)}{\partial(DISTDO)} = \frac{-KOEFF2}{\rho c \; SITTY3}(TEMFED) \qquad (3-114)$$

where

TEMFED=TEMFOR - TEWAAM

This equation was similar to the one-dimensional conservation of
mass equation for a substance undergoing first order decay.  For
conditions of constant plant heat input the equation reduced to:

$$\text{SITTY4} \frac{\partial(\text{TEMFED})}{\partial(\text{DISTDO})} = -\frac{\text{KOEFF2}}{\rho c \text{ SITTY3}}(\text{TEMFED}) \qquad (3\text{-}115)$$

The solution of this equation under conditions of constant SITTY4, KOEFF2, SITTY3, and a uniform rate of heat addition HEET at DISTDO=0 was

$$\text{TEMFED} = \frac{\text{HEET}}{\rho c \text{ FLOPLA}} \left( \exp- \frac{\text{DISTDO KOEFF2}}{\text{SITTY4} \rho c \text{ SITTY3}} \right) \qquad (3\text{-}116)$$

where

HEET=uniform rate of heat rejection, BTU/sec

FLOPLA=circulating water flow, $ft^3$/sec

The depth of the river, SITTY3, in this equation was modified to SITTY3/2.0 since it was assumed that a stratified heated layer would form with no complete vertical mixing due to the buoyant surface discharge. Thus, the heat was assumed fully mixing over the top half of the cross sectional area with no vertical mixing for the temperature decay.

$$\text{TEMFED} = \frac{\text{HEET}}{\rho c \text{ FLOPLA}} \left[ \exp - \left( \frac{\text{DISTDO KOEFF2}}{\text{SITTY4} \rho c \frac{\text{SITTY3}}{2}} \right) \right] \qquad (3\text{-}117)$$

A model for the far-field temperature distribution due to a source of finite extent, which is appropriate for heated water discharge, was given by Ditmars (1972-2). With either a surface discharge or diffuser, the near-field mixing results in an initial far-field temperature distribution of some finite depth and width. The model given was developed by Brooks (1960) for the spread of sewage effluent fields and rewritten in terms of temperature by Ditmars. The vertical variations in temperature were neglected, and the far-field excess temperature was assumed initially to be width, WIDTH,

and depth, SITTY3, which was again defined as the water body depth divided by 2.0 for this study due to the buoyant plume, and to have an excess temperature TEMFCD. Also, the depth of the temperature field was assumed to remain constant at SITTY3; the current was not to vary with the depth over the thickness of the field and to be unidirectional; the discharge for power plant was steady; and the lateral eddy diffusion coefficient varied with the size of the plume.

The four-thirds law for lateral eddy diffusion, KZO, was determined to be most applicable for the great lake, coastal, and offshore ocean sity type. (see Equation 3-38) The temperature distribution for this case was given by

$$
\text{TEMZ} = \text{TEMCEN} \frac{\text{EXP}}{2} \left[ -\frac{\text{KOEFF2 XDIST}}{62.4 \frac{\text{SITTY3}}{2} \text{SITTY4 24 3600}} \right] \cdot
$$

$$
\left[ \text{ERF} \left( \frac{\text{Z1} + \frac{\text{WIDTH}}{2}}{2 \text{ WIDTH}} \sqrt{\frac{24}{\left(1 + \frac{8\text{KZO XDIST}}{\text{SITTY4 WIDTH}^2}\right)^3 - 1}} \right) \right.
$$

$$
\left. - \text{ERF} \left( \frac{\text{Z1} - \frac{\text{WIDTH}}{2}}{2 \text{ WIDTH}} \sqrt{\frac{24}{\left(1 + \frac{8\text{KZO XDIST}}{\text{SITTY4 WIDTH}^2}\right)^3 - 1}} \right) \right] \qquad (3\text{-}118)
$$

where

TEMZ=temperature rise at some point in far-field, $^{\circ}$ F

TEMCEN=initial centerline temperature excess at boundary of far-field, $^{\circ}$ F

Z1=lateral distance from plume centerline, ft

WIDTH=initial far-field excess temperature width, ft

XDIST=longitudinal distance from source, ft

SITTY4=ambient current velocity, fps

KOEFF2=surface heat exchange coefficient, $BTU/ft^2-day-{}^{\circ}F$

SITTY3=water body depth, ft

ERF=standard error function defined as (see Equation 3-39)

Similarly, the centerline excess temperature may be found from the
centerline solution of the above equation (Z1=0). This solution
was given in Equation 3-40.

For the great lake, coastal, and offshore ocean sites, the
initial conditions for the far-field temperature prediction model
were determined from the output of the near-field surface discharge
model for the centerline temperature, TEMCEN, and the width of the
plume, WIDTH. The heat rejection, HEET, was determined assuming no
heat loss in the near-field region. It should also be noted that
for the offshore ocean site, the depth, SITTY3, was set equal to 30
feet since the initial mixing will not be over the entire depth in
the near-field region but limited to a reasonable depth of a dis-
charge canal. The initial water surface temperature, TEMFOR, was
determined by adding TEMCEN to the ambient water temperature
TEWAAM.

For each longitudinal segment, defined in 528 foot increments
from the source, the evaporation was calculated in 100 foot sections
laterally from the centerline until the evaporation was less than the
evaporation limit, EVALIM. When the limit was reached, the solution
proceeds to the centerline section for the next segment where the
same procedure was followed until all the segments and sections
with EVALIM greater than the limit had been calculated. The

equations and procedure for the actual evaporation calculations were
the same as those described in the previous section on river sites.

The evaporative losses due to the addition of waste heat at an
estuary site were determined according to the solution developed
by Huber (1965) with inclusion of the capability of determining the
longitudinal dispersion coefficient as developed by Thatcher and
Harleman (1972). The computations for this study assumed the
estuary site was in the salinity intrusion region.

The estuary was assumed to be of constant cross-section.
According to Harleman (1972), for the longitudinal distribution of
excess temperature the following equation was applicable.

$$\frac{\partial (TEMFCD)}{\partial t} + U \frac{\partial (TEMFCD)}{\partial x} = DISP2 \frac{\partial^2 (TEMFCD)}{\partial x^2} \qquad (3\text{-}119)$$

$$- \frac{KOEFF2}{\rho c\ h} (TEMFCD)$$

where

TEMFCD=temperature rise above ambient, $^{\circ}$ F

U=instantaneous tidal velocity, ft/sec

x=longitudinal distance along axis of estuary, ft

KOEFF2=surface heat exchange coefficient, $BTU/ft^2$-day-$^{\circ}$ F

h=instantaneous position of the water surface from a horizontal
 reference datum, ft

The tidal velocity may be obtained by the simultaneous solution of
the continuity and momentum equations, and it can be used for pre-
dictive purposes. The use of this technique for solving tidal
hydraulic problems was given in Harleman and Lee (1969).

The longitudinal dispersion coefficient was included in the
estuary model since, according to Harleman (1972), fairly large
gradients of temperature may occur during the period of slack tide,
and within the salinity intrusion region, the dispersion induced by
salinity gradients was important.  The relationship developed by
Thatcher and Harleman (1972) for the longitudinal dispersion
coefficient was

$$DISP2_{(x,t)} = K_s |SALGRA| + E_t \qquad\qquad (3\text{-}120)$$

where

$DISP2_{(x,t)}$=longitudinal dispersion coefficient, $ft^2/sec$

$SALGRA = \dfrac{\partial \overset{o}{s}}{\partial \overset{o}{x}}$, where $\overset{o}{s} = {}^s/s_o$ and $\overset{o}{x} = {}^x/LESTUR$ for LESTUR equal to

length of estuary to head of tide and $s_o$ ocean salinity

$E_t$=dispersion coefficient in fresh water tidal region upstream

of the limit of salinity intrusion, $ft^2/sec$

The term $K_s, |SALGRA|$ accounts for the additional dispersion in the
region of salinity intrusion.  $K_s$ may be approximated by

$$K_s = \frac{UTIDAL\ LESTUR}{1000} \qquad\qquad (3\text{-}121)$$

where

UTIDAL=maximum tidal velocity, ft/sec

LESTUR=length of estuary to heat of tide, ft

The length of the tidal excursion in the estuary site was
computed by

$$LINTRU = \frac{UTIDAL\ PERIOD}{\pi} \qquad\qquad (3\text{-}122)$$

where –

LINTRU=length of tidal excursion, ft

PERIOD=tidal period, seconds

It should be noted that a tidal region of uniform salinity may be
considered in the same category as a fresh water tidal region where
the longitudinal dispersion coefficient may be determined by

$$E_t=100 \text{ MANNIN UTIDAL HYRAD}^{5/6} \tag{3-123}$$

where

$E_t$=longitudinal dispersion coefficient, $ft^2/sec$

MANNIN=Manning roughness "n"

UTIDAL=maximum tidal velocity, ft/sec

HYRAD=hydraulic radius, ft

The solution of Equation 3-119 was then determined for an idealized
estuary of constant cross-sectional area, where the tidal velocity
was a function of time and independent of x and the longitudinal
dispersion coefficient was constant. The longitudinal temperature
distribution due to the addition of HEET, BTU/hr at DISTDO equal to
0 was determined as a function of DISTDO and TIME. The tidal
velocity was assumed to be a harmonic function of time in the form

$$U(t)=\text{UFRESH} + \text{UTIDAL·SIN (SIGMA TIME)} \tag{3-124}$$

where

U(t)=tidal velocity function

UFRESH=velocity due to fresh water inflow, ft/sec

SIGMA=$2\pi$/PERIOD when PERIOD=tidal period, sec

A numerical evaluation was required using a time dependent velocity
for a non-conservative substance. This numercial evaluation was

taken from Harleman (1971), who presented a solution for the concentration distribution due to the continuous input of a substance at a section as a function of x and t. The substance underwent first-order decay and was non-conservative.

$$\frac{C}{C_o} = \int_o^t \frac{U_f}{o\sqrt{4\pi \, E_L(t-\tau)}} \exp\left\{ \frac{-\left[x - U_f\,(t-\tau) + \frac{U_T}{\sigma}(\cos\sigma t - \cos\sigma\tau)\right]^2}{4\,E_L(t-\tau)} - k(t-\tau) \right\} d\tau$$

$$(3-125)$$

where

$C_o$ = mass rate of continuous substance injection or dilution ratio

k = first order decay rate

C = resultant concentration distribution

x = distance x

t = time t

$\tau$ = integration variable

$E_L$ = longitudinal dispersion coefficient

This integral could not be evaluated in a closed form, but was programmed from numerical evaluation on a computer by Huber (1965). This program was used in a slightly modified manner to calculate the temperature decay and the resulting evaporative losses for the estuary site, by calculating $C/C_o$ for each segment and setting it equal to $\Delta T/\Delta T_o$ and replacing $k_d$ by KOEFF2. The details of this solution will not be presented here, but some comments on the solution technique are appropriate.

The number of tidal periods used in this solution was 50 with the temperature distributions reaching a quasi-steady state at that time. The tidal period, approximately 12.4 hours, was analyzed in

24 parts, or at approximately half-hour intervals. The equation
is evaluated at the mid-point of an interval and multiplied by
DTAU to determine the solution. These values were determined from
trial runs to yield suitable results for typical data. The longi-
tudinal dispersion coefficient can be determined for both salinity
and non-salinity regions, but for each model run, one or the other
must be selected at the present time. The actual evaporation was
computed in the same manner as described in the surface discharge
river site and again only one-half of the estuary flow was assumed
for dilution due to the surface discharge. The decay coefficient
was also estimated based on one-half estuary depth. For the up-
stream section, segment lengths of one-half mile were selected and
a total distance of 15 miles was analyzed. For the downstream end,
the segment lengths were 1 mile and a total distance of 40 miles
was analyzed.

The evaporative losses for a surface discharge on a small lake
site were computed according to the normal evaporative loss calcula-
tion method as described for the surface discharge river site. The
increase in temperature in the small lake; BETA; and the surface
heat loss coefficient, KOEFF2; were computed in the new intake
temperature calculations. It was assumed that the entire surface
area of the pond was at TEMFCD for the evaporative loss computations.
The latent heat of vaporization and the wind function were computed
and the evaporative loss then was determined according the the
following relation:

$$RRT(2) = \left( \frac{WIND\ BETA\ TEMFCD}{\rho c\ 864000\ LATHET} \right) AREAFT \qquad (3\text{-}126)$$

where

RRT(2)=evaporative losses, cfs

AREAFT=surface area of small lake, $ft^2$

BETA=proportionality factor

TEMFCD=temperature rise above equilibrium temperature, $^\circ F$

The evaporative losses for the diffuser technology for all the feasible sites were calculated in a manner similar to the development of the surface discharge. The principal difference was that in the diffuser scheme the entire cross sectional area of the river and estuary are involved in the mixing process to compute the initial temperature excess and the entire depth of the river and estuary were used in the temperature decay process. In the great lake and coastal sites the entire depth of the water body will be assumed for the temperature decay equations, and for the offshore ocean site a depth of 1/12 of the total jet trajectory length, estimated at $\sqrt{2}$ SITTY3, was used for the heated surface layer. Also, the initial far-field width was assumed equal to the length of the diffuser for the shallow sites, and was computed for the offshore ocean site according to Ditmars (1972) who presented graphical solutions of the jet half-width given by Fan and Brooks (1969); and the initial temperature rise TEMFCD, was the temperature rise calculated from the multi-diffuser equation or the submerged jet solution. For the small lake site, the same procedure was followed as with the surface discharge.

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The evaporative losses in the cooling pond were computed in the following manner. The forced evaporative loss, EVAPFT, due to the addition of heat was calculated according to the following equation:

$$EVAPFT = \frac{WIND}{\rho c} \frac{BETA}{LATHET} \frac{TEMFCD}{24} \frac{AREAFT}{3600} \qquad (3-127)$$

where

EVAPFT=evaporative loss due to heat addition, cfs

TEMFCD=forced temperature rise, $^{\circ}$F =TEMFOR -TEQUIL

AREAFT=surface area of cooling pond, ft$^2$

Since the water body was constructed in this alternative, an increase over the natural evapotranspiration, EVAPTR, takes place, and this loss should be charged to the plant. The normal losses due to the evapotranspiration were estimated at 600 BTU/ft$^2$-day. The equation for the total net evaporative loss, EVAPNA, from the pond surface was computed according to:

$$EVAPNA = \frac{((17.2 \ WINVEL \ (PRSAWA -PRPAVA)) -EVAPTR)}{LATHET \ \rho c \ 24 \ 3600} \qquad (3-128)$$

where

EVAPNA=net natural evaporative loss, cfs

This equation determined the natural evaporative loss, and then subtracted the normal evapotranspiration loss, yielding the net increase in evaporative losses due to construction of the cooling pond.

The total evaporative loss, EVAP, was equal to the sum of EVAPFT and EVAPNA.

The forced evaporative loss for the spray canal system due to the addition of waste heat was developed according to a relation

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developed from an assumption of 80% of the heat loss from the canal

is due to evaporative heat loss. Thus,

$$EVAPFT = \frac{0.80}{62.4} \frac{HEREJC}{3600.0} \frac{PLASIZ}{LATHET} \qquad (3-129)$$

where

EVAPFT=evaporation loss of water, cfs

LATHET=latent heat of vaporization, BTU/lb

PLASIZ=plant size, kw

The net increase in natural evaporative losses, EVAPNA, was

computed in the same manner as the cooling pond. The total evapora-

tive loss, EVAP, was set equal to the sum of these two components.

# CHAPTER FOUR

## PLANT EVALUATION MODEL

The Plant Evaluation Model was developed in an interdisciplinary effort to determine the capital and operating costs, the fuel consumption, and the environmental resource requirements of a given plant alternative at a particular site with specified pollution abatement technologies. This model considers the environmental aspects of both thermal and air pollution, and the effect of controls imposed in these areas on the economics and alternatives available for the siting of electric power plants.

## IV. A. Thermal Pollution Abatement Evaluation Model

The thermal pollution abatement model was developed in an attempt to provide a method of analysis for this aspect of electric utility decision-making on a regional planning basis. The formulation was set up such that the model can be easily updated in the future as more refined information becomes available, and so that the abatement technologies which were not developed in this study may be incorporated into it at a later date.

The thermal pollution evaluation model analyzes the abatement technologies of surface discharge, diffuser, cooling pond, spray canal, and wet mechanical draft cooling towers. The typical site types selected for evaluation were a river, small lake, great lake, coastal, estuary, offshore ocean, and water poor site.

In order to evaluate the many feasible site and abatement technology alternatives available with a electric utility region, a

screening capability is necessary for the resources required for the

construction and operation of a power plant, and to determine if the

plant alternative is able to meet the requirements of thermal

standards. The resource requirements calculated are: the consump-

tive use of water, including evaporative losses, blowdown, and make-

up requirements; the land area required for the thermal pollution

abatement equipment; and the amount of area of the water body which

will be heated above 0.5 degrees F as a measure of the amount of

site which would be pre-empted by the selection of one plant alterna-

tive.

The model also generates the abatement technology characteris-

tics and produces these quantities as output. An example of this

type of information would be the depth of the discharge canal, the

initial Froude number, etc.

The plant performance penalties due to thermal pollution are

also calculated by the model. This is accomplished by computing

the new intake temperature to the condenser from the water body and

the annual electric power requirements of the thermal pollution

equipment.

Finally, the economic aspects of the thermal pollution

abatement alternatives are calculated. This is accomplished by

estimating the capital costs, fixed operating, maintenance, and

repair costs and the variable operating, maintenance, and repair

costs.

## Figure 4.1

### THERMAL POLLUTION EVALUATION MODEL

<u>Site Types Evaluated</u>:  river, small lake, great lake, coastal,

estuary,  offshore ocean, and water poor

<u>Abatement Technologies Evaluated</u>:  surface discharge, diffuser,

cooling pond, spray canal, and wet mechanical draft cooling

tower

<u>Given</u>:  Plant type, plant size, site type, abatement technology,

plant heat rejection rate, plant temperature rise, thermal

water quality standards, allowable mixing zone, dry-bulb

temperature, wet-bulb temperature, dew point temperature,

ambient water temperature, and average wind velocity.

<u>Determine</u>:

1.  Ability to comply with thermal standards;

2.  Abatement technology characteristics;

3.  Consumptive use of water;

4.  Land area required for abatement technology;

5.  New intake temperature to plant;

6.  Heated surface area of water body;

7.  Power requirements for abatement technology;

8.  Capital costs for abatement technology;

9.  Fixed operating costs for abatement technology;

10.  Variable operating costs for abatement technology.

IV. A. 1. State of the Art

In order to evaluate the environmental impact of electric power

generating plants certain analysis techniques are required, including

computer programs. An effort was made in this study to develop the

required codes and techniques in such a way as to provide meaningful

inputs to decision-makers on these complex public policy issues. An

integral part of the development of these codes was a review of

previous work in this field, and adoption, revision, and improvement

of these works where applicable to the thermal pollution evaluation

techniques.

Dynatech R/D Study. The Dynatech R/D Company undertook a

program for the Environmental Protection Agency (then the Federal

Water Pollution Control Administration) in December 1968 to perform

a survey and economic analysis of the alternate methods of cooling

condenser discharge water from thermal power plants. The first phase

of this study consisted of a gathering of present state-of-the-art

information in the areas of heat rejection equipment, power plant

operating characteristics, and community considerations. The

second phase of the program included work in the areas of: selection

of input parameters and optimization criteria; limitations and

possible advances in heat rejection units; modifications of present

power cycles; and advanced total community concepts relating to

thermal discharge.

Within the second phase of the program, an attempt was made to

quantify cooling system costs as a function of certain parameters,

to define interface requirements between the power plant and cooling

system, and to optimize the total power cost. Another section of the report analyzed the alternate methods of transferring large quantities of rejected heat to the atmosphere. Among the conclusions of this report was that, for a given heat level and ambient conditions the size and cost of heat rejection equipment decreases with an increase in temperature rise across the condenser. Studies were also made to determine the increase in power plant cost as a result of an increase in condenser temperature.

The methodology included the development of a computer program to determine both the cooling system and power plant costs, and the minimum total cost for a given set of design conditions. The sensitivity of parameters was also examined to determine which have significant effects on the cooling schemes, and which are important in the computation of power plant costs. Thus, the design equations were selected based on these parameters for both cooling systems and power plants, and then they were incorporated into a computer program to calculate the minimum total cost. Among the options available for the user are full or part time use of the cooling system, an open or closed cooling system, a specified or designed condenser, and variable ambient conditions. The capability to match projected power plant operation at different capacities over varying time periods was also provided. The part time use of the cooling system is only applicable in the case of cooling systems using a water cooled condenser, and the same applies to the open cooling system or "topping" operation.

The water cooled condenser may be "designed" by the program or specified so that existing plants requiring external cooling systems may either add on an oversized system to match the existing condenser or rebuild the condenser and match it to the external cooling system such that both are of minimum cost. The operation of the power plant and the cooling system was provided at various ambient conditions for different periods of time to allow for design of the system for seldom occurring adverse conditions and then calculation of operating costs of both the cooling system and power plant at up to five other sets of ambient conditions with a specified operating time per year for each. Five off-design capacities of the plant were also provided for a certain number of hours per year and this also was required to simulate actual power plant practice. This involved specifying the operating characteristics (heat rate and auxiliary power) for each capacity used. The total design and optimization program was made up of a mathematical description of system costs and operating characteristics of the power plant itself, a model for alternative cooling schemes, and a means of utilizing both these systems together to determine the total cost. The Power Plant Model received and manipulated input data, and then simulated plant operation and provided heat rejection requirements and plant cost data to the cooling system subroutines. Their study considered a once-through system, a cooling pond, a natural draft wet cooling tower, and a mechancial draft wet cooling tower.

Unfortunately, the Dynatech study does not address itself to the question of thermal standards which was an important considera-

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tion in this study. One of the important constraints in the model is whether a given plant type and capacity could be built and operated at a given site in accordance with thermal pollution standards. The concept of resource requirements at a site were also not developed in the Dynatech study, except for evaporative losses. Thus, land surface area, and heated water surface area had to be developed. The physical aspects of the once-through system (surface discharge and diffuser) were also lacking, and recently literature has become available to evaluate these alternatives. The spray canal technology has also become a more feasible solution during recent years and although the existing data now available is far from complete, enough information is available to develop an analysis model for this technology. The model is also oriented to a river or estuary site, but not in particular to the great lake, coastal, offshore ocean, or small lake sites that were required for this study.

The Dynatech study includes some approaches which should be incorporated into the model presented in this study in its further development. Included would be operating the plant at various ambient conditions for different periods of time, since cooling systems are designed for adverse and seldom occurring ambient conditions and plants do not actually operate at these conditions during a majority of the time. Their program accounted for this by calculating the operating costs of both the cooling system and power plant for as many as five other sets of ambient conditions with a specified annual operating time for each. The Dynatech study also provides the capability of looking into full and part time use of

the cooling system in the case of cooling towers and cooling ponds, which could be incorporated into this model as the combination cooling systems are developed.

Jirka and Marks. Another study of the environmental aspects of power plant siting was made by Jirka and Marks (1971). The result of this study was a method by which the effects of environmental constraints, in particular due to thermal pollution, on the expansion of an electric power generating system can be analyzed. These effects were set forth as on the overall cost of system operation and expansion and on the selection of new sites, and thus the model developed was used to determine the change in optimal plant locations and the resulting change in total system cost which was incurred due to the imposition of water quality standards on temperature in the water bodies from which cooling water is drawn.

The method of analysis developed included two sub-models. The site evaluation model determined either the compatibility with legal requirements or the additional capital and operating costs which were required in order to comply with thermal standards at a given site. This model was based upon mathematical models which analyze the dispersion of heated discharge and the resultant temperature rises within the studied water bodies for various physical conditions. The parameters for the model were the site characteristics, the type of discharge structure, and the particular water body from which the cooling water was supplied. For varying levels of thermal pollution standards, this model generated a range of possible alternatives, and their cost for inclusion in the optimal plant location model. The

costs of environmental control were defined as the overall cost increment after prescribing certain temperature standards in comparison to no restrictions.

The site evaluation model used the predictive relationships developed, and the input of temperature standards, to determine a maximum permissible heat input at a site under the given conditions. If this value was less than the heat input which would occur if the plant were constructed, then a thermal pollution abatement technique would be required or the site would be declared incompatible. Thus, the model may be used to determine whether a given plant alternative at a site will meet the thermal standards, since there were no extra costs assigned due to thermal pollution abatement requirements if the temperature standards were met. When the standards could not be met, however, certain abatement techniques became necessary and additional costs were imposed.

The second model developed was the optimal plant location model and it determined the minimum total cost set of plant alternatives which would satisfy the expected demand requirements, and capacity constraints, within a given planning period while meeting the environmental constraints. The objective function of this linear programming problem was to minimize the total cost of all new plant construction and operating costs, the thermal pollution abatement costs, and the power transmission costs. The decision variables were the set of alternatives, and the amount of energy shipped between points in the system. The set of constraints included meeting demand, capacity limits on facilities, and the conservation of

energy in the system. This model may be run several times under variations in input data. These input variations are calculated by the site evaluation model which determines an increase in cost for a given plant alternative as a function of the physical conditions existing at the site and the thermal water quality standards.

Other factors considered in the optimal plant location model were the structure of the power demand, the cost of operation of existing plants, the additional costs of thermal pollution control, the cost of construction and operation of proposed plants, the cost of power imports and exports, and the cost of transmitting and distributing power between generating plants and areas of demand.

The methods developed in this study are useful in a variety of applications. The effect of thermal standards can be interpreted in economic terms. The consequences of site denials due to environmental impact can be demonstrated, as well as the long-term effects on power plant siting. Finally, the site evaluation model was developed so it could be used independently in other areas of operations research.

Although the model is among very few which address the environmental aspects of power plant siting, it has several drawbacks for its use for comprehensive regional planning in electric power generation systems. The base load components of the system are the only ones considered in the model formulation, plant operating histories are assumed, fuels and their interaction are not considered, plant performance losses are not considered, cost of thermal abatement was not estimated beyond $1,000/Mw, and actual physical checks of meeting standards are not made. The resource requirements of the

sites for the plant and abatement technology alternative were also not considered. Analysis of concepts of offshore ocean siting, and the explicit selection and analysis of a means of abatement, and the comparison among these alternatives was also required for the model presented in this report.

ITC Report C645 - The U. S. Energy Problem. As part of a comprehensive study on the energy problem in the United States, Inter Technology Corporation prepared a report which included models of the cost and performance of the various means of thermal pollution abatement including a once-through system, a wet natural draft cooling tower, a wet tower with forced convection, an artificial lake or pond, a spray pond and both natural and forced draft dry cooling towers. These estimates were developed to analyze the relationships between the costs and benefits of research and development programs. A technoeconomic model was developed for the analysis, including a thermodynamic model of the plant, some typical designs of a plant, cost correlations for the components used in the plant and or analysis of the effects of discount rates and equipment effective lifes.

In addition to developing equations on system performance, computations were carried out to determine the size of the components required to meet the performance characteristics. Among the technical models developed were the ones for the condenser cooling water systems. The models were developed using classical engineering techniques for analysis and prediction, and correlations of data available from the TVA were used to derive these costs. Computer

simulations for: a river water system, a wet tower with natural convection, a wet tower with forced convection, an artificial lake or pond, a spray pond, and a natural draft dry cooling tower were developed for the study.

The technoeconomic model was developed so that it would be representative of all power plants. The task of minimizing the cost for about 20 state variables required to simulate actual outside performance was not attempted, and instead the optimization was limited to the reheat pressure and the low-temperature feedwater pressure since the cost of electricity is most sensitive to these variables. Comparisons were made with the model output and acutal data from the Bull Run TVA Plant. A comparison with an "average" U. S. plant was not attempted due to the lack of information from a significant sampling of plants. A comparison of available data was made in some cases though, and, in general, it was reported that the cost of energy which the model predicted fell between the costs found for actual plants, although the cost predicted was lower than the national average due to an assumption that the plant operates at full load continuously.

The report also presented a significant amount of performance data from TVA plants and the development of performance characteristics from an analysis of the data presented. Computer codes for the condenser cooling water system were also presented.

A cost tradeoff analysis was performed to measure the cost-benefit levels as performance, operational, or physical characteristics of the system that had been modeled were altered by the desired

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amounts. This type of analysis enables the decision-maker to examine

an exhaustive selection of design parameters, system configurations,

etc. in determining the optimal design for a given system or

choosing the most economical system from among several competing

candidates. The cost components analyzed include research and

development costs, capital investment costs, and the annual operating,

maintenance, and repair costs.

The cost correlation used in the simulation programs of

installed power plant equipment was done by ITC since equipment

vendors and contractors generally claimed that cost correlations

were too inaccurate to be useful. Among the developed correlations

for the costs were: land, land improvements, pumps and motors to

circulate the condenser cooling water, the condenser cooling water

intake structure, intake lines, discharge lines, and miscellaneous

equipment associated with cooling water including controls and

condenser connections.

The ITC study provided input to the model presented in this

report in the area of cost correlations developed for some of the

thermal pollution abatement equipment. However, the question of the

thermal standards at the particular site was not addressed. The

resource requirements for the various types of thermal pollution

abatement equipment were also not evaluated. A more detailed rela-

tion ship between the abatement technologies considered and the

available sites was required for this report. Thus, while the ITC

study was a valuable source of input to the model developed by the

author, it was not able to fulfill the requirements of this study of itself.

IV. A. 2. Problem Formulation

This section provides a detailed description of the computational technique and the problem formulation for the analysis of the thermal pollution abatement alternatives considered in this study. The basic equations used in the study were previously enumerated in Chapter Three.

The method of problem formulation used for this report was to quantify the performance, cost, and resource requirements of an electric power plant cooling water system. The computer models developed were then to be used within the Plant Expansion Model as an input to decision-making in regional electric utility expansion. This method required a screening capability for certain resources (land area, consumptive use of water, etc.) to determine if a site could support a given plant; a performance capability to determine if the plant and abatement technology alternative could meet thermal standards at the site type under consideration; and an economic capability to determine the cost of complying with different levels of standards.

This model will generate a set of possible alternatives for a given level of thermal pollution control considering only this criteria, and the site evaluation model after further screening and cost analysis for air pollution control will then allow these

alternatives to be included for consideration in the Generation
Expansion Model.

The model was formulated with the meteorological conditions and
the physical site characteristics as design conditions. Since
thermal standards were analyzed by the model, this evaluation had to
take place under the "worst" case conditions. This was taken to
assume that the siting schematization would be at low flow conditions
and the meteorological conditions would be those occuring in the late
summer. For the river and estuary site types, it was assumed that
the adverse meteorological and stream flow conditions would occur at
approximately the same time during the year. Also, the sizing of the
cooling pond, spray canal, and cooling tower which were to be
compared with the other alternatives required the use of the most
adverse conditions. These assumptions allowed the use of one set of
typical sites and one set of meteorological conditions for a given
area of the region. Therefore, although the model development
provided for a number of different meteorological and pollution limit
sets within a region under study, only one set was assumed to be
applicable at a given site under consideration.

Thus, given the input of physical conditions, plant size and
type, and temperature standards, the thermal pollution evaluation
model will yield an output of the physical aspects, costs, resource
requirements or site incompatibility if appropriate.

Schematization of Sites. The development of a regional planning
model for the consideration of the thermal pollution aspects of
electric power generation required the assumption of typical site

characteristics for the various water bodies under consideration. The sites considered in the study for which typical conditions were developed include river, great lake, coastal, offshore ocean, water poor, estuary, and small lake.

The river site had a width, SITTY2, of 1000 ft; a depth, SITTY3, of 20 ft; and an average velocity, SITTY4, of 0.5 ft/sec. These conditions provide for an average flow of 10000 cfs.

The great lake and coastal sites were both assumed to have the same physical conditions. The depth, SITTY3, was set equal to 30 ft and the average velocity, SITTY4, was assumed to be 0.5 ft/sec. The direction of the current was assumed to be parallel to the shoreline at the site.

The estuary site was assumed to have a width, SITTY2, of 5000 ft; a depth, SITTY3, of 25 ft; a fresh water inflow velocity, SITTY4, of 0.2 ft/sec; a maximum tidal velocity, SITTY5, of 2.0 ft/sec; and a length of estuary to the head of tide, SITTY6, equal to 700000 ft. The typical estuary site was also assumed to be within the salinity intrusion region of the estuary.

The offshore ocean site was included due to recent developments in the area of offshore power plant siting, particularly in the case of floating nuclear power plants. The offshore ocean site was assumed to be located in water with a depth, SITTY3, of 100 ft with a velocity of 1 ft/sec.

The small lake site was assumed to include those sites which would be similar to a cooling pond in behavior, but constructed on a natural water body where thermal standards are applicable. A

reservoir or existing small lake would be included in this category. This site type was assumed to have a depth, SITTY3, of 30 ft, a velocity of 0.5 ft/sec with the direction parallel to the shoreline, and a surface area, SITTY9, of 2000 acres.

Finally, the water poor site was defined as that site where a small dependable supply of water is available which would provide for the consumptive use requirements of a closed cycle system, plus the initial make-up supply in the case of a cooling pond or spray canal abatement technology, but where the water available was an order of magnitude less than that which would be required for once-through cooling with a diffuser or surface discharge. A site located near a mine where fuel costs are low but the water supply is limited would be an example of this type of site.

Computational Schematization. The computer program formulation is a simple one which was developed in such a manner to allow the inclusion of other site alternatives and abatement technologies in the future development of the model. Thus, a major portion of the work of this study was devoted to developing a framework which would fulfill this requirement. Another consideration which received a great deal of attention was to develop the coding in the various models in such a way as to provide easy understanding by the user. This allows the user to follow this authors method of analysis, and provides the ability to quickly alter the program if it would serve the user's needs. Once this framework was decided upon, the process of developing the necessary subroutines was initiated in order to

allow the analysis of a limited number of site and abatement
alternatives and to determine if the framework performed in a
satisfactory manner.

The solution begins by initialization of the variables and
reading the input data for the various sites, ambient conditions,
and abatement technology data.  The solution then proceeds by
selecting the abatement technology and site type model, and then
performs the necessary computations to determine the economic and
physical aspects of that abatement-site alternative for each plant
being considered.  The program is made up of a main program and
five major subroutines and a number of second and third level
subroutines.  This section will enumerate the subroutines used and
provide a brief description of the computations performed in each.

MAIN:    This program provides a dummy interface for the Plant
         Evaluation Model, and when the thermal pollution abatement
         model is run with the Generation Expansion Model this
         program and its computations will be superseded.  However,
         this point of development has not yet been attained, and
         the program MAIN now provides the necessary computations
         to generate and pass the required data to the five major
         subroutines.  The program reads the necessary pollution
         limits and ambient conditions, and initializes some of the
         variables.  The plant and site alternative which is to be
         considered is then read in, along with the necessary
         characteristics, and the program uses this data to

determine and call the appropriate subroutine to analyze the abatement technology.

SURF: This subroutine is called for a surface discharge alternative and first reads in the data required to analyze this abatement technique. Conversion of some of the data passed from MAIN then takes place to make the input data compatible with the thermal pollution evaluation computations. This subroutine then determines the site type from the input data, and calls the appropriate second level subroutine to evaluate the abatement technology-site type alternatives. A check is also made to determine if the abatement-site alternative is a feasible one, and if not a message indicating so is printed out.

DIFF: This second major subroutine performs a similar function for the diffuser abatement technique. However, in this case no data is required as further input to analyze this particular technology. These first level subroutines also result in the print out of the plant characteristics, thermal pollution limits, meteorological conditions, abatement technology and site type.

COPON: This subroutine performs the actions described above for the cooling pond alternative.

SPPON: The spray canal alternative is analyzed in a similar manner in this subroutine.

CTWMC: This subroutine follows a similar procedure for the wet

mechanical draft cooling tower. For this alternative, however, this subroutine also reads in the data required to evaluate this abatement technology.

SURF1: This second-level subroutine analyzes the surface discharge on a river site. The site type data are initialized, and the subroutine then performs the calculations or calls the required third level subroutine to compute the required output. The printed output is also controlled by this subroutine.

SURF2: This subroutine evaluates the great lake and coastal sites in the above described manner for a surface discharge.

SURF3: The site alternative of offshore ocean with a surface discharge is considered in this subroutine.

SURF4: This subroutine analyzes the estuary site alternative for the case of surface discharge.

SURF5: The site type of a small lake for a plant alternative with a surface discharge is evaluated in this subroutine.

DIFF1: The diffuser abatement technology on a river site is analyzed in this subroutine in a similar manner as that described for the surface discharge.

DIFF2: This subroutine evaluates the great lake and coastal sites with a diffuser alternative.

DIFF3: The estuary site alternative with a diffuser is considered in this subroutine.

DIFF4: The submerged single round jet for an offshore ocean site is evaluated in this subroutine.

DIFF5:      The small lake site with a diffuser is analyzed by this
            subroutine.

COPON1:     This subroutine analyzes the cooling pond abatement
            technology in a manner similar to the procedure outlined
            for the surface discharge.  However, in this case the site
            alternatives considered were all the feasible ones,
            including river, great lake, coastal, estuary, small lake
            or water poor site.  The temperature standards are not
            checked with this alternative since the system is assumed
            to be a closed cycle one.  Also, all computations are
            performed in this subroutine with no third level subroutines
            called upon for calculations.

SPPON1:     The spray canal abatement technology is analyzed by this
            subroutine in a manner similar to the procedure outlined
            for the cooling pond above.  Again, all the feasible site
            alternatives were evaluated by this subroutine and the
            system is assumed to be operated in the closed cycle
            mode.  All the necessary calculations are performed by
            this subroutine with no third level programs required.

CTWMC1:     This subroutine evaluates the wet mechanical draft
            cooling tower for all the feasible site alternatives
            assuming a closed cycle operation.  In this subroutine
            third level routines are used to perform some of the
            necessary thermodynamic calculations.

FROUD:      This third level subroutine computes the surface discharge
            characteristics, and determines the Froude number of the

heated discharge in order to select the appropriate three-dimensional model solution to be incorporated into this analysis.

AREA: This subroutine checks the thermal standards for an area type of mixing zone for the previously determined Froude number of the waste heat discharge.

OUT1: This subroutine results in the calculated variables being printed out in formatted form for an area type of mixing zone.

DIST: A check of thermal standards for a mixing zone defined as a distance from the point of discharge is provided in this subroutine for the previously calculated Froude number.

OUT2: The calculated variables are printed out for a distance type of mixing zone according to the procedures outlined in this subroutine.

EVAS1: The evaporative loss of water due to the addition of a heated discharge for a river site with a surface discharge is determined in this subroutine.

EVAS2: For the site alternatives of great lake, coastal, and offshore ocean this subroutine calculated the increase in evaporative loss from the water body due to the addition of waste heat through a surface discharge.

EVAS3: This subroutine computes the increase in evaporative loss both upstream and downstream of the point of discharge for a heated discharge to an estuary by means of a surface

discharge. The distance upstream and the distance down-
stream to a temperature rise of $0.5^{o}$ F are also computed
in this subroutine for determination of the heated
surface area requirements.

HAREA: The heated surface area of a water body with a temperature
increase in excess of $0.5^{o}$ F is computed in this subroutine
for the coastal, great lake, and offshore ocean site types
with a surface discharge.

LANS1: This subroutine calculates the land area requirements for
the surface discharge abatement technology on all the
feasible site types.

POWS1: The annual pumping power requirements for the cooling
water system in the plant alternatives with a surface
discharge at any of the feasible sites are computed in this
subroutine.

COSCS1: This subroutine calculates the total capital cost of the
surface discharge abatement technology for all the
feasible alternatives. The capital costs of: land; land
improvements; pumps, motors, and the pumping station; the
intake structure; the intake line; the discharge canal;
and other equipment are included in the total cost
calculations. The dollars per kilowatt for the abatement
technology are also computed. A cost differential is
provided for the salt water sits.

COSOS1: The fixed annual operating, maintenance, and repair costs
for the surface discharge are calculated by this sub-

routine for all the feasible site alternatives, with increased costs allocated for the salt water sites.

COSVS1:  The variable annual operating, maintenance, and repair costs for the surface discharge at all feasible sites are evaluated in this subroutine.

SHIFT:  This subroutine performs a character shift on some initial variables to allow a comparison with plant identification data.

SHIFT1:  This subroutine performs a character shift on some initial variables to allow a comparison with the thermal pollution abatement technology data.

OUT3:  The calculated variables for the shallow diffuser models are printed out in a formatted form according to the procedure given in this subroutine.

EVAD1:  This subroutine computes the increase in evaporative loss due to the addition of waste heat by means of a diffuser pipe at a river site.

EVAD2:  The increase in evaporative loss for the great lake, coastal, and offshore ocean site types with a diffuser, or a deeply submerged round jet in the ocean site, due to the addition of waste heat is computed in this subroutine.

EVAD3:  For a diffuser on an estuary site, the increase in evaporative loss due to the discharge of waste heat through a diffuser is computed in this subroutine for the areas both upstream and downstream of the point of discharge.  The subroutine also computes the distances

upstream and downstream to a temperature rise of

0.5° F for use in the heated surface area computations.

Also, the temperature rise at a distance of 1000 feet

upstream is determined for the new intake temperature.

HAREAD:   The heated surface area of a water body with a temperature

increase in excess of 0.5° F is computed for discharge

through a diffuser or a deeply submerged round jet for

the great lake, coastal, and offshore ocean site alterna-

tives.

LAND1:   The land area requirements for the diffuser or deeply

submerged round jet alternatives are computed for all

feasible sites in this subroutine.

POWD1:   For the diffuser or deeply submerged jet, the pumping

power requirements for the cooling water system at all

feasible sites are determined by means of this subroutine.

COSCD1:   The total capital cost of the diffuser or submerged round

jet abatement technology for all the feasible site types

in the subroutine are computed in this subroutine with

consideration given to the costs of:   land; land improve-

ments; pumps, motors, and pumping station; the intake

structure; the intake line; the discharge line; the

diffuser pipe; and other equipment.   The dollars per

kilowatt for this abatement technology are computed, and

a cost differential is provided for the salt water  sites.

COSOD1:   This subroutine computes the fixed annual operating,

maintenance, and repair costs for the diffuser abatement

technology at all of the feasible sites with an increased

cost due to salt water sites added on.

COSVD1: This subroutine computes the variable operating, main-
tenance, and repair costs for a diffuser or a submerged
jet at all the feasible sites.

AIR: This third level subroutine is used in conjunction with
the wet mechanical draft cooling towers to evaluate the
relative humidity, specific humidity, and the enthalpy
of the corresponding air mass.

PSAT: This is a function which determines the saturation
pressure of steam for a given temperature.

The computational procedure for the surface discharge and
diffuser alternatives will be terminated if any of the following
occur:

1. the abatement technology and site alternative do not
present a feasible combination.

2. the plant requires more than a specified limit of 30% of
the river or estuary flow for these site types.

3. the dilution flow is greated than twice the normal plant
cooling water flow.

4. the temperature standards cannot be met within the defined
mixing zone with maximum dilution flow.

5. the small lake site has a loading less than or equal to
0.5 acres/Mw.

6. for the surface discharge, if the Froud number is less
than 3.57 or in excess of 25.

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For the cooling pond, spray canal, and wet mechanical draft cooling tower alternatives the computations will be terminated when:

1. the abatement technology and site alternative do not present a feasible solution.

For all site and abatement technology alternatives the computations will terminate if the maximum allowable water temperature is less than the inputed ambient water temperature since standards could never be met in this case.

### IV. A. 3. Solution

The model was developed to be run in conjunction with the Plant Evaluation Model, which would pass some data to the thermal pollution abatement model. In this report, however, the model development process has been explained and the model will be presented in the final development form prior to its inclusion in the Plant Evaluation Model. This will mean that all the data which would normally be passed to the model will be read into the model as input instead. It should be noted that this data transfer process will be carried out by means of a COMMON statement, and this allows the variables used in the thermal pollution abatement model to represent the same quantities in the Plant Evaluation Model with different variable names.

Input Format. The input to the thermal pollution abatement model is in three forms, and each form will be explained separately. These forms include the data which would be passed to the model, the required data which would be read into the model, and the

assumptions which are found within the various subroutines them-
selves. The set up and formulation of the model were required to
include the capability of computation within the Plant Evaluation
Model, including the air pollution abatement model. The complete
definition of variables and input for that model will be available in
a publication currently under preparation by Mr. Frederick Woodruff
and Mr. Dennis Farrar, Research Assistants at M.I.T., who developed
the Plant Evaluation Model, the Plant Expansion Model, and the
Generation Expansion Model which will be explained in greater
detail in the following chapter. This report will mainly concentrate
on those requirements for input to the thermal pollution abatement
model.

The model was formulated with the capability of handling 10 sets
of pollution limits and ambient conditions which are denoted by
(INDXST), where INDXST corresponds to the current set of limits
and conditions. The model reads in data on: the allowable
temperature rise above ambient conditions, TERIAL; the maximum
allowable temperature in the water body, TEMAAL; the mixing zone
area, ALLOW; the dry-bulb temperature of the air, TEDRBU; the wet-
bulb temperature, TEWEBU; the dew-point temperature, TEMDEW; the
wind velocity, WINVEL; and the ambient water temperature, TEWAAM.
The other values which relate to the air pollution conditions were
read into the model as equal to zero.

The plant and site identification factors PID(3), PID(5), and
PID(6) are also read into the model. The plant size is represented
by PID(3), the site characteristics by PID(5) and the thermal

pollution abatement technology by PID(6). The other values of PID which relate to the plant type, fuel type, start up date, and air pollution abatement technology were set equal to zero.

The plant efficiency, PLAEFF, was read into the model for each plant alternative so that the heat rejection, QR, by the condenser to the circulating water for the given plant size, PID(3), may be computed. The temperature rise of the cooling water in the condenser, CTR, is also read into the model. The plant intake temperature, TIN, which is computed by the model is read in at a zero value as was the boiler efficiency, DBEFF. It should be noted that the computation of the heat rejection, QR, by the condenser to the cooling water in the condenser was computed assuming an average heat loss to the atmosphere of 10%. This approach was selected in lieu of reading in the PID(1) card for plant type, checking the plant type, and computing the corresponding heat rejection rate. This will result in a conservative estimate for the fossil-fuel type of plant where the heat loss to the atmosphere is normally 15%. However, the heat rejected to the cooling water for a nuclear plant will be underestimated since the usual loss to the atmosphere is approximately 5%.

When these values have been read into model and these preliminary computations have been made by the program MAIN the model is in the state which will occur when the thermal model is run with the plant model. If the model were to be run alone, this data would have to be read into the model. The complete definitions

and dimensions of these variables are included in the **supplementary volume of this report referenced in Chapter One.**

The format requirements for the input which would be passed to the thermal model are as follows:

<u>Input Data</u>                                                          <u>Format</u>

Meteorological and pollution limits (up to

   10 sets of conditions)

    ST(INDXST), TERIAL(INDXST), TEMAAL(INDXST),

       ALLOW(INDXST), APL(INDXST),SO2EL

       (INDXST), GLSO2(INDXST), SGL24M

       (INDXST), SGL1M(INDXST)                                    9F7.1

    PEL(INDXST), GLCP(INDXST), GLC24M(INDXST),

       GLC1M(INDXST), TEDRBU(INDXST), TEWEBU

       (INDXST), TEMDEW(INDXST), WINVEL

       (INDXST), TEWAAM(INDXST)                                   9F7.1

Number of plant-site alternatives to be

  considered

    NUM                                                           I4·

Plant identification data

    PID(3), PID(5), PID(6), PLAEFF, CTR,

       INDXST                                       I4,1A1,1A3,2F10.2,I4

where

    INDXST=index indicating set of pollution limits and ambient

       conditions

    ST(INDXST)=site type (=0)*

    TEMAAL(INDXST)=maximum allowable temperature outside mixing zone

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TERIAL(INDXST)=allowable temperature rise above ambient

    conditions outside of the mixing zone

ALLOW(INDXST)=allowable mixing zone area

APL(INDXST)=relative air pollution level (=0)*

SO2EL(INDXST)=sulfur dioxide emission limit (=0)*

GLSO2(INDXST)=sulfur dioxide ground level concentration, annual

    arithmetic mean (=0)*

SGL24M(INDXST)=sulfur dioxide ground level concentration, 24

    hour maximum (=0)*

PEL(INDXST)=particulate emission limit (=0)*

GLCP(INDXST)=particulate ground level concentration annual

    arithmetic mean (=0)*

GLC24M(INDXST)=particulate ground level concentration, 24

    hour maximum (=0)*

GLC1M(INDXST)=particulate ground level concentration, 1 hour

    maximum (=0)*

TEDRBU(INDXST)=dry-bulb temperature of air

TEWEBU(INDXST)=wet-bulb temperature

TEMDEW(INDXST)=dew point temperature

WINVEL(INDXST)=design wind velocity at 2 meters elevation

TEWAAM(INDXST)=ambient water temperature

NUM=number of alternatives to be considered

PID(3)=plant size

PID(5)=site characteristics

PID(6)=thermal pollution abatement technology

PLAEFF=plant efficiency

CTR=condenser temperature rise

*These variables correspond to air pollution characteristics,

and for runs of the thermal pollution abatement model

separately may be read in as 0.

The variable PID(5) includes only one alphabetic character, the first, which is used with the thermal pollution model to identify the site characteristrics. The following table lists these characters and the applicable site characteristics.

Table 4.1

| Character | Site |
|-----------|------|
| G | Great Lake |
| O | Offshore Ocean |
| C | Coastal |
| E | Estuary |
| R | River |
| L | Small Lake |
| N | Water Poor |

Similarly, the variable PID(6) includes the first three alphabetic characters for the thermal pollution model. The third character should be either an O or a C to distinguish between an open and closed cycle system. The first two letters identify the abatement technology as given in the following table.

Table 4.2

| Characters | Abatement Technology |
|------------|---------------------|
| SD | Surface Discharge |
| DI | Diffuser |
| WM | Wet Mechanical Draft Cooling Tower |
| WN | Wet Natural Draft Cooling Tower |
| DM | Dry Mechanical Draft Cooling Tower |
| DN | Dry Natural Draft Cooling Tower |
| SP | Spray Canal |
| CP | Cooling Pond |

The second input classification is the required data which would

have to be read into the thermal pollution abatement model. For the

surface discharge model, the initial dimensionless values (=0) of XX,

CC, YY were read into the model corresponding to the solutions of

the model presented in Stolzenbach, Adams, and Harleman (1972) with

no bottom slope consideration for the case of no cross flow and an

aspect ratio of ½ for Froude numbers equal to 3, 4.75, 6.25, 8 and

12. The 10 representative values of the solution for XX, CC, SS,

and BB were then read into the model for the same Froude number,

and stored in the memory for future reference. These values

are used in the computation of the temperature distribution due to

the heated discharge.

The wet mechanical draft cooling tower model developed by

Woodruff also requires input data to the model. The values of: the

approach,A; the fan efficiency, FANEF; the pump efficiency, EFFICI;

the capital cost of the cooling tower per tower unit, CPTU; the

fixed operating, maintenance, and repair costs per tower unit, FPTU;

and the variable operating, maintenance and repair costs per tower

unit, VPTU are read into the model for this alternative.

The format requirements for this input data which must be

read into the model for the analysis of the surface discharge and

wet mechanical draft cooling towers are as follows:

Surface Discharge

Initialize the variables (one set for each

   Froude number considered)

      XX(IO,1), CC(IO,1), YY(IO,1)                3F12.4

where

     XX=dimensionless distance from point of discharge in x-

        coordinate direction

     YY=dimensionless lateral spread of plume

     CC=dimensionless centerline temperature concentration

     IO=index corresponding to Froude number

Variables from three-dimensional model output (one set of 10 values

   for each Froude number considered)

      XX(IO,ID), CC(IO,ID), SS(IO,ID), BB(IC,ID)       4F12.4

where

     SS=dimensionless horizontal distance from the jet centerline to

        , the boundary of the core region

     BB=dimensionless horizontal surface distance from core

        boundary to jet boundary

     ID=index corresponding to number of data values for each

        Froude number (=10)

Wet Mechanical Draft Cooling Tower

     A, FANEF, EFFICI, CPTU, FPTU, YPTU            6F10.2

     The third set of input data for the model are the assumptions

made by the author in the development of the various models. These

will be enumerated, and the values used in the models will be listed

so that future users of the model may change the numerical values if desired. The assumptions for the typical site types were enumerated in a previous section and will not be repeated at this time. The variable, AMIXZO, which indicates the type of mixing zone in the surface discharge model was assumed equal to 2.0 for the model runs. MIXZON, which would indicate the allowable distance from the point of discharge in that type of mixing zone, was set equal to 500 ft. The limiting width of the discharge canal, MAXWID, was equal to 200 ft. The maximum specified ratio of the river or estuary for, RATFL1, allowed for use as either condenser cooling water or dilution flow was set equal to 0.30. For the open cycle systems, the limit of temperature rise due to the waste heat discharge for the heated surface area computations was $0.5^{\circ}$ F. The pumping head through the plant, HEAD, was assumed to equal 20 feet in all cases. The assumptions concerning the lengths of the intake and discharge structures, and the make-up water system were enumerated in the section on cost and will not be repeated here.

The maximum limit of the dilution flow, FLODIL, was set equal to 200% of the condenser cooling water flow, FLOPAL. The estuary site alternative was assumed to be in the salinity intrusion region, SITTY7=1.0, for this study. The loading limit, LOAD, for the small lake site was set equal to 0.5 acres/Mw. The average incoming solar radiation, SOLRAD, was assumed to be 2000 BTU/$ft^2$-day. The maximum allowable velocity in the surface discharge canal, MAVELO, was 10 ft/sec, and the aspect ratio of the discharge canal, ASPECT, was equal to one-half.

The segment increment, DISTDO, for the river evaporation computations was set at one-mile. The minimum evaporation considered, EVALIM, was $1.25 \times 10^{-8}$ cfs/ft$^2$. For the great lake and coastal sites, the longitudinal segment interval for the evaporation calculations, XDIST, was equal to 528 ft and the lateral segment length was 100 ft. In the estuary evaporation calculations, the tidal period, PERIOD, was 44712 seconds, the Manning coefficient "n", MANNIN, was to 0.028, the number of tidal periods, NUMPER, was 50, and the tidal period was separated into 24 increments, DELTA, for the computational analysis. The maximum salinity gradient, SALGRA, was assumed equal to 2. The segment increment, DIST, in the estuary upstream direction was 2640 ft and the number of segments considered, NUMX, was 30. Similarly, for the downstream direction, DIST, was equal to 5280 ft with NUMX equal to 40.

The pump efficiency, EFFICI, was assumed as 0.75 and the motor efficiency was set equal to 0.95 for estimating the power requirements. The assumed unit costs, cost factors, and lengths used to determine the capital and fixed operating, maintenance, and repair costs for all the abatement alternatives and site types were discussed in a previous section and will not be repeated at this time.

For the diffuser technology the port diameter, DIAMPO, was assumed equal to 2 ft for the shallow water bodies. Also, the velocity through the port, VELPOR, was set equal to 15 ft/sec. The port spacing, PORSPA, was equal to the water body depth. The port direction, PORTDI, was assumed to be with the current for the

river, great lake, coastal, and small lake sites, and PORTDI, was

assumed to be in alternating directions for the estuary site. The

pumping head, HEAD, for the diffuser alternative was set equal to

the plant loss of 20 ft, plus the water body depth, and an addition

20 ft for losses.

For the cooling pond alternative, the depth of the pond, DEPTHP,

was assumed equal to 15 ft. The minimum number of hours, HOURS, for

which the pond must be capable of containing the plant cooling water

flow as 96 hours. The minimum pond loading, LOAD, was 2 acres per

Mw with the maximum load assumed at 1 acre per Mw. The average

normal evaporative loss due to evapotranspiration, EVAPTR, was set

equal to 600 BTU/ft$^2$-day. The total pumping head for the cooling

pond system was set equal to 20 ft.

Finally, for the wet mechanical draft cooling tower the latent

heat of vaporization, LATHET, was assumed to be equal to 1060 BTU/lb.

Also the concentration factor for the tower, CONC, was assumed to be

equal to 5.0. The tower deck height, DECKHT, was set equal to 2 ft

and the water loading, WLOAD, was assumed to be equal to 2500 lbm/

hr/ft$^2$. The area per tower unit, APTU, was equal to 0.2 ft$^2$. The

pumping power head, HEAD, was assumed to be equal to 20 ft plus the

packing height, PHT. For the make-up water system, the pumping power

head, HEADM, was assumed equal to 20 feet.

Output Format. The model first prints out the input data for

the pollution limits and meteorological conditions to allow for a

check of the input data. For all abatement technologies, the plant

size, condenser temperature rise, the mixing zone type, the pollu-

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tion limits, and the meteorological conditions are printed out in the initial stage of the output. The abatement technology under consideration and system type (open or closed cycle) are then given in the output. Next, the plant heat rejection rate, the required cooling water flow, and the relative humidity are presented. Finally, the site type and the physical characteristics of the site are printed out.

For the surface discharge alternative, the output continues with the thermal pollution limits and the corresponding values for the plant alternative under consideration, including the area within the isotherm corresponding to the limiting temperature where applicable. The dilution flow, if any, is then presented. The abatement characteristics (canal velocity, Froude number, etc.) are then printed out, followed by the evaporative loss due to the heated discharge and the longitudinal distance to the point where the minimum evaporation limit is reached. The heated surface area, the longitudinal distance to the temperature limit for this area, the new plant intake temperature, the land surface area requirement for the abatement technology and the annual power requirements are then printed out. The capital cost is presented for each of the components considered along with the total capital cost and the dollars per kilowatt. The fixed and variable operating, maintenance, and repair costs are also printed out. For the small lake site, the lake loading, and the other physical characteristics are printed out. The new intake temperature, the plant discharge temperature, and the average surface temperature are also given for this alternative.

With the diffuser alternative, a similar format was followed with the thermal pollution limits printed out, but in this case only the temperature rise at the surface is presented if it is less than the allowable value since this sub-model does not have the capability of differentiating between the area and distance type of mixing zone. The abatement characteristics of the diffuser are also printed out (port diameter, port spacing, etc.) including the direction in which the ports are facing (with or against the current). The remainder of the format is the same as with the surface discharge previously described.

The cooling pond output is also on the same format as was described for the surface discharge. In this case, no standards are printed out since the system was assumed to operate in the closed cycle mode. The abatement characteristics are printed out (depth of the pond, surface area of the pond, etc.) along with the equilibrium temperature, the new intake temperature, the plant discharge temperature, the average surface temperature of the pond and the surface heat exchange coefficient. The evaporative losses, the blowdown requirements, and the total make-up water requirements are also given. The horsepower and power requirements for the make-up water system are also included in the output for this alternative.

The spray canal alternative provides output similar to the previously described cooling pond. In this area, however, the consumptive use output includes drift losses from the spray modules and the horsepower and power requirements output include the spray modules.

Finally, the wet mechanical draft cooling tower alternative was prepared by Woodruff and has a significantly different format. The output presented in this case includes the abatement characteristics of the tower (tower units, relative rating factor, etc.), the fan, pump, and make-up water system horsepower and power requirements, meteorological conditions, and the enthalpy of the air. The print out also includes the consumptive use of water, including evaporative loss, drift, bleed, and the total make-up requirements, the unit costs for the capital, and fixed and variable operating, maintenance, and repair costs along with the capital cost of each item considered, the total capital costs, and the capital dollar cost per kilowatt.

For those alternatives which cannot be built to meet standards a message is printed out indicating the corresponding reason and stating that consideration of that alternative has been discontinued. The same is applicable in the case where a site-abatement alternative is not feasible (such as a diffuser on a water poor site).

Within the program, a number of write and format statements are on data cards which begin with a CP in the first two colums which is meant to signify Comment - Print. These write statements result in the generation of output which was used by the author to check upon the validity of the equations developed in the model, to make data comparisons, and to determine appropriate cut off points for a number of the computations as mentioned previously in the text. The model will develop the results for the areas mentioned in the description of its capabilities and print out these details in summary form in its present state. However, if a user were

interested in examining the incremental output from the actual

equations, these cards would simply have to be replaced with the

same cards except for the deletion of CP in the first two columns.

A sample of the problem output is provided in Chapter Six.

Applications of Model. The thermal pollution abatement model

would be used with the Plant Evaluation Model to evaluate the trade

offs between the dollar cost of electrical energy generation,

reliability, and air and thermal pollution. The model would also

provide an input to an effort to determine the optimal regional

generation expansion and plant operation plan by means of the

Generation Expansion Model. This input would be specifically in

the model's capability of screening a plant-site alternative with a

specified means of thermal pollution abatement as feasible or non-

feasible based upon site compatibility and the ability of the

alternative to comply with thermal standards. Also, the model will

generate the capital and fixed and variable operating, maintenance,

and repair costs for the use of a given thermal pollution abatement

alternative along with the resource requirements. The evaluation of

the thermal pollution costs and alternatives provided by the model

would also be necessary as an input to an effort to determine the

effect of a technological advance on the cost of electricity.

The model may also be used to provide an insight into the

environmental effects of proposed additions to an electric system

such as pollution abatement equipment. For a given plant-site

alternative, the thermal pollution abatement model could be run with

the one plant-site alternative with each method of thermal pollution

abatement to determine which combinations would be feasible and to make an economic and resource requirement comparison between alternatives. This information would be useful to decision-makers who must include an analysis of the costs and environmental impacts of the alternatives to a proposed action under NEPA. The model may also be run with a number of plant-site alternatives with one type of thermal pollution abatement technology specified to determine the site alternatives within a region which would be available for development and the economic costs of each. The site alternative and thermal pollution abatement technology may be held constant with the plant sizes allowed to vary to examine the resulting trends in cost and resource requirments.

It should be emphasized, however, that decision-making and analysis in the electric utility system will require a comprehensive analysis of the actual plant under consideration and its inter-relationship with the entire regional system. Thus, the air pollution costs and requirements, and the fuel costs must also be considered along with the cost of thermal pollution at all the available alternatives in order for the optimal operation and expansion plant may be obtained. The electrical energy system study, of which this model is a part, has addressed itself to the development of this type of method of analysis.


IV. B.  Plant Evaluation Model

The Plant Evaluation Model is a technical simulation model whose function is to determine the capital and operating costs, the

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environmental resource requirements, and the fuel consumption for each alternative being considered. The model requires the following as input data: the list of the alternatives being considered (plant, abatement technology, and site type); a set of assumed capacity factor histories for each alternative; and the climatological conditions required to determine the resource requirements and the compliance with pollution standards. The fuel requirements are estimated from the assumed plant histories and an iterative procedure is used to determine the optimal capacity factor history for each alternative. Data is also required on the capital and operating costs and the performance characteristics of the plant and pollution abatement types in order to calculate the costs, resource requirements, and fuel consumption. The evaluation model provides data to the Plant Expansion Model, described in the following chapter, on the annual fuel consumption, the capital and operating costs, the resource requirements and the assumed capacity factor history for each plant.

The thermal pollution abatement model, which has been described in previous sections, and the air pollution abatement model determine the capital and operating costs along with the resource requirements. The air pollution abatement model will be outlined in this section.

The air pollution abatement model requires the input of alternatives, ambient conditions, pollution limits, and the cost and performance data. The plant identification passed to this model includes the site type, the plant type, the plant capacity and efficiency, and the air pollution abatement technique. The air pollution site types include coast, valley, and plain for both rural

and urban areas. The air pollution abatement technologies considered include wet limestone scrubbing, catalytic oxidation, magnesium oxide scrubbing and a tall stack. Consideration is also provided for whether or not by-product credit is available. The ambient meteorological conditions are also passed to the model. Pollution limits for the air pollution model include: a relative air pollution level; a sulfur dioxide emission limit; ground level sulfur dioxide concentrations based on a one hour maximum, a twenty-four hour maximum, and an annual arithmetic mean; a particulate emission limit; ground level particulate concentrations based on a one hour maximum, a twenty-four hour maximum, and an annual arithmetic mean. The stack gas composition and flow is also passed to the model in the form of the fuel heat equivalent, the sulfur content, the ash content, the total gas flow, the gas temperature entering the stack, and the heat supplied to the boiler.

The model developed computes the cost of the air pollution abatement equipment, the fixed and variable operating costs of the air pollution equipment, the power requirements for the equipment, and the resource requirements for the equipment. The model also computes the change in boiler efficiency after the inclusion of the thermal pollution abatement equipment.

Thus, the model developed to analyze the cost of air pollution control will determine the trade off between economic costs, ambient air quality standards, and emission standards with an input requirement of specific fossil plant type and site, and data on the site conditions and emission control effectiveness and costs. The output

of the model may be used to determine when:  the control should be changed to fuel treatment from abatement technology; site changes become economical; the incremental cost of a change in standards becomes prohibitive; and emission standards dominate the air quality standards.  This will provide more information to regulatory and electric utility interests concerning the economic cost associated with complying with different levels of emission standards and air quality criteria as implementation plans are developed to meet the ambient air quality standards, and the required determination of the economic impact on the affected industries.  The electric utility would also find the model output useful in the evaluation of the alternatives and tradeoffs involved in site and fuel selection.

The relationship of the Plant Evaluation Model with the Plant Expansion Model and the Generation Expansion Model will be further developed in the following chapter.

CHAPTER FIVE

GENERATION EXPANSION MODEL

The Generation Expansion Model was developed in conjunction

with the energy studies here at M.I.T. in an effort to evaluate the

economic, environmental and security aspects of generation expansion

schemes for electrical energy. The M.I.T. Energy Laboratory which

was formed in November of 1972 is a major new laboratory in which

interdisciplinary teams of scientists and engineers will combine

to conduct research on these problems posed by the nation's current

energy crisis. The primary purpose of the laboratory will be to

identify and work toward socially and ecologically acceptable short-

term and long-range energy solutions. This current generation model

represents a work towards this goal in the area of electrical energy.

The model includes sub-models which may be consecutively used to

determine the least dollar cost for various generation expansion

schemes in regional electric systems along with the corresponding

operating plans. The use of sub-models in the formulation provides

flexibility in application by providing the decision-maker with the

opportunity to use each of these models in various related studies.

The Generation Expansion Model examines the decision variables

of: plant alternatives, site alternatives, and plant operating

histories; the associated fuel costs; fuel consumption rates; forced

outage rates; and electrical demand forecasts. The model also

considers a set of constraints on: site availability, air and

thermal pollution limits, fuel availability and system reliability.

The model determines the plant and site alternatives, and operating

histories which will minimize the total present worth of capital, operating, and fuel costs while satisfying the demand for electricity, site availability, pollution limits, fuel availability, and reliability constraints. The model is capable of evaluating the costs and performance of most of the feasible combinations of generating plant and pollution abatement technologies.

Thus, the set of feasible plant and site alternatives, the general operating history of each plant type, and the corresponding air and thermal pollution abatement technologies make up the decision variables for this model. Each plant alternative includes a plant type, plant capacity, fuel type, vintage, thermal and air pollution abatement technology and site type. The model is capable of handling any of the current plant technologies, such as gas turbine, fossil steam, etc. and it is also possible to incorporate technologies which are not yet commercially available, such as the fast breeder. The model may also evaluate the physical performance and costs of many combinations of electric power plant pollution abatement technologies. Included in the thermal pollution alternatives are once-through cooling systems with surface discharge, or diffusers; and closed cycle cooling with cooling ponds, spray canals, and wet mechanical cooling towers. The site alternatives are specified by the air pollution characteristics (valley, plain, etc.); the thermal pollution characteristics (river, lake, offshore ocean, coastal, estuary, etc.); and the land requirements.

Certain environmental resources are also associated with each type of site. Included in these resources are the amount of water

surface area available for the dissipation of waste heat in the once-through cooling systems, the water available for consumptive use, the levels of particulate matter and sulfur dioxide that can be sustained with respect to air pollution, and the amount of land available for construction of the plant and the pollution abatement technologies. There is an amount of each of these resources necessary for construction and operation of an alternative which will meet the air and thermal standards for that type of plant, the thermal and air pollution abatement technology, and the site combination. The model will determine this environmental resource consumption for each alternative, and declare the alternative as infeasible if the site cannot supply the required resources.

Thus, the Generation Expansion Model will be of use in the evaluation of the economic, environmental, and security aspects of generation expansion schemes in electric utilities. The complete solution of this model is made up of the set of plants with their corresponding operating histories that will meet the demand for electric power over the planning period with a minimum cost. The expansion plan generated by the model will also meet the constraints on thermal and air pollution, site availability, fuel availability, and some reliability criteria. The model will also provide a set of auxiliary output including: the capital costs and annual cash flows for each alternative; the net fuel consumption for each plant and for the entire generation system under consideration; the loss of load probability; and the expected energy not supplied by the system.

The model is made up of three sub-models: the Plant Evaluation

Model, the Plant Expansion Model, and the Plant Operation Model

which may be used consecutively to determine the optimal generation

expansion and operating plans described above.

Plant Evaluation Model. This sub-model determines the capital

and operating costs, the environmental resource requirements, and the

fuel consumption of each alternative considered. This model was

discussed in detail in a previous section.

Plant Expansion Model. The Plant Expansion Model employs the

mathematical programming technique of linear programming to determine

an optimal solution to a set of model equations and inequalities.

This technique allows an exhaustive and systematic search of all

possible plant alternatives to develop the optimal solution. If

certain of the constraints or restrictions are removed, this tech-

nique will indicate directions for improving the optimal plant. This

allows the decision-maker to modify the input data and test to

determine how sensitive the plan is to his assumptions, and then use

this information to direct his attention to gather more substantial

data and to more carefully evaluate the sensitive areas.

The function of this sub-model is to determine the least cost

capacity expansion plan which will meet the projected electrical

demand with constraints such as site availability, environmental

standards, fuel availability, committed plants, and class introduc-

tion rates. A portion of the input data for this model comes

directly from the Plant Evaluation Model. The capital and operating

costs, environmental resources requirements, annual fuel consumption,

and the assumed capacity factor history for each plant are included

in this data. This data is input directly to the model and includes the expected electric power demand for the study period, the site availability, the list of committed or constructed plants, and the fuel availability and cost.

Plant Operation Model. This sub-model will determine the optimal operating history for each of the plants selected by the Plant Expansion Model by means of probabilistic simulation techniques. In the event that the capacity factor histories calculated by this sub-model are not equal to the ones assumed originally, they are then used as feedback to the Plant Expansion Model with the process continuing until the plant histories converge on a solution. The loss of load probability and the expected energy not supplied are also calculated by this sub-model. If this loss of load probability is outside of the specified limits, the margin of reserve is recalculated and fed back to the peak power constraints in the Plant Expansion Model, and again an iterative process is used until the reliability constraints are met.

Uses of Generation Expansion Model. The primary use of the Generation Expansion Model is to analyze and compare regional electric power generation plans within the United States. The model may also be used on a regional basis to assess the cost of environmental and reliability standards.

An example of a use of the model would be an analysis of the electric power generation system in the New England region. In this particular study, data would be required on the cost and performance characteristics of each plant and pollution abatement technology in

Model, the Plant Expansion Model, and the Plant Operation Model which may be used consecutively to determine the optimal generation expansion and operating plans described above.

Plant Evaluation Model. This sub-model determines the capital and operating costs, the environmental resource requirements, and the fuel consumption of each alternative considered. This model was discussed in detail in a previous section.

Plant Expansion Model. The Plant Expansion Model employs the mathematical programming technique of linear programming to determine an optimal solution to a set of model equations and inequalities. This technique allows an exhaustive and systematic search of all possible plant alternatives to develop the optimal solution. If certain of the constraints or restrictions are removed, this technique will indicate directions for improving the optimal plant. This allows the decision-maker to modify the input data and test to determine how sensitive the plan is to his assumptions, and then use this information to direct his attention to gather more substantial data and to more carefully evaluate the sensitive areas.

The function of this sub-model is to determine the least cost capacity expansion plan which will meet the projected electrical demand with constraints such as site availability, environmental standards, fuel availability, committed plants, and class introduction rates. A portion of the input data for this model comes directly from the Plant Evaluation Model. The capital and operating costs, environmental resources requirements, annual fuel consumption, and the assumed capacity factor history for each plant are included

in this data. This data is input directly to the model and includes the expected electric power demand for the study period, the site availability, the list of committed or constructed plants, and the fuel availability and cost.

Plant Operation Model. This sub-model will determine the optimal operating history for each of the plants selected by the Plant Expansion Model by means of probabilistic simulation techniques. In the event that the capacity factor histories calculated by this sub-model are not equal to the ones assumed originally, they are then used as feedback to the Plant Expansion Model with the process continuing until the plant histories converge on a solution. The loss of load probability and the expected energy not supplied are also calculated by this sub-model. If this loss of load probability is outside of the specified limits, the margin of reserve is recalculated and fed back to the peak power constraints in the Plant Expansion Model, and again an iterative process is used until the reliability constraints are met.

Uses of Generation Expansion Model. The primary use of the Generation Expansion Model is to analyze and compare regional electric power generation plans within the United States. The model may also be used on a regional basis to assess the cost of environmental and reliability standards.

An example of a use of the model would be an analysis of the electric power generation system in the New England region. In this particular study, data would be required on the cost and performance characteristics of each plant and pollution abatement technology in

the set of feasible alternatives for the region within the next two decades. Other input required would be the forecasted electric demand, the site availability, and fuel costs. The model could then be run with this input data and the current reliability data as well as the present thermal and air pollution standards. The output from this run could then be used as a "base" solution for sensitivity studies involving the environmental and reliability constraints. The thermal standards used as constraints in the "base" model could be raised and lowered to determine the effect of these modifications on the optimal solution. A similar evaluation procedure could be used to determine the trade offs between the cost of electricity and the level of system security.

Another function of the model is to evaluate the effect of technological advances and their timing on the fuel consumption, cost of electricity, and the environmental impact of the electric power generation. An example of such a study would be an analysis of the effect of the introduction of fast breeder reactors on the optimal generation expansion plan for New England. This could be accomplished by including the breeder plants as an alternative, running the model and then comparing the results with the "base" solution.

Aggregate fuel consumption by the electric power industry can be evaluated when the Generation Expansion Model is utilized as a national model. This type of study would prove useful in analyzing the interaction of the nuclear technologies, such as light water reactors and fast breeders.

Finally, although the model does not consider the demand for

electricity as endogenous, the model can be used to examine the change in the optimal generation expansion plan caused by changes in the amount and location of the demand for electricity. The analysis of the effect of large scale use of electric automobiles on the electrial energy system would be an example of such a study. Since these vehicles would usually be recharged during off peak hours, there would be a net increase in the load factor of a system. This would tend to increase the number of base load plants in the optimal generation expansion plan, and the model could be used to quantify this increase and determine the effects on the cost of electricity.

# CHAPTER SIX

## CASE STUDY

### VI.  A.  Scope of Study

The case study, for the thermal pollution abatement model, undertaken in this report addressed itself:  to the determination if the adopted problem formulation was a valid one; to a verification of the model's capability to calculate the required outputs; and to a determination, in a general manner, of the difference in costs and resource requirements among the thermal plant alternatives for each of the sites and abatement technologies considered.  Thus, the conceptual framework which was developed in the previous sections was implemented by means of a theoretical situation  of 10 alternatives, in order to evaluate for an electric utility system the economic cost of thermal pollution abatement, and the compatability of site alternatives and abatement technologies due to the resource requirements and thermal standards.

The results of this type of case study may serve as a basis for an overall review of the economic and resource requirement aspects of the imposition of thermal standards.  In a future case study of a more comprehensive nature, one plant size could be analyzed, and the costs  and resource requirements for all the site abatement technologies compared for this typical plant.  Also input parameters could be varied to examine the sensitivity in the areas of cost and resources to these conditions. The concept of mixing zones and their different definitions could be examined by running the model once with an area type of mixing zone and once with a distance mixing zone.

The effect of the imposition of the zero discharge criteria would
also be examined by only considering those feasible abatement alterna-
tives in the closed cycle system.

The ten sites and abatement technologies selected for this
study were chosen on a basis of being representative of the alterna-
tives which the model has a capability to analyze.  In this manner,
a good trial run of the model could be obtained.

## VI.  B.  Test Problem

The development and computation of the test problem required
the assembly and definition of the test problem data, the actual
determination of the results of the computations using this test
data, and the author's analysis of the output data.

## VI.  B.  1.  Test Data

The pollution limits data was set equal for all the available
alternatives, INDXST, within the region due to limited nature of the
objectives of this case study, that is to examine the problem formu-
ation and to generate the required costs and resource requirements.
The values used for the study were a maximum allowable temperature
rise, TERIAL, of $5^o$ F, a maximum water body temperature, TEMAAL, of
$80^o$ F, and an allowable mixing zone area, ALLOW, of 20 acres.  A
similar reasoning was followed in the establishment of the input
meteorological conditions.

Again, all areas within the region were assumed to have the
same design climatological conditions for the purposes of this study.

The values used for the study were a dry-bulb temperature, TEDRBU, of 74° F, a wet-bulb temperature, TEWEBU, of 67° F, a dew-point temperature, TEMDEW, of 62° F, an average wind velocity, WINVEL, of 5 mph at an elevation of 2 meters, and an ambient water, TEWAAM, temperature of 72° F. It should be again noted, however, that the model is not limited to the analysis of one set of pollution limits and meteorological conditions, but the capability has been provided for analysis of up to 10 complete sets of pollution limits and meteorological conditions in more detailed studies which will involve the analysis of an actual regional system. The set of limits and conditions used in this study are presented in the following table. (see table 6.1)

Table 6.1

Pollution Limits and Ambient Conditions for Case Study

| INDXST | TERIAL | TEMAAL | ALLOW | TEDRBU | TEWBU | TEMDEW | WINVEL | TEWAAM |
|--------|--------|--------|-------|--------|-------|--------|--------|--------|
| 1 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 2 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 3 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 4 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 5 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 6 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 7 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 8 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 9 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |
| 10 | 5 | 80 | 20 | 74 | 67 | 62 | 5 | 72 |

The plant alternatives, along with the corresponding sites and pollution abatement technologies, which were considered in this case study are presented in the following table. (see table 6.2)

Table 6.2

## Plant Alternatives Considered in the Case Study

| Plant Size (Mw) | Site Type | Abatement Technology | Efficiency (%) | Condenser Temperature Rise (°F) | INDXST |
|---|---|---|---|---|---|
| 2000 | E | SDO | 33 | 20 | 1 |
| 1200 | O | SDO | 33 | 10 | 2 |
| 1600 | G | SDO | 32 | 20 | 3 |
| 1100 | L | SDO | 38 | 14 | 4 |
| 1000 | E | SDO | 40 | 26 | 5 |
| 800 | R | DIO | 38 | 16 | 6 |
| 600 | E | SDO | 36 | 18 | 7 |
| 800 | N | CPC | 37 | 30 | 8 |
| 800 | C | WMC | 35 | 16 | 9 |
| 1000 | E | SPC | 30 | 14 | 10 |

For the wet mechanical draft cooling tower, the input data used

was: an approach temperature, A, of $10°$ F; a fan efficiency, FANEF, of

80%; and pump efficiency, EFFICI, of 75%; and the capital cost per

tower unit CPTU, equal to 5; the fixed operating cost per tower

unit, FPTU, equal to .25; and the variable cost per tower unit,

VPTU, equal to zero since the model formulation has assumed all

variable operating costs equal to zero. The input data for the

analysis of the surface discharge by means of the output of three-

dimensional will not be repeated at this time. This data is avail-

able in the supplementary volume in tabular form for the six Froude

numbers considered in the formulation.


VI. B. 2. Results of the Case Study

This section will discuss the output from the model for the

selected case study with reference to the economic costs, the

physical aspects of the abatement technology and site combination,

and the various resource requirements. Figures 6.1 through 6.11
give the resulting output for the case study.

The first alternative considered (see figure 6.1) was a 2000 Mw
plant on an estuary site with a surface discharge. The alternative
was declared not feasible in this instance because the calculated
densimetric Froude number of the heated discharge was less than 3.57
which was the limit for the application of the theoretical approach
developed in this study for the analysis of the surface discharge.
The second alternative considered (see figure 6.2) was a 1200 Mw
plant on an offshore ocean site, also with a surface discharge. As
in the case of the first alternative, this option was also declared
infeasible since the densimetric Froude number of the heated dis-
charge was below the theoretical limit of 3.57.

The third alternative (see figure 6.3) was a 1600 Mw plant with
a surface discharge on a great lake site. The site was declared
a feasible alternative since the surface area within the mixing zone
for a $5^{\circ}$ F temperature rise was 3.6 acres and thus less than the
prescribed limit of 20 acres. No dilution flow was required by this
alternative in order to comply with the standards. The design flow
for the discharge canal was 2325 cfs and the resulting depth was
10.5 ft, the width was 42 ft, and the discharge velocity was 5 ft/
sec. The consumptive use of water from evaporative losses due to
the addition of waste heat was 2.4 cfs; the heated surface area to
the $0.5^{\circ}$ F limit of the river was 23,430 acres which corresponds to a
distance from the point of discharge of approximately 10 miles; and
the land surface area requirement for this abatement technology was

1.2 acres.  The new intake temperature to the plant was

72° F, and the annual power requirements for the thermal discharge

equipment were 48,878,200 kilowatts per year.  Finally, the total

capital cost of the equipment was $8,420,000 which represents a

figure of $5.42/kw.  The main elements of this cost were $1,600,000 for

pumps, $2,000,000 each for the intake structure and intake line,

$800,000 for the discharge canal, and $1,880,000 for other equipment.

The fixed operating costs were computed at $150,000 per year.

A small lake site type with a surface discharge was the fourth

alternative considered.  (see figure 6.4)  In this case, the site and

plant alternative was also declared a feasible one since the surface

area within the mixing zone for a 5° F allowable temperature rise

was less than the prescribed limit of 20 acres.  The standards were

complied with in this case without the use of dilution flow.  The

depth of flow in the discharge canal was 10 ft, the width was 40 ft,

and the discharge velocity was 4.4 ft/sec.  These conditions

correspond to a plant flow of 1753 cfs.  The lake loading was 1.82

acres/Mw, not 1.82 Mw/acre as given in the output, and this value

was within the acceptable limits.  The lake would provide sufficient

volume for a detention time of the heated water of approximately

17 days.  The heated surface area to the 0.5° F limit was the entire

lake surface area of 2000 acres; the land area required for the

abatement technology was 1 acre; and the consumptive use of water

from evaporative losses due to the heated discharge was 11.3 cfs.

The new plant intake temperature was 88° F and the annual pumping

power requirement was 36,481,000 kilowatts.  The total capital

# ALTERNATIVE ONE

PLANT SIZE TERIPL MIKZON--TERIAL TERAAL MIKOIA MIKAREA--TEMAM TEMBU TEDABU TEMDEN MIMWEL
2000000.0  20.0   5.0   2.0   80.2  500.0   20.0   72.0   67.0   74.0   62.0   5.0

SURFACE DISCHARGE      ONCE THROUGH SYSTEM

HEAT REJECTED IS  62366.5 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS       2776.  CFS
THE RELATIVE HUMIDITY IS  85.98 PERCENT

ESTUARY SITE

ESTUARY WIDTH IS EQUAL TO  5000.0 FEET
ESTUARY DEPTH IS EQUAL TO  25.0 FEET
FRESH WATER INFLOW VELOCITY IN ESTUARY IS EQUAL TO  0.20  FEET PER SECOND
MAXIMUM TIDAL VELOCITY IN THE ESTUARY IS EQUAL TO  2.00  FEET PER SECOND
LENGTH OF ESTUARY TO HEAD OF TIDE IS EQUAL TO        700000.0  FEET
THE FLOW IN THE ESTUARY IS   25000.00 CFS

FROUDE NUMBER IS LESS THAN 3.57 -- CANNOT BE HANDLED COMPUTATIONALLY -- BEYOND THE LIMITS OF THE THEORY
DISCONTINUE CONSIDERATION OF THIS ALTERNATIVE

Figure 6-1

# ALTERNATIVE TWO

PLANT SIZE TEXIPL MIXZON--TERIAL TEMAL MIXDIA MIXAREA--TEMAM TEMESW TEGESW TEMBSW MIXVEL
1200000.0  10.0  2.0  5.0  60.0  900.0  26.0  72.0  67.0  74.0  62.0  5.0

SURFACE DISCHARGE    ONCE THROUGH SYSTEM

HEAT REJECTED IS  6236.5 BTU PER HOUR
THE REQUIRED FLOW OF COOLING WATER IS       3331. CFS
THE RELATIVE HUMIDITY IS   85.90 PERCENT

OFFSHORE OCEAN SITE

OFFSHORE OCEAN DEPTH IS EQUAL TO 100.0 FEET
OFFSHORE OCEAN VELOCITY IS EQUAL TO 1.00 FEET PER SECOND

FROUDE NUMBER IS LESS THAN 3.57 -- CANNOT BE HANDLED COMPUTATIONALLY -- BEYOND THE LIMITS OF THE THEORY
DISCONTINUE CONSIDERATION OF THIS ALTERNATIVE

Figure 6-2

ALTERNATIVE THREE

PLANT SIZE TERIPL MIXION--TERIAL TEMAAL MIXDIA MIXAREA--TEMAM TEHEBU TEOMBU TEMDEM MINVEL
1600000.0 20.0 2.0 5.0 80.0 500.0 20.0 20.0 72.0 67.0 74.0 62.0 5.0

SURFACE DISCHARGE    ONCE THROUGH SYSTEM

HEAT REJECTED IS 6527.4 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS 2325. CFS
THE RELATIVE HUMIDITY IS 85.98 PERCENT

GREAT LAKE SITE

LAKE DEPTH IS EQUAL TO 30.0 FEET
VELOCITY IN THE LAKE IS EQUAL TO 0.50 FEET PER SECOND

THE AREA WITHIN THE 5.00 DEG. F. ISOTHERM IS EQUAL TO 15501B. SQUARE FEET OR 4. ACRES
TEMPERATURE RISE IS LESS THAN ALLOWABLE AT THE EDGE OF THE MIXING ZONE
DISTANCE TO THE POINT OF MAXIMUM DILUTION IS 1085.5 FEET
SURFACE AREA 3.6 ACRES IS LESS THAN PRESCRIBED MIXING ZONE
ALLOWABLE AREA FOR THE MIXING ZONE IS 20.0 ACRES
TEMPERATURE RISE AT THE EDGE OF MIXING ZONE IS 5.0 DEGREES F.
MAXIMUM ALLOWABLE TEMPERATURE RISE AT THE EDGE OF MIXING ZONE IS 5.0 DEGREES F.
WATER TEMPERATURE AT THE EDGE OF MIXING ZONE IS 77.0 DEGREES F.
MAXIMUM ALLOW TEMPERATURE AT EDGE OF MIXING ZONE IS 80.0 DEGREES F.
THE FLOW THROUGH THE PLANT IS 2324.56 CFS
DILUTION FLOW IS EQUAL TO 0.0 CFS
LIMITING VALUE OF FROUDE NUMBER BASED ON WATER BODY DEPTH IS 4.8
LIMITING VALUE OF FROUDE NUMBER BASED ON CANAL VELOCITY IS 10.7
DESIGN VALUE OF THE FROUDE NUMBER IS 4.8
VALUE OF MOBO IS 218.72
VALUE OF SCALING FACTOR IS 14.79
FLOW IN THE CANAL IS 2324.6 CFS
TEMPERATURE RISE AT END OF DISCHARGE CANAL IS 20.0 DEGREES F.
VELOCITY IN CANAL IS EQUAL TO 5.31 FEET PER SECOND
DEPTH OF FLOW IN CANAL IS EQUAL TO 10.5 FEET
WIDTH OF CANAL IS EQUAL TO 41.8 FEET
VALUE OF B IS EQUAL TO 20.9 FEET
ASPECT RATIO IS EQUAL TO 0.50
FROUDE NUMBER FOR ANALYSIS IS EQUAL TO 5.8
SURFACE EVAPORATION LOSS IS EQUAL TO 2.393 CFS
DISTANCE FROM THE END OF THE NEAR FIELD TO EVAPORATIVE LOSS LESS THAN LIMIT IS 24816. FEET
THE HEATED SURFACE AREA IS EQUAL TO 23432. ACRES
THE DISTANCE FROM THE POINT OF DISCHARGE TO 0.5 DEG. F. RISE IS 55640. FEET
THE INTAKE TEMPERATURE FROM THE GREAT LAKE IS 72.00 DEG. F.
POWER REQUIREMENT IS 4837616.0 KILOWATTS PER YEAR
LAND AREA REQUIRED FOR DISCHARGE CANAL AND INTAKE PIPE IS 1.2 ACRES
THE COST OF THE REQUIRED LAND IS EQUAL TO 480. DOLLARS
THE COST OF LAND IMPROVEMENTS IS EQUAL TO 42. DOLLARS
PUMPS, MOTORS, AND PUMPING STATION CAPITAL COST IS EQUAL TO 1596520. DOLLARS
THE INTAKE STRUCTURE CAPITAL COST IS EQUAL TO 2079728. DOLLARS
THE INTAKE LINE CAPITAL COST IS EQUAL TO 2059200. DOLLARS
DISCHARGE CANAL CAPITAL COST IS EQUAL TO 803200. DOLLARS
TOTAL CAPITAL COST OF OTHER-CONTROL EQUIPMENT IS EQUAL TO 1082649. DOLLARS
THE TOTAL CAPITAL COST FOR ALL THERMAL POLLUTION ABATEMENT EQUIPMENT IS 8410410. DOLLARS
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO 148801. DOLLARS
THE VARIABLE ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO 0. DOLLARS

Figure 6-3

# ALTERNATIVE FOUR

PLANT SIZE TERIPL MIXION--TERIAL TEMBAL MIXDIA MIXAREA--TEMAAM TEMEBU TEMBU TEMOBW MINVEL
1100000.0   14.0    2.0    5.0   80.0   500.0   20.0   72.0   67.0   74.0   62.0   5.0

SURFACE DISCHARGE     ONCE THROUGH SYSTEM

HEAT REJECTED IS  5011.7 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS        1753.  CFS
THE RELATIVE HUMIDITY IS   85.98 PERCENT

SMALL LAKE SITE

LAKE DEPTH IS EQUAL TO  30.0 FEET
LAKE SURFACE AREA IS EQUAL TO    2000.  ACRES
VELOCITY IN THE LAKE IS EQUAL TO  0.50  FEET PER SECOND

THE AREA WITHIN THE   5.00  DEG. F. ISOTHERM IS EQUAL TO       48705.  SQUARE FEET OR     1. ACRES
TEMPERATURE RISE IS LESS THAN ALLOWABLE AT THE EDGE OF THE MIXING ZONE
DISTANCE TO THE POINT OF MAXIMUM DILUTION IS        1036.2  FEET
SURFACE AREA       1.1  ACRES  IS LESS THAN PRESCRIBED MIXING ZONE
ALLOWABLE AREA FOR THE MIXING ZONE IS       20.0 ACRES
TEMPERATURE RISE AT THE EDGE OF MIXING ZONE IS    5.0    DEGREES F.
MAXIMUM ALLOWABLE TEMPERATURE RISE AT EDGE OF MIXING ZONE IS  5.0  DEGREES F.
WATER TEMPERATURE AT THE EDGE OF MIXING ZONE IS  77.0  DEGREES F.
MAXIMUM ALLOW TEMPERATURE AT EDGE OF MIXING ZONE IS  80.0  DEGREES F.
THE FLOW THROUGH THE PLANT IS       1752.93  CFS
DILUTION FLOW IS EQUAL TO       0.0  CFS
LIMITING VALUE OF FROUDE NUMBER BASED ON WATER BODY DEPTH IS   5.1
LIMITING VALUE OF FROUDE NUMBER BASED ON CANAL VELOCITY IS  16.1
DESIGN VALUE OF THE FROUDE NUMBER IS   5.1
VALUE OF MORO IS     198.52
VALUE OF SCALING FACTOR IS    14.09
FLOW IN THE CANAL IS     1752.9  CFS
TEMPERATURE RISE AT END OF DISCHARGE CANAL IS      14.0  DEGREES F.
VELOCITY IN CANAL IS EQUAL TO      4.41 FEET PER SECOND
DEPTH OF FLOW IN CANAL IS EQUAL TO  10.0 FEET
WIDTH OF CANAL IS EQUAL TO   39.9 FEET
VALUE OF B IS EQUAL TO   14.9 FEET
ASPECT RATIO IS EQUAL TO     0.50
FROUDE NUMBER FOR ANALYSIS IS EQUAL TO   6.0
THE LOADING OF THE LAKE IS    1.82  MW/ACRE
THE DEPTH OF THE  SMALL LAKE IS      30.00  FEET
THE VOLUME OF THE SMALL LAKE IS       261360000.  CUBIC FEET
THE SURFACE AREA OF THE SMALL LAKE IS      2000.0 ACRES
THE FLOW THROUGH THE PLANT IS     1752.9  CFS
THE VOLUME OF THE SMALL LAKE IS EQUAL TO THE PLANT     FOR A    414.16  HOUR PERIOD
THE VOLUME OF THE SMALL LAKE IS EQUAL TO THE PLANT FLOW FOR A     17.26  DAY PERIOD
THE HEATED SURFACE AREA IS EQUAL TO    2000.0  ACRES
THE EQUILIBRIUM TEMPERATURE IS 79.80  DEG. F.
THE INTAKE TEMPERATURE FROM THE LAKE IS      68.39 DEG. F.
THE TEMPERATURE OF THE PLANT DISCHARGE TO THE LAKE IS  102.30  DEG. F.
THE AVERAGE SURFACE TEMPERATURE OF THE LAKE IN OPERATION IS    87.55   DEG. F.
THE SURFACE HEAT EXCHANGE COEFFICIENT IS EQUAL TO     175.44  BTU/SQ. FT. -- DAY -- DEG. F.
FOR A FORCED TEMPERATURE RISE OF  7.75  DEG. F., THE EVAPORATIVE LOSS FROM THE POND IS    11.32  CFS
THE TOTAL CONSUMPTIVE USE OF WATER IS      11.3  CFS
POWER REQUIREMENT IS   36481488.0  KILOWATTS PER YEAR
LAND AREA REQUIRED FOR DISCHARGE CANAL AND INTAKE PIPE IS       1.0  ACRES
THE COST OF THE REQUIRED LAND IS EQUAL TO      412.  DOLLARS
THE COST OF LAND IMPROVEMENTS IS EQUAL TO     36.  DOLLARS
PUMPS, PCTQAS, AND PUMPING STATION CAPITAL COST IS EQUAL TO    1230304.  DOLLARS
THE INTAKE STRUCTURE CAPITAL COST IS EQUAL RO   1607648.  DOLLARS
THE INTAKE LINE CAPITAL COST IS EQUAL TO   1252800. DOLLARS
DISCHARGE CANAL CAPITAL COST IS EQUAL TO    72000. DOLLARS
THE CAPITAL COST OF OTHER CONTROL EQUIPMENT IS EQUAL TO  1190400. DOLLARS
TOTAL CAPITAL COST FOR ALL THERMAL POLLUTION ABATEMENT EQUIPMENT IS    5977768. DOLLARS
THE TOTAL CAPITAL COST IS EQUAL TO  5.43  DOLLARS PER KILOWATT
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO   114126.  DOLLARS
THE VARIABLE ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO   0.  DOLLARS

## Figure 6-4

ALTERNATIVE FIVE

PLANT SIZE TERIPL MIXION--TERIAL TEMAL MIXOIA MIXAREA--TEMAAM TEMEBU TEDABU TENDEH MINMEL
109002U.J  26.0  2.0   5.0  80.3  950.0  25.3  72.0  67.0  74.0  62.0  5.0

SURFACE DISCHARGF   ONCE THROUGH SYSTEM

HEAT REJECTED IS  4607.5 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS        700. CFS
THE RELATIVE HUMIDITY IS   85.98 PE LENT

ESTUARY SITE

ESTUARY WIDTH IS EQUAL TO  5300.0 FEET
ESTUARY DEPTH IS EQUAL TO   25.0 FEET
FRESH WATER INFLOW VELOCITY IN ESTUARY IS EQUAL TO  0.25 FEET PER SECOND
MAXIMUM TIDAL VELOCITY IN THE ESTUARY IS EQUAL TO  2.00 FEET PER SECOND
LENGTH OF ESTUARY TO HEAD OF TIDE IS EQUAL TO   700000.0 FEET
THE FLOW IN THE ESTUARY IS   25300.33 CFS

THE AREA WITHIN THE  5.00 DEG. F. ISOTHERM IS EQUAL TO            45102. SQUARE FEET OR      1. ACRES
RATIO OF THE PLANT FLOW TO ESTUARY FLOW IS       0.0
TEMPERATURE RISE IS LESS THAN ALLOWABLE AT THE EDGE OF THE MIXING ZONE
DISTANCE TO THE POINT OF MAXIMUM DILUTION IS       688.1 FEET
SURFACE AREA       1.0 ACRES IS LESS THAN PRESCRIBED MIXING ZONE
ALLOWABLE AREA FOR THE MIXING ZONE IS   20.0 ACRES
TEMPERATURE RISE AT THE EDGE OF MIXING ZONE IS   5.0 DEGREES F.
MAXIMUM ALLOWABLE TEMPERATURE RISE AT EDGE OF MIXING ZONE IS  5.0 DEGREES F.
WATER TEMPERATURE AT THE EDGE OF MIXING ZONE IS   77.0 DEGREES F.
MAXIMUM ALLOW TEMPERATURE AT EDGE OF MIXING ZONE IS  80.0 DEGREES F.
THE FLOW THROUGH THE PLANT IS       700.84 CFS
DILUTION FLOW IS EQUAL TO       0.0 CFS
LIMITING VALUE OF FROUDE NUMBER BASED ON WATER BODY DEPTH IS   8.2
LIMITING VALUE OF FROUDE NUMBER BASED ON CANAL VELOCITY IS   11.9
DESIGN VALUE OF THE FROUDE NUMBER IS   8.2
VALUE OF MORO IS       53.13
VALUE OF SCALING FACTOR IS       7.79
FLOW IN THE CANAL IS       700.9 CFS
TEMPERATURE RISE AT END OF DISCHARGE CANAL IS   26.0 DEGREES F.
VELOCITY IN CANAL IS EQUAL TO   7.42 FEET PER SECOND
DEPTH OF FLOW IN CANAL IS EQUAL TO   5.2 FEET
WIDTH OF CANAL IS EQUAL TO   20.6 FEET
VALUE OF B IS EQUAL TO   10.3 FEET
ASPECT RATIO IS EQUAL TO       0.50
FROUDE NUMBER FOR ANALYSIS IS EQUAL TO       9.7
SURFACE EVAPORATION LOSS IS EQUAL TO  0.383 CFS
DISTANCE DOWNSTREAM TO EVAPORATIVE LOSS LIMIT IS               0. FEET
DISTANCE DOWNSTREAM TO 0.5 DEG. F. RISE IS EQUAL TO           51600. FEET
DISTANCE UPSTREAM TO 0.5 DEG. F. RISE IS EQUAL TO          -21130. FEET
THE HEATED SURFACE AREA IS EQUAL TO   4061. ACRES
THE INTAKE TEMPERATURE FROM THE ESTUARY IS 72.00 DEG. F.
POWER REQUIREMENT IS   1641920.0 KILOWATTS PER YEAR
LAND AREA REQUIRED FOR DISCHARGE CANAL AND INTAKE PIPE IS        0.5 ACRES
THE COST OF THE REQUIRED LAND IS EQUAL TO       213. DOLLARS
THE COST OF LAND IMPROVEMENTS IS EQUAL TO        19. DOLLARS
PUMPS, MOTORS, AND PUMPING STATION CAPITAL COST IS EQUAL TO   724365. DOLLARS
THE INTAKE STRUCTURE CAPITAL COST IS EQUAL TO   811491. DOLLARS
THE INTAKE LINE CAPITAL COST IS EQUAL TO   1292803. DOLLARS
DISCHARGE CANAL CAPITAL COST IS EQUAL TO   723000. DOLLARS
THE CAPITAL COST OF OTHER CONTROL EQUIPMENT IS EQUAL TO   293409. DOLLARS
TOTAL CAPITAL COST FOR ALL THERMAL POLLUTION ABATEMENT EQUIPMENT IS   3002906. DOLLARS
THE TOTAL CAPITAL COST IS EQUAL TO   3.80 DOLLARS PER KILOWATT
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO   59249. DOLLARS
THE VARIABLE ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO       0. DOLLARS

Figure 6-5

# ALTERNATIVE SIX

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PLANT SIZE TGRIPL MIXZON--TERIAL TEMAAL MIXDIA MIXAREA--TEMAAM TEMBAU TEMBAU TEMBAU MIMWBL
800000.0   16.0    2.0     5.0   80.0  500.0   80.0   72.0   67.0   74.0   62.0    5.0

DIFFUSER     ONCE THROUGH

HEAT REJECTED IS  5011.7 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS        1115.  CFS
THE RELATIVE HUMIDITY IS   85.90 PERCENT

RIVER SITE

RIVER WIDTH IS EQUAL TO  1000.0 FEET
RIVER DEPTH IS EQUAL TO   20.0 FEET
RIVER VELOCITY IS EQUAL TO  0.90 FEET PER SECOND
THE RIVER FLOW IS   10000.00 CFS

RATIO OF THE PLANT FLOW TO THE RIVER FLOW IS      0.0
TEMPERATURE RISE IS LESS THAN ALLOWABLE AT THE EDGE OF THE MIXING ZONE
TEMPERATURE RISE AT THE EDGE OF MIXING ZONE IS      1.5       DEGREES F.
MAXIMUM ALLOWABLE TEMPERATURE RISE AT THE EDGE OF MIXING ZONE IS    5.0  DEGREES F.
WATER TEMPERATURE AT THE EDGE OF MIXING ZONE IS   73.5 DEGREES F.
MAXIMUM ALLOW TEMPERATURE AT EDGE OF MIXING ZONE IS  80.0 DEGREES F.
THE DIAMETER OF THE PORTS OF THE DIFFUSER IS   2.0 FEET
THE VELOCITY AT THE PORT OF THE DIFFUSER IS      15.00 FEET PER SECOND
THE FLOW THROUGH EACH PORT OF THE DIFFUSER IS      47.1 CFS
THE NUMBER OF PORTS IS      24
THE PORTS ARE SPACED AT A CENTER TO CENTER DISTANCE OF      20  FEET
THE LENGTH OF THE DIFFUSER IS EQUAL TO  480.0 FEET
THE AREA OF EACH PORT IS EQUAL TO     3.  SQUARE FEET
FROUDE NUMBER AT THE POINT OF DISCHARGE IS      42.4
THE DILUTION FLOW IS EQUAL TO       0.  CFS
PORTS ARE DIRECTED WITH THE CURRENT
SURFACE EVAPORATION LOSS IS EQUAL TO  2.391 CFS
DISTANCE DOWNSTREAM TO EVAPORATIVE LOSS LIMIT IS      163000. FEET
THE HEATED SURFACE AREA IS EQUAL TO  11030.  ACRES
THE DISTANCE DOWNSTREAM TO 0.5 DEG. F. IS      465700. FEET
THE INTAKE TEMPERATURE FROM THE RIVER IS 72.00 DEG. F.
THE LAND REQUIRED FOR DIFFUSERS AND THE INTAKE PIPE IS      0.0 ACRES
POWER REQUIREMENT IS  6444544.9 KILOWATTS PER YEAR
THE COST OF THE REQUIRED LAND IS EQUAL TO      0.  DOLLARS
THE COST OF LAND IMPROVEMENTS IS EQUAL TO      0.  DOLLARS
PUMPS, MOTORS, AND PUMPING STATION CAPITAL COST IS EQUAL TO   2216152.  DOLLARS
THE INTAKE STRUCTURE CAPITAL COST IS EQUAL TO  1081231. DOLLARS
THE INTAKE LINE CAPITAL COST IS EQUAL TO  1252802. DOLLARS
DISCHARGE PIPE CAPITAL COST IS EQUAL TO  1702400. DOLLARS
THE DIFFUSER CAPITAL COST IS EQUAL TO   583600. DOLLARS
THE CAPITAL COST OF OTHER CHEMICAL EQUIPMENT IS EQUAL TO   532636. DOLLARS
TOTAL CAPITAL COST FOR ALL THERMAL POLLUTION ABATEMENT EQUIPMENT IS     7368697. DOLLARS
THE FIXED ANNUAL CAPITAL COST IS EQUAL TO   9.21 DOLLARS PER KILOWATT
THE CAPITAL, OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO   299505. DOLLARS
THE VARIABLE ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO      0. DOLLARS
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Figure 6-6

# ALTERNATIVE SEVEN

| PLANT SIZE | TERIPL | MIXION--TERIAL | TEMAAL | MIXOIA | MIXAREA--TEHAAM | TEMBU | TEOABU | TENDEN | MINVEL |
|---|---|---|---|---|---|---|---|---|---|
| 600000.0 | 18.0 | 2.0  5.0 | 80.0 | 500.0 | 20.0 | 72.0 | 67.0  74.0 | 62.0 | 5.0 |

SURFACE DISCHARGE     CNCE THROUGH SYSTEM

HEAT REJECTED IS   5460.8 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS     810. CFS
THE RELATIVE HUMIDITY IS   85.98 PERCENT

ESTUARY SITE

ESTUARY WIDTH IS EQUAL TO   5000.0 FEET
ESTUARY DEPTH IS EQUAL TO   25.0 FEET
FRESH WATER INFLOW VELOCITY IN ESTUARY IS EQUAL TO   0.20 FEET PER SECOND
MAXIMUM TIDAL VELOCITY IN THE ESTUARY IS EQUAL TO   2.00 FEET PER SECOND
LENGTH OF ESTUARY TO HEAD OF TIDE IS EQUAL TO   703003.0 FEET
THE FLOW IN THE ESTUARY IS   25000.00 CFS

THE AREA WITHIN THE   5.00 DEG. F. ISOTHERM IS EQUAL TO   24936. SQUARE FEET OR   1. ACRES
RATIO OF THE PLANT FLOW TO ESTUARY FLOW IS   0.0
TEMPERATURE RISE IS LESS THAN ALLOWABLE AT THE EDGE OF THE MIXING ZONE
DISTANCE TO THE POINT OF MAXIMUM DILUTION IS   632.5 FEET
SURFACE AREA   0.6 ACRES IS LESS THAN PRESCRIBED MIXING ZONE
ALLOWABLE AREA FOR THE MIXING ZONE IS   20.0 ACRES
TEMPERATURE RISE AT THE EDGE OF MIXING ZONE IS   5.0 DEGREES F.
MAXIMUM ALLOWABLE TEMPERATURE RISE AT EDGE OF MIXING ZONE IS   5.0 DEGREES F.
WATER TEMPERATURE AT THE EDGE OF MIXING ZONE IS   77.0 DEGREES F.
MAXIMUM ALLOW TEMPERATURE AT EDGE OF MIXING ZONE IS   80.0 DEGREES F.
THE FLOW THROUGH THE PLANT IS   810.30 CFS
DILUTION FLOW IS EQUAL TO   0.0 CFS
LIMITING VALUE OF FROUDE NUMBER BASED ON WATER BODY DEPTH IS   6.9
LIMITING VALUE OF FROUDE NUMBER BASED ON CANAL VELOCITY IS   14.8
DESIGN VALUE OF THE FROUDE NUMBER IS   6.9
VALUE OF HOBO IS   76.25
VALUE OF SCALING FACTOR IS   8.62
FLOW IN THE CANAL IS   810.3 CFS
TEMPERATURE RISE AT END OF DISCHARGE CANAL IS   18.0 DEGREES F.
VELOCITY IN CANAL IS EQUAL TO   5.46 FEET PER SECOND
DEPTH OF FLOW IN CANAL IS EQUAL TO   6.1 FEET
WIDTH OF CANAL IS EQUAL TO   24.4 FEET
VALUE OF B IS EQUAL TO   12.2 FEET
ASPECT RATIO IS EQUAL TO   0.50
FROUDE NUMBER FOR ANALYSIS IS EQUAL TO   8.2
SURFACE EVAPORATION LOSS IS EQUAL TO   0.253 CFS
DISTANCE DOWNSTREAM TO EVAPORATIVE LOSS LIMIT IS   0. FEET
DISTANCE DOWNSTREAM TO 0.5 DEG. F. RISE IS EQUAL TO   5280. FEET
DISTANCE UPSTREAM TO 0.5 DEG. F. RISE IS EQUAL TO   -10560. FEET
THE HEATED SURFACE AREA IS EQUAL TO   1018. ACRES
THE INTAKE TEMPERATURE FROM THE ESTUARY IS 72.00 DEG. F.
POWER REQUIREMENT IS   16863856.0 KILOWATTS PER YEAR
LAND AREA REQUIRED FOR DISCHARGE CANAL AND INTAKE PIPE IS   0.6 ACRES
THE COST OF THE REQUIRED LAND IS EQUAL TO   252. DOLLARS
THE COST OF LAND IMPROVEMENTS IS EQUAL TO   22. DOLLARS
PUMPS, MOTORS, AND PUMPING STATION CAPITAL COST IS EQUAL TO   74.2046. DOLLARS
THE INTAKE STRUCTURE CAPITAL COST IS EQUAL TO   829186. DOLLARS
THE INTAKE LINE CAPITAL COST IS EQUAL TO   125280O. DOLLARS
DISCHARGE CANAL CAPITAL COST IS EQUAL TO   720300. DOLLARS
THE CAPITAL COST OF OTHER CONTROL EQUIPMENT IS EQUAL TO   307250. DOLLARS
TOTAL CAPITAL COST FOR ALL THERMAL POLLUTION ABATEMENT EQUIPMENT IS   3851558. DOLLARS
THE TOTAL CAPITAL COST IS EQUAL TO   6.42 DOLLARS PER KILOWATT
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO   60781. DOLLARS
THE VARIABLE ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO   0. DOLLARS

Figure 6-7

ALTERNATIVE EIGHT

PLANT SIZE MW T RISE — ALLOW T RISE MAX ALLOW T ALLOW MIX AREA — AND WATER T WET BULB T DRY BULB T DEW POINT T DES WIND VEL
80C203.0   30.0       5.0                 80.0              20.0              72.0      67.0      76.0      62.0       5.0

COOLING POND     CLOSED LOOP

HEAT REJECTED IS 5230.2 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS      621. CFS
THE RELATIVE HUMIDITY IS   85.00 PERCENT

WATER POOR SITE

POND IS CONSERVATIVELY DESIGNED WITH A LOADING OF        1.00 MW/ACRE
THE DEPTH OF THE COOLING POND IS      15.00 FEET
THE VOLUME OF THE COOLING POND IS         52720000. CUBIC FEET
THE SURFACE AREA OF THE COOLING POND IS        803.0 ACRES
THE FLOW THROUGH THE PLANT IS         620.9 CFS
THE VOLUME OF THE COOLING POND IS EQUAL TO THE PLANT FLOW FOR A      233.87 HOUR PERIOD
THE VOLUME OF THE COOLING POND IS EQUAL TO THE PLANT FLOW FOR A        9.74 DAY PERIOD
THE EQUILIBRIUM TEMPERATURE IS 81.40 DEG. F.
THE INTAKE TEMPERATURE FROM THE POND IS   86.34 DEG. F.
THE TEMPERATURE OF THE PLANT DISCHARGE TO THE POND IS  116.30 DEG. F.
THE AVERAGE SURFACE TEMPERATURE OF THE POND IN OPERATION IS    91.39 DEG. F.
THE INCREASE IN NATURAL EVAPORATIVE LOSSES DUE TO CONSTRUCTION OF THE COOLING POND IS EQUAL TO     6.92 CFS
THE SURFACE HEAT EXCHANGE COEFFICIENT IS EQUAL TO   187.68 BFJ/SQ. FT. — DAY — DEG. F.
FOR A FORCED TEMPERATURE RISE OF  9.95 DEG. F., THE EVAPORATIVE LOSS FROM THE POND IS    0.54 CFS
THE TOTAL EVAPORATIVE LOSS IS EQUAL TO     14.46 CFS
THE LOSSES DUE TO BLOWDOWN EQUAL     6.21 CFS
THE TOTAL CONSUMPTIVE USE OF WATER IS     21.2 CFS
THE HEATED SURFACE AREA IS EQUAL TO        0.0 ACRES
LAND AREA REQUIRED IS        960.0 ACRES
PUMPING HORSEPOWER REQUIRED FOR CIRCULATING WATER SYSTEM IS      1078.4 HP
PUMPING HORSEPOWER REQUIRED FOR THE MAKE-UP WATER SYSTEM IS        64. HP
TOTAL PUMPING HORSEPOWER REQUIRED IS      1142. HP
THE POWER REQUIREMENT FOR THE CIRCULATING WATER SYSTEM IS    12921361.0 KILOWATTS PER YEAR
THE POWER REQUIREMENT FOR THE MAKE-UP WATER SYSTEM IS    440602.2 KILOWATTS PER YEAR
THE TOTAL POWER REQUIREMENT IS     13361963.0 KILOWATTS PER YEAR
THE COST OF THE REQUIRED LAND IS EQUAL TO    384000. DOLLARS
THE COST OF THE LAND IMPROVEMENTS IS EQUAL TO    768000. DOLLARS
PUMPS, MOTORS, AND PUMPING STATION FOR CIRCULATING WATER SYSTEM CAPITAL COST IS EQUAL TO    486596. DOLLARS
THE INTAKE STRUCTURE CAPITAL COST IS EQUAL TO    672741. DOLLARS
DISCHARGE CANAL CAPITAL COST IS EQUAL TO    400000. DOLLARS
THE CAPITAL COST OF THE OTHER CONTROL EQUIPMENT IS EQUAL TO    184947. DOLLARS
PUMPS, MOTORS, AND PUMPING STATION FOR MAKE-UP WATER SYSTEM CAPITAL COST IS EQUAL TO    30526. DOLLARS
THE MAKE-UP LINE CAPITAL COST IS EQUAL TO    300000. DOLLARS
BLOWDOWN LINE CAPITAL COST IS EQUAL TO    300000. DOLLARS
TOTAL CAPITAL COST FOR ALL THERMAL POLLUTION ABATEMENT EQUIPMENT IS    3436806. DOLLARS
THE TOTAL CAPITAL COST IS EQUAL TO    4.30 DOLLARS PER KILOWATT
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS FOR THE CIRCULATING WATER SYSTEM ARE EQUAL TO    63019. DOLLARS
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS FOR THE MAKE-UP WATER SYSTEM ARE EQUAL TO     4797. DOLLARS
THE TOTAL FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO    44816. DOLLARS
THE VARIABLE ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO      0. DOLLARS

Figure 6-8

# ALTERNATIVE NINE

```
PLANT SIZE KW T RISE -- ALLOW T RISE MAX ALLOW T ALLOW MIX AREA -- AMB WATER T WET BULB T DRY BULB T DEW POINT T DES WIND VEL
800000.0    16.0              5.0      80.0       20.0           72.0       67.0      74.0      62.0          5.0

WET MECHANICAL DRAFT COOLING TOWER      CLOSED LOOP


HEAT REJECTED IS  5704.6 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS   1270.  CFS
THE RELATIVE HUMIDITY IS  85.98 PERCENT


COASTAL SITE


NUMBER OF TOWER UNITS          721733.06
RELATIVE RATING RATING FACT         1.26

AIR FLOW RATE                257229368.       LB/HR     508844&0.0     CFM
WATER FLOW RATE              285343232.       LB/HR     569086.37      GPM
L/G                              1.11
PACKING HEIGHT                  24.53         FT
PACKING PRESSURE DROP            0.48         IN H2O
FAN EFFICIENCY                  80.00         %
FAN HORSEPOWER                5539.96         HP
PUMP HEAD                       44.53         FT
PUMP EFFICIENCY                  0.75
PUMP HORSEPOWER              14154.83         HP

WET BULB TEMPERATURE            67.00         F
APPROACH                        10.00         F
WATER TEMP ENTERING TOWER       93.00         F
WATER TEMP LEAVING TOWER        77.00         F
AIR ENTHALPY ENTERING TOWER     31.38         BTU/LB
AIR ENTHALPY LEAVING TOWER      49.12         BTU/LB
AIR DENSITY ENTERING TOWER       0.073        LB/CUFT

EVAPORATION                   3646382.00      LB/HR
DRIFT                           85602.94      LB/HR
BLEED                          830902.25      LB/HR
MAKEUP                        4582976.00      LB/HR

CAPITAL COST                    5.00          $/TU
FIXED OPERATING COST            0.25          $/YR/TU
VARIABLE OPERATING COST         0.0           $/MCF/YR/TU

COST OF REQUIRED LAND           1325.68       $
COST OF LAND IMPROVEMENTS        116.00       $
PUMPS CAPITAL COST          3595443.00        $
INTAKE CAPITAL COST         1208590.00        $
OTHER EQUIP CAPITAL COST     643263.56        $
MAKE-UP PUMPS CAPITAL COST    29789.57        $
MAKE-UP LINE CAPITAL COST    300000.00        $
BLOWDOWN LINE CAPITAL COST   200000.00        $
RETURN LINE CAPITAL COST    1152000.00        $
DISCHARGE LINE CAPITAL COST 1216000.30        $
TOWER CAPITAL COST          3609665.00        $
TOTAL CAPITAL COST         11977190.0         $
DOLLARS PER KILOWATT            14.97         $/KW

FIXED OPERATING COST          397125.56       $/YR
VARIABLE OPERATING COST          0.0          $/CF/YR
```

Figure 6-9

# ALTERNATIVE TEN

PLANT SIZE KW  T RISE — ALLOW T RISE  MAX ALLOW MIX AREA -- AMB WATER T  WET BULB T  DRY BULB T  DEW POINT T  DES WIND VEL
1000000.0  14.0  5.0  80.0  20.0  72.0  67.0  74.0  62.0  5.0

SPRAY CANAL    CLOSED LOOP

HEAT REJECTED IS 7167.3 BTU PER KWHR
THE REQUIRED FLOW OF COOLING WATER IS 2270. CFS
THE RELATIVE HUMIDITY IS 89.90 PERCENT

ESTUARY SITE

THE NUMBER OF MODULES IS 4.
THE EQUIVALENT WET BULB TEMPERATURE IS EQUAL TO 69.00 DEG. F.
THE INTAKE TEMPERATURE IS EQUAL TO 79.00 DEG. F.
THE OUTLET TEMPERATURE IS EQUAL TO 93.00 DEG. F.
THE CHARACTERISTIC TEMPERATURE IS EQUAL TO 17.00 DEG. F.
THE TOTAL HEAT DISSIPATED IS 716.7291390. BTU/HOUR
THE MINIMUM AREA REQUIRED FOR THE SPRAY MODULES IS
THE NUMBER OF UNITS IS 328.0
THE WATER SURFACE AREA IS EQUAL TO 72.2 ACRES
NEW INTAKE TEMPERATURE IS EQUAL TO 79.00 DEG. F.
THE EVAPORATIVE LOSS IS EQUAL TO 24.57 CFS
DRIFT LOSS IS EQUAL TO 22.79 CFS
LOSSES DUE TO BLOWDOWN EQUAL 136.74 CFS
TOTAL CONSUMPTIVE USE OF WATER IS 186.1 ACRES
THE HEATED SURFACE AREA IS EQUAL TO 0.0 ACRES
LAND AREA REQUIRED IS 86.6 ACRES
PUMPING HORSEPOWER REQUIRED FOR CIRCULATING WATER SYSTEM IS 6894.0 HP
PUMPING HORSEPOWER REQUIRED FOR THE MAKE-UP WATER SYSTEM IS 957. HP
PUMPING HORSEPOWER REQUIRED FOR THE SPRAY MODULE UNITS IS 24400. HP
TOTAL PUMPING HORSEPOWER REQUIRED IS 32052. HP
THE POWER REQUIREMENT FOR THE CIRCULATING WATER SYSTEM IS 47429540.0 KILOWATTS PER YEAR
THE POWER REQUIREMENT FOR THE MAKE-UP WATER SYSTEM IS 3031516.0 KILOWATTS PER YEAR
THE POWER REQUIREMENT FOR THE SPRAY MODULE UNITS IS 169221024. KILOWATTS PER YEAR
THE TOTAL POWER REQUIREMENT IS 220482046. KILOWATTS PER YEAR
THE COST OF THE REQUIRED LAND IS EQUAL TO 34636. DOLLARS
PUMPS, MOTORS, AND PUMPING STATION FOR CIRCULATING WATER SYSTEM CAPITAL COST IS EQUAL TO 1081982. DOLLARS
THE INTAKE STRUCTURE CAPITAL COST IS EQUAL TO 204206. DOLLARS
CAPITAL COST OF THE OTHER CONTROL EQUIPMENT IS EQUAL TO 181941. DOLLARS
PUMPS, MOTORS, AND PUMPING STATION FOR MAKE-UP WATER SYSTEM CAPITAL COST IS EQUAL TO 127262. DOLLARS
THE MAKE-UP LINE CAPITAL COST IS EQUAL TO 30000. DOLLARS
THE BLOWDOWN LINE CAPITAL COST IS EQUAL TO 200000. DOLLARS
THE CANAL CAPITAL COST IS EQUAL TO 19715125. DOLLARS
THE CAPITAL COST OF THE SPRAY MODULE UNITS IS EQUAL TO 6683198. DOLLARS
TOTAL CAPITAL COST FOR ALL THERMAL POLLUTION ABATEMENT EQUIPMENT IS 28811648. DOLLARS
THE TOTAL CAPITAL COST IS EQUAL TO 28.81 DOLLARS PER KILOWATT
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS FOR CIRCULATING WATER SYSTEM ARE EQUAL TO 169642. DOLLARS
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS FOR MAKE-UP WATER SYSTEM ARE EQUAL TO 150094. DOLLARS
THE FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS FOR SPRAY MODULE UNITS ARE EQUAL TO 531098. DOLLARS
THE TOTAL FIXED ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO 704933. DOLLARS
THE VARIABLE ANNUAL OPERATING, MAINTENANCE, AND REPAIR COSTS ARE EQUAL TO 0. DOLLARS

Figure 6-10

Figure 6-11

cost was $5,980,000 which corresponds to a figure of $5.43/kw. This cost was made up principally of a $1,200,000 pump cost, a $1,600,000 intake structure, a $1,250,000 intake line, a $720,000 discharge canal, and $720,000 for other equipment. The fixed annual operating costs were $114,000 per year.

A 1000 Mw plant on an estuary site with a surface discharge was the next alternative considered. (see figure 6.5) The thermal standards were complied with since the surface area of 1 acre within the $5^o$ F isotherm was less than the allowable limit of 20 acres and thus the alternative was set forth as a feasible one. The use of dilution flow was not required to comply with the standards. The discharge canal depth was equal to 5.2 ft, the width equal to 20.6 ft, and the velocity equal to 7.4 ft/sec for a flow of 789 cfs. The consumptive use of water from evaporative losses due to the heated discharge was 0.4 cfs; the heated surface area to the $0.5^o$ F limit was 6060 acres, corresponding to a total distance of approximately 4 miles upstream and 6 miles downstream from the point of discharge; and the land area required for the discharge canal was 0.5 acres. The new intake temperature to the plant was $72^o$ F, and the pumping power requirements were 16,417,900 kilowatts per year. The total capital cost was $3,800,000 with the major contributions being from the pumps at $720,000, the intake structure at $811,500, the intake line at $1,250,000, and the discharge canal at $720,000. The cost per kilowatt was $3.80/kw and the fixed operating costs were $60,000 per year.

The sixth alternative (see figure 6.6) was an 800 Mw plant on a

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river site with a diffuser. The plant alternative was included in the feasible set since the temperature rise in the near-field was only 1.5° F with an allowable temperature rise of 5° F. The use of dilution flow was not required to bring compliance with the standards. For the assumed conditions, the number of ports required was 24, and this resulted in a diffuser length of 480 feet with an initial densimetric Froude number at the point of discharge equal to 42. The ports were assumed to be in the direction of the current. The land area required for this abatement technology was zero; the heated surface area to the 0.5 degree limit was 11,030 acres, with a corresponding distance downstream of approximately 92 miles; and the consumptive use of water in the form of evaporative losses due to the heated discharge was 2.4 cfs. The pumping power requirement was 69,646,500 kilowatts per year and the new plant intake temperature was 72° F. The total capital cost was equal to $7,370,000 with a pump cost of $2,210,000 , an intake structure cost of $1,080,000, an intake line cost of $1,250,000, a discharge pipe cost of $1,700,000, a diffuser cost of $580,000, and the cost of other equipment of $530,000. The dollars per kw cost was $9.21/kw and the fixed annual operating cost was $210,000.

A smaller 600 Mw plant on an estuary site with a surface dis-charge was examined in the seventh alternative. (see figure 6.7) Again, the alternative was declared feasible since the thermal standards were met with a surface area of 0.6 acres for the 5° F isotherm which was less than the maximum allowable area of 20 acres. No dilution flow was required to meet the standards. For a plant

flow of 810 cfs, the discharge canal velocity was 5.5 ft/sec., the depth was 6.1 ft, and the width was 24.4 ft. The heated surface area to the 0.5° F limit was 1800 acres, corresponding to a distance of 1 mile upstream and 2 miles downstream; the land area required for the discharge canal was 0.6 acres; and the consumptive use of water as a result of evaporative losses due to the heated surface discharge was 0.3 cfs. The pumping power requirement was 16,863,900 kilowatts per year and the new intake temperature was 72° F. The total capital cost was $3,800,000 with the pump cost at $740,000, the intake structure at $830,000, the discharge canal at $720,000, and the intake line at $1,250,000. The total capital cost was equal to $6.42/kw and the fixed annual operating costs were $61,000.

A closed cycle cooling pond system on a water poor site with an 800 Mw plant was considered in the eighth alternative. Since the system was assumed to operate on a closed cycle, no check for thermal standards was made. An 800 acre pond was analyzed which would provide a 9.7 day detention period for the cooling water flow. The new plant intake temperature was equal to 86° F. The consumptive use of water was equal to 21.2 cfs, with 8.5 cfs due to an increase in natural evaporation as a result of the pond construction, 6.4 cfs due to the heated discharge water, and 6.2 cfs due to blowdown water requirements. The heated surface area was set equal to zero due to the closed cycle cooling and the land area required was 960 acres. The total power requirement was 13,361,900 kilowatts per year with 440,600 kilowatts per year included in this total for the make-up

water system. The total capital cost was $3,436,200 with the dollars per kilowatt figure at $4.30/kw. In this case the principal cost items were the land improvements at $768,000, the intake structure at $672,000, the pumps at $486,000, and the discharge canal at $400,000. The total fixed operating costs, including those for make-up, were $43,000 per year. (see figure 6-8)

An 800 Mw plant on a coastal site with a wet mechanical draft cooling tower system was analyzed in the ninth alternative. (see figure 6.9) The thermal standards were not checked since the system was operated in the closed cycle mode. The number of tower units was 721,700 and the tower relative rating factor was 1.26. The consumptive use of water was determined in lb/hr for this alternative as 3,666,382 lb/hr for evaporation, 85,600 lb/hr for drift, and 831,000 lb/hr for bleed requirements. The total make-up needs were therefore equal to 4,583,000 lb/hr which is approximately equal to 20.2 cfs. The heated surface area would be equal to zero and the land area required would be approximately 3.3 acres at 0.2 sq. ft. per tower unit. The new intake temperature of the plant would be 77° f, and the power requirements were not given in the print out. The total capital cost was $11,977,000 with a dollar per kilowatt figure of $15.0/kw. The principal components of the capital cost were the pumps at $3,595,000, the tower at $3,609,000, the intake structure at $1,209,000, the intake pipe at $1,216,000, and the return line cost at $1,152,000. The fixed annual operating cost was $397,000 per year.

The final alternative evaluated was a spray canal system on an

estuary site for a 1000 Mw plant.  (see figure 6-10)  The thermal
standards were not analyzed since the system will be operating in a
closed cycle mode.  The new intake temperature was 79° F, and the
number of spray module units required was 328.  The consumptive
use of water was 184 cfs with evaporative losses contributing 24.
cfs due to both an increase in natural losses due to the canal
construction and due to the heated discharge; drift losses
contributing 23.  cfs; and blowdown requiring 137.  cfs.  The heated
surface area was set equal to zero and the land area requirement was
86.6 acres.  The annual power requirements were equal to 220,221,000
kilowatts with the cooling water system requiring 47,429,500
kilowatts, the make-up system 3,831,500 kilowatts, and the spray
modules requiring 169,221,000 kilowatts.  The total capital cost
was $28,812,000 with a dollar per kilowatt cost of $28.21/kw.  The
principal elements of the capital cost were the canal cost,
$15,715,100; the spray module units cost, $6,691,000; the intake
structure cost, $2,042,100; and the pumps and other equipment costs,
both of which were equal to approximately $1,800,000.  The fixed
annual costs were $706,800 of which $531,000 was for the spray
modules, $160,000 was for the cooling water system, and the
remainder was for the make-up water system.

Finally, figure 6-11 presents  the initial output from the
model which would be used as a check to determine that the pollution
limits and meteorological conditions information has been read into
the program satisfactorily.

VI. B. 3. Comments

The results in the first two alternatives considered indicated
that these options were infeasible since the calculated densimetric
Froude number was less than the theoretical limit of 3.57. At
first glance, the inability of the model to consider a discharge
with a lower densimetric Froude number appears to be a significant
limitation. However, since all sites with a surface discharge
considered by this model must comply with thermal standards,
usually with the temperature dilution taking place in a relatively
small mixing zone, and since the smaller values of the Froude
number will lead to an increase in the surface spreading of the
heated discharge, this limitation may not be as significant. In
fact, the elimination of these sites appears to be a valid considera-
tion which corresponds to the actual physical situation in which the
sites would not be able to comply with standards.

The third alternative was declared a feasible solution and the
numerical results appear to be reasonable for the given physical
conditions. The total capital cost appears to be somewhat high in
magnitude at $5.40/kw for a once-through system when compared with
published values. This may be due to the large cost assumed for
other equipment which came out as $1,880,000 in this alternative.
This item of cost may, therefore, require further study in the future.

The fourth alternative was also declared a feasible solution
with the numerical results within expected values for the given
physical conditions. As mentioned previously, the total capital
cost appears somewhat high for a once-through system, but the close

correspondence in cost per kw of both the alternatives is noteworthy. The use of the small lake in this case resulted in the effects of recirculation taking place and caused an increase in the plant intake temperature to $88^{\circ}$ F.

The feasible solution presented for the fifth alternative on the estuary site also indicated that the computed values were within the expected ranges for the physical conditions. It should be noted that the total capital cost, which in the formulation was assumed to be related to the plant cooling water flow, was much lower in this case as was the cooling water flow. The dollar cost per kw also decreased significantly to $3.80/kw due to this much smaller cooling water flow. This trend indicates the flow of cooling water plays a dominant role in the determination of the capital cost of this abatement technology, and it also agrees with the expected trend of the costs of thermal pollution abatement equipment decreasing with a larger plant temperature rise for a once-through cooling system. The evaporative losses of water were also significantly smaller and this was due to the increased dilution in the receiving water body due to the large mixing flow in the estuary. The assumption of complete mixing over the top-half of the cross-section of the estuary caused a decrease in both the forced temperature rise and the resulting evaporation. The seventh alternative was similar to the fifth in the quantity of cooling water flow, but the plant size was much smaller and the temperature rise was also significantly less. The heated surface area was much smaller in this seventh alternative due to the case the small initial temperature rise, but the consumptive use of

water and land area requirements were approximately equal. It is
also interesting to note that the total capital cost was about
equal in both cases, as were the individual components, but the
dollars per kw cost nearly double for the smaller plant analyzed
in the seventh alternative due to the decrease in plant size with
the same required plant flow.

The sixth alternative of a diffuser on a river site required
no land area for the thermal pollution abatement alternative since
the piping required would be all underground. The heated surface
area was significant in this case, however, and the length of 92
miles downstream appears to be excessive. This may require more
analysis in the future. It should be noted that the pumping power
requirement for the diffuser alternative increased significantly due
to the additional pumping head requirements with the diffuser. This
pumping power also resulted in a significant increase in the capital
cost of the pumps. This increase in cost, along with additional
cost for the diffuser and the discharge pipe, resulted in a dollars
per kw figure of $9.21/kw. The fixed operating cost of this alterna-
tive also increased due to the additional power requirements.

The cooling pond alternative of case eight indicates that the
numerical values are within the expected range. The consumptive
use of water requirement increased significantly with this alterna-
tive due to the blowdown needs and the increased evaporative losses.
Since the system was operated in a closed mode the heated surface
area requirement was set equal to zero. The land area requirements
and the land costs increased significantly over the once-through

systems due to the area required for the construction of the pond. The dollars per kw and total capital cost of the pond were low for this alternative, however, due to the large plant temperature rise of $30^\circ$ F and the relatively small cooling water flow of 600 cfs. The additional cost of the cooling pond and make-up system, however, was $1,650,000 or nearly 40% of the total capital cost.

The wet mechanical draft cooling tower analysis appears to generate most of the numerical values within the expected limits. The consumptive use of water, 20 cfs, was comparable with the cooling pond. The approach of $10^\circ$ F was selected in this case to allow a comparison with the spray canal system where the approach was also assumed to be equal to $10^\circ$ F. The power requirements, the consumptive use of water, the heated surface area, and the land requirements were not included in the print out, but these values will be incorporated in the near future. The cost of $15/kw may be high along with the fixed annual operating cost estimate of $397,000 per year. These values will require further analysis in the model development to ascertain their validity.

The most noticeable features of the spray canal alternatives considered were the blowdown requirements and the tremendous increase in power requirements. Since the site was a salt water site, and the evaporative loss accounts for 80% of the heat transfer in spray canal alternative, the blowdown was assumed at 6% of the cooling water flow to prevent a rapid concentration of solids build-up. It appears that there may be justification for reducing the figure to 4% of the flow. The increase in the total power require-

ments was due mainly to the spray module units where the horsepower estimates were valid. Thus, although an order of magnitude larger than some of the once-through alternatives, this figure appears to be a valid one. In as much as this is a relatively new technology, the cost information was speculative in some instances, such that the cost data may require further analysis. The canal requirement, however, would be over 3 miles in length for this alternative and the construction of this type of structure would involve a considerable cost. Also, the cost of 328 spray modules appears to be reasonable at $6,691,000. The fixed annual operating costs were based upon the horsepower requirements and thus can be expected to increase accordingly.

Thus, the case study has demonstrated that the model, as formulated, will provide valid estimates of the physical aspects, resource requirements, and economic costs of thermal pollution abatement equipment. The alternatives selected for the case study, and the resulting output allowed a general analysis of the sensitivity of the cost estimates to different variables, and a comparison of the costs and resource requirements of different thermal pollution abatement technologies at selected site alternatives.

# CHAPTER SEVEN

## SUMMARY AND CONCLUSIONS

The controls on thermal pollution as set forth under the

Federal Water Pollution Control Act Amendments of 1972 will have a

dual effect on the planning procedure of an electric utility system.

The resource requirements for the various thermal pollution abate-

ment technologies and the ability of a plant to be constructed and

operated in compliance with thermal standards may affect the

selection of sites where new electric generation facilities can be

developed. The overall costs of operation and expansion will

also increase due to the additional capital and operating costs

which arise from the implementation of controls due to the utiliza-

tion for thermal pollution abatement equipment. In this study, a

systematic approach was formulated to determine these resources and

costs, and their relationship with thermal water quality standards.

The problem of thermal pollution was reviewed including the

temperature standards and criteria, the concept of mixing zones, and

the alternatives available for thermal pollution abatement. In

order to develop a thermal pollution abatement model, the economic

theory of thermal pollution management was reviewed. The cost

aspects of the various abatement alternatives were examined, and the

physical modeling of heated discharge was then reviewed. The

thermal pollution abatement model framework was then established and

the necessary cost and physical performance models were developed to

evaluate the economic and resource aspects of the thermal pollution

abatement and site alternatives. The model has the capability of

determining if a site is feasible due to the legal and resource requirements. For the feasible options, the model determines the additional capital and operating costs of the abatement technology as a function of the thermal pollution limits, the meteorological conditions, and the plant characteristics.

A case study was undertaken in this report to determine if the adopted problem formulation was a valid one; to verify the model's capability to calculate the required outputs; and to determine the difference in costs and resource requirements among the thermal pollution abatement technologies.

The thermal pollution abatement model will be used with the Plant Evaluation Model, developed by Woodruff and Farrar in conjunction with this electrical energy study, to evaluate the trade offs between the cost of electrical energy generation, and air and thermal pollution. The model will also provide an input to the Generation Expansion Model which will attempt to determine an optimal regional generation expansion and plant operation plan. The model may also be used to provide an insight into the environmental effects of proposed additions to an electric utility system such as thermal pollution abatement equipment.

The development of this model resulted in several problems which deserve further research efforts. Consideration will have to be given to the off-design operation and other considerations which arise during operation which affect the performance and economics of heat rejection systems. The ambient climatological conditions, which were formulated in this model to change within a region, also

vary with time and this capability could also be included in the model in future development. The future model development also will require the inclusion of the abatement alternatives not included in the model at this time, such as wet natural draft cooling towers and dry cooling towers. The combination system where thermal pollution abatement equipment is used as a treatment prior to discharge rather than in a closed cycle mode should also be incorporated into the model. Finally, future research will also be required with running the model to determine the sensitivity of variables and then to make the necessary revisions.

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# LIST OF FIGURES

## THERMAL STANDARDS

Recommendations of National Technical Advisory Committee on
Water Quality Criteria - May, 1968.

The Subcommittee on Recreation recommend that:

In primary contact recreation waters maximum temperatures should
not exceed 85° F (30° C) except where caused by natural conditions.
Criteria recommended for water used for agriculture are as follows:

Excessively high and low temperature in irrigation may affect
crop growth and yield. A desirable range of water temperature is
55° F to 85° F.

The Subcommittee on Public Water Supplies recommended that:

Surface water temperatures vary with geographical location and
climatic conditions. Consequently no fixed criteria are feasible.
However, any of the following conditions are considered to detract
(sometimes seriously) from raw water quality for public water supply
use:

(1) Water temperature higher than 85° F

(2) More than 5° F water temperature increase in excess of that
    caused by ambient conditions;

(3) More than 1° F hourly temperature variation over that
    caused by ambient conditions;

(4) Any water temperature change which adversely affects the
    biota, taste, and odor, or the chemistry of the water;

(5) Any water temperature variation or change which adversely
    affects water treatment plant operation (for example,

speed of chemical rea.:tions, sedimentation basin

hydraulics, filter wash water requirements, etc.)

(6) Any water temperature change that decreases the acceptance

of the water for cooling and drinking purposes.

The Subcommittee on Fish, Other Aquatic Life, and Wildlife recom-

mended:

Criteria to apply to fresh water organisms.

Recommendation for Warm Waters: To maintain a well-rounded

population of warm-water fishes, the following restrictions on

perature extremes and temperature increases are recommended:

(1) During any month of the year, heat should not be added to

a stream in excess of the amount that will raise the

temperature of the water (at the expected minimum daily

flow for that month) more than $5^o$ F. In lakes and reser-

voirs, the temperatures of the epilimnion, in these areas

where important organisms are most likely to be adversely

affected, should not be raised more than $3^o$ F above that

which existed before the addition of heat of artificial

origin. The increase should be based on the monthly aver-

age of the maximum daily temperature. Unless a special

study shows that a discharge of a heated effluent into the

hypolimnion or pumping water from the hypolimnion (for

discharging back into the same water body) will be desir-

able, such practice is not recommended.

(2) The normal daily and seasonal temperature variations that

were present before the addition of heat, due to other than

natural causes, should be maintained.

(3) The recommended maximum temperatures that are not to be
exceeded for various species of warm-water fish are given
in table A-1.

Recommendation for Cold Waters:  Because of the large number of
trout and salmon waters which have been destroyed, or made marginal
or nonproductive, the remaining trout and salmon waters must be
protected if this resource is to be preserved:

(1) Inland trout streams, headwaters of salmon streams, trout
and salmon lakes and reservoirs, and the hypolimnion of
lakes and reservoirs containing salmonids should not be
warmed.  No heated effluents should be discharged in the
vicinity of spawning areas.

For other types and reaches of cold-water streams,
reservoirs, and lakes, the following restrictions are
recommended.

(2) During any month of the year, heat should not be added to a
stream in excess of the amount that will raise the tem-
perature of the water more than $5^\circ$ F (based on the minimum
expected flow for that month).  In lakes and reservoirs,
the temperature of the epilimnion should not be raised
more than $3^\circ$ F by the addition of heat of artificial
origin.

(3) The normal daily and seasonal temperature fluctuations
that existed before the addition of heat due to other than
natural causes should be maintained.

(4). The recommended maximum temperatures that are not to be exceeded for various species of cold-water fish are given in table A-1.

NOTE: For streams, total added heat (in BTU's) might be specified as an allowable increase in temperature of the minimum daily flow expected for the month or period in question. This would allow addition of a constant amount of heat throughout the period. Approached in this way for all periods of the year, seasonal variation would be maintained. For lakes the situation is more complex and cannot be specified in simple terms.

TABLE A-1

Provisional maximum temperatures recommended as compatible with the well-being of various species of fish and their associated biota

93 F: Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.

90 F: Growth of largemouth bass, drum, bluegill, and crappie.

84 F: Growth of pike, perch, walleye, smallmouth bass, and sauger.

80 F: Spawning and egg development of catfish, buffalo, threadfin shad, and gizzard shad.

75 F: Spawning and egg development of largemouth bass, white, yellow, and spotted bass.

68 F: Growth of migration routes of salmonids and for egg development of perch and smallmouth bass.

55 F: Spawning and egg development of salmon and trout (other than lake trout).

48 F: Spawning and egg development of lake trout, walleye, northern

pike, sauger, and Atlantic salmon.

Note: Recommended temperatures for other species, not listed above, may be established if and when necessary information becomes available.

Criteria to apply to marine and estuarine organisms:

Recommendation: In view of the requirements for the well-being and production of marine organisms, it is concluded that the discharge of any heated waste into any coastal or estuarine waters should be closely managed. Monthly means of the maximum daily temperatures recorded at the site in question and before the addition of any heat of artificial origin should not be raised by more than $4^o$ F during the fall, winter, and spring (September through May), or by more than $1.5^o$ F during the summer (June through August). North of Long Island and in the waters of the Pacific Northwest (north of California), summer limits apply July through September, and fall, winter, and spring limits apply October through June. The rate of temperature change should not exceed $1^o$ F per hour except when due to natural phenomena.

Suggested temperatures are to prevail outside of established mixing zones as discussed in the section on zones of passage.

ZONES OF PASSAGE

Recommendations of the National Technical Advisory Committee on

Water Quality Criteria - May, 1968.

The Subcommittee for Fish, Other Aquatic Life, and Wildlife recom-

mended:

It is essential that adequate passageways be provided at all

times for the movement or drift of the biota. Water quality criteria

favorable to the aquatic community must be maintained at all times

in these passageways. It is recognized, however, that certain areas

of mixing are unavoidable. These create harmfully polluted areas

and for this reason it is essential that they be limited in width and

length and be provided only for mixing. The passage zone must pro-

vide favorable conditions and must be in a continuous stretch

bordered by the same bank for a considerable distance to allow safe

and adequate passage up and down the stream, reservoir, lake, or

estuary for free-floating and drift organisms.

The width of the zone and the volume of flow in it will depend

on the character and size of the stream or estuary. Area, depth,

and volume of flow must be sufficient to provide a usable and desir-

able passageway for fish and other aquatic organisms. Further, the

cross-sectional area and volume of flow in the passageway will

largely determine the percentage of survival of drift organisms.

Therefore, the passageway should contain preferably 75 percent of

the cross-sectional area and/or volume of flow of the stream or

estuary. It is evident that where there are several mixing areas

close together they should all be on the same side so the passageway
is continuous. Concentrations of waste materials in passageways
should meet the requirements for the water.

The shape and size of mixing areas will vary with the location,
size, character, and use of the receiving water and should be
established by proper administrative authority. From the stand-
point of the welfare of aquatic life resource, however, such areas
should be as small as possible and be provided for mixing only.
Mixing should be accomplished as quickly as possible through the use
of devices which insure that the waste is mixed with the allocated
dilution water in the smallest possible area. At the border of this
area, the water quality must meet the water quality requirements for
that area. If, upon complete mixing with the available dilution
water these requirements are not met, the waste must be pretreated
so they will be met. For the protection of aquatic life resources,
mixing areas must not be used for, or considered as, substitute for
waste treatment, or as an extension of, or substitute for, a waste
treatment facility.