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E. Eric Adams and Donald R.F. Harleman

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ABSTRACT

Over the past three years, the Energy Laboratory, in cooperation with the R.M. Parsons Laboratory for Water Resources and Hydrodynamics at M.I.T. has been under contract with DOE/ECT to study various water and waste heat management issues associated with the choice of cooling systems for large steam-electric power plants. The purpose of this report is to summarize the major findings to-date of this study. In addition, an introduction or background section proceeds the summary so that the results can be better integrated into the larger picture of water and waste heat management.

ACKNOWLEDGMENTS

This report is part of an interdisciplinary effort by the MIT Energy Laboratory to examine issues of power plant cooling system design and operation under environmental constraints. The effort has involved participation by researchers in the R.M. Parsons Laboratory for Water Resources and Hydrodynamics of the Civil Engineering Department and the Heat Transfer Laboratory of the Mechanical Engineering Department. Financial support for this research effort has been provided by the Division of Environmental Control Technology, U.S. Dept. of Energy, under Contract No. EY-76-S-02-4114.A001. The assistance of Dr. William Mott, Dr. Myron Gottlieb and Mr. Charles Grua of DOE/ECT is gratefully acknowledged. Reports published under this sponsorship include:

"Computer Optimization of Dry and Wet/Dry Cooling Tower Systems for Large Fossil and Nuclear Plants," by Choi, M., and Glicksman, L.R., MIT Energy Laboratory Report No. MIT-EL 79-034, February 1979.

"Computer Optimization of the MIT Advanced Wet/Dry Cooling Tower Concept for Power Plants," by Choi, M., and Glicksman, L.R., MIT Energy Laboratory Report No. MIT-EL 79-035, September 1979.

"Operational Issues Involving Use of Supplementary Cooling Towers to Meet Stream Temperature Standards with Application to the Browns Ferry Nuclear Plant," by Stolzenbach, K.D., Freudberg, S.A., Ostrowski, P., and Rhodes, J.A., MIT Energy Laboratory Report No. MIT-EL 79-036, January 1979.

"An Environmental and Economic Comparison of Cooling System Designs for Steam-Electric Power Plants," by Najjar, K.F., Shaw, J.J., Adams, E.E., Jirka, G.H., and Harleman, D.R.F., MIT Energy Laboratory Report No. MIT-EL 79-037, January 1979.

"Economic Implications of Open versus Closed Cycle Cooling for New Steam-Electric Power Plants: A National and Regional Survey," by Shaw, J.J., Adams, E.E., Barbera, R.J., Arntzen, B.C., and Harleman, D.R.F., MIT Energy Laboratory Report No. MIT-EL 79-038, September 1979.

"Mathematical Predictive Models for Cooling Ponds and Lakes," Part B: User's Manual and Applications of MITEMP by Octavio, K.H., Watanabe, M., Adams, E.E., Jirka, G.H., Helfrich, K.R., and Harleman, D.R.F.; and Part C: A Transient Analytical Model for Shallow Cooling Ponds, by Adams, E.E., and Koussis, A., MIT Energy Laboratory Report No. MIT-EL 79-039, December 1979.

"Summary Report of Waste Heat Management in the Electric Power Industry: Issues of Energy Conservation and Station Operation under Environmental Constraints," by Adams, E.E., and Harleman, D.R.F., MIT Energy Laboratory Report No. MIT-EL 79-040, December 1979.

TABLE OF CONTENTS

I BACKGROUND

1.1 Overview of Energy Consumption and Waste Heat

The continuously increasing demand for electric power in the United States, both in absolute terms and as a fraction of the total energy consumption, documents the attractiveness of this energy form for domestic, commercial and industrial consumers. Presently, the generation of electric energy requires about 30% of the nation's overall energy usage, and this percentage is expected to increase in the future. Table 1.1 shows the nature of this increasing energy demand for both total energy consumption and electricity consumption in the U.S. The large variation in the projected demands cited by different investigators reflects the difficulty in predicting the nation's energy needs. It is clear, nonetheless, that many more power facilities will be required to meet the growing demand for electricity.

The two principal sources of electric energy are (1) by the conversion of heat in central steam-electric generating stations (presently about 84% of the total national generation) and, (2) by kinetic energy conversion of falling water in hydroelectric power stations (about 13% presently). Our studies have been concerned with steam-electric power generation where the increase in the number of power plants inherently means large costs (both capital and operating), increased fuel and water consumption, and more environmental impacts.

In steam-electric power plants the chemical energy of the prime mover, either fossil or nuclear fuels, is ultimately converted into electric energy. The overall conversion efficiency of these stations, however, is low; on the order of 33% to 40% for modern facilities. This means that

Table 1.1

ENERGY FORECASTS

SOURCE		TOTAL ENERGY (10^{15} BTU)		ELECTRICITY (10^{12} KWH)		ELECTRICITY* Share (%)	
ACTUAL - 1975		79.7		1.90		24.4	
		1985	2000	1985	2000	1985	2000
Chapman, *et al.* (1972)	High				9.890		
	Med.				3.450		
	Low				2.010		
Dupree-West (1972)		116.6	191.9	4.140	9.010	36.4	48.1
Bureau of Mines (1973)**				4.378	10.432		
Hudson-Jorgenson (1974)		108.2	164.5	3.363	6.981	31.8	43.4
ERDA-48 (1975)	Scenario: 0	107.3	165.5	3.455	6.903	33.0	42.7
	I	96.9	122.5	3.199	4.152	33.8	34.7
	II	107.3	165.4	3.455	6.792	33.0	42.0
	III	106.7	161.2	3.747	8.236	36.0	52.3
	IV	107.0	158.0	3.334	4.694	31.7	30.4
	V	98.1	137.0	3.217	4.335	33.6	32.4
ERDA (1976)							
Import Dependence		100.0	156.2	3.321	5.860	34.0	38.4
Domestic Development		96.7	135.9	3.321	6.349	35.2	47.8
FERC (1977)**		103.7	163.4	4.070	9.332	40.3	58.5
EPRI (1977)		100.9	142.4	2.880	5.030	29.2	36.2
EPRI (1978)	High	104.8	196.0	3.889	9.200	38.0	48.1
	Base	97.6	159.0	3.655	7.400	38.3	47.7
	Low	94.4	146.0	3.544	6.600	38.4	46.3

* Assuming heat rate = 10,238 BTU/KWH

** As reported by U.S. Water Resource Council, 1977 about two thirds of the energy of the prime mover is lost in the form of "waste heat" discharged into rivers, lakes, oceans and the atmosphere. In view of the national goal of conservation of energy resources, this appears to be a highly wasteful process and suggests that any effort to improve this efficiency should be pursued. Also, since all large steam-electric power plants use water for steam condensation, there are environmental impacts as well as large water requirements associated with the cooling process. The management of waste heat from steam-electric power plants is thus significant with regard to environmental impacts and the potential for energy and water conservation. The MIT research program deals with one area in which all these factors come together -- namely, the selection of the waste heat rejection system.

1.2 Waste Heat Management

The objective of waste heat management is to find economically and socially acceptable solutions to the trade-offs between environmental protection and energy production. Waste heat management is an integral aspect of almost all energy conversion facilities including steam-electric power stations, liquified natural gas facilities and coal gasification plants. The problem is of particular concern for present day multi-unit generating stations and in the planning of future facilities such as "power parks". Three important aspects of waste heat management are 1) the effect on energy conversion efficiency, 2) the effect of waste heat on the environment, and 3) the control and possible utilization of waste heat emissions.

The conversion efficiency of steam-electric power stations expresses the fraction of the chemical or nuclear energy of the primary fuel which is produced as electrical power. This efficiency is determined by the thermodynamics of the conversion process -- in particular, by the temperature of the heat sink, which is controlled by the choice of the waste heat disposal system. Waste heat may be transferred directly into an adjacent water body such as a large lake, river, estuary or coastal water by means of once-through cooling systems. In any event the ultimate sink for the heat is outer space via the earth's atmosphere. Closed cycle systems, such as cooling towers, result in heat sink temperatures that are higher than once-through systems. The consequence is a reduction in generating efficiency. These energy losses, when coupled with safety constraints related to cooling water temperature, are highly dynamic in nature because of large daily variations in meteorological conditions controlling the rate of heat dissipation. Furthermore, the total energy requirements of cooling systems must be considered. Closed-cycle systems represent large capital and resource investments and in the case of forced-draft towers utilize significant amounts of energy in their operation.

Waste heat, whether discharged into water or air, has effects on the environment. Yet the understanding of these effects, in many instances, is qualitative, subjective and fragmentary. Temperature has a profound effect on all forms of life and governs the rate and mode of all biochemical reactions. There have been a large number of studies on the biological level, such as the tolerance and behavior of certain species of fish under heat influence. At the ecological level, which must account for the interrelationships between species and the environment, only limited information is available. Studies necessary for the systematic assessment of waste heat effects are difficult to perform for a number of reasons: a vast amount of data must be collected and processed in order to describe an ecological system; there are strong natural variabilities in the environment which make it extremely difficult to distinguish between natural and man-made changes; it is difficult to put a qualitative value measure on man-made changes (i.e., how detrimental is a certain shift in the ecological structure?).

The control of waste heat discharges ranges from in-plant measures for reducing waste heat to plant design and operation measures aimed at an optimal interphasing with the environment. In-plant measures relate to improved waste heat abatement technologies, such as new heat exchange surfaces for cooling towers. The design and operation of heat disposal systems relates to the multiplicity of choices which have bearing on the environmental performance. There are questions such as the location of the power plant, the design of heated discharge outfalls and the operation of disposal systems during transient environmental conditions. At the heart of these choices lie models for the prediction of waste heat effluents in the environment. Only through these models is it possible to relate the waste heat source and its spatial and temporal influence on the environment. Without predictive models, meaningful strategies for waste heat management are not possible.

Beneficial utilization of waste heat means the economic utilization of a portion of the energy content of the waste heat before it is discharged into the water body. Alternatively, beneficial effects of waste heat may arise directly within the water body.

Proposed concepts of beneficial use include space heating or refrigeration for industrial or domestic purposes, waste water treatment, aquaculture and thermal agriculture, and winter navigation. An extensive review of possible beneficial uses for these purposes has been given by Cook and Biswas (1974). The problem of beneficial uses with current power plant design practices can be summarized as follows:

- Waste heat effluents are usually low grade heat, that is, large amounts of water with only small temperature rises are discharged. For example, a typical 1000 Mw nuclear plant may discharge 1,500 cfs (55 m^3/s) at a temperature rise of 20°F (11°C). On the other hand, requirements for industrial or domestic usage call for much higher grade heat, i.e., smaller flows at higher temperatures. If higher grade waste heat is to be produced, then the efficiency of any energy conversion process will decline as the steam condensing temperature is increased.
- Waste heat is produced throughout the year while most beneficial uses are strongly seasonally dependent.

In summary, beneficial utilization is (with some exceptions, such as space heating in Arctic zones) not an economical proposition.

Direct beneficial effects of waste heat within a water body are "open" aquaculture and the use for navigation. "Open" aquaculture relates to the positive effects which accrue from the temperature change within the thermal plume area of a discharge. Commercially desirable species of fish and shellfish may propagate in this area as has been demonstrated by several research and commercial applications. Again, the seasonality poses a problem, as the artificial temperature rise is useful in winter but may be detrimental in the summer. The advantage for navigation stems from the possibility of prolonging shipping seasons by keeping portions of a river free from ice.

1.3 Regulatory Aspects

Environmental regulation can be defined as a set of procedures and guidelines which are formulated and enforced by public authorities with the purpose of ensuring that waste heat disposal practices are applied to protect the environment in a socially beneficial manner. Because of the difficulty of finding common qualifying measures for different objectives, global optimization procedures are not possible. Consequently environmental regulations are essentially a recognition of the necessity of making use of simpler, sub-optimal procedures.

Regulatory standards are usually given in numerical values, sometimes supported by verbal descriptions. In the water environment, these may be in the form of "stream standards" specifying allowable temperatures or temperature rises outside of a "mixing zone" which may or may not be defined by area or volume measures. "Effluent standards" apply to the effluent at the point of discharge. The major problem in setting common standards is the extreme temporal and spatial variability of specific site conditions. The extent to which a standard relies on numerical as opposed to verbal descriptions in large part determines the task of the planning and design team for a given facility. At one extreme the planner is not faced with considering environmental impacts but only with detail design to meet the standards. An example is the specification of an allowable temperature rise of 1.5°F at the edge of a 6-acre mixing zone at the water surface.

The basis for thermal analysis including the requirement for monitoring has developed in the United States through a number of legislative steps and court decisions. The Water Quality Act of 1965 authorized the states to establish water quality standards for interstate streams, including coastal waters, and to submit these for approval to the Environmental Protection Agency. Under the National Environmental Policy Act of 1969 (NEPA), Federal agencies whose actions may impact upon the environment were required to take that potential impact into account in their decisions. These decisions include licensing of nuclear power plants and issuing of permits to discharge into navigable water (under the Refuse Act of 1899).

As an enforcement of the standards which followed the Water Quality Act of 1965, the Water Quality Improvement Act of 1970 provided that the applicant for a Federal license must furnish to the licensing agent a certification (issued from the State or appropriate interstate agency) of reasonable assurance that the discharge will not violate applicable standards. For the case of thermal discharges from power plants this established the need for thermal analysis to be prepared by applicants.

As a major consequence of NEPA, the U.S. Atomic Energy Commission was required (through the Calvert Cliffs court decision of 1971) to <u>independently</u> assess the impact of a nuclear power plant upon water quality even though a state certification may have been obtained. Thus, the need for thermal analysis for nuclear generating stations was established for the AEC. (Since 1975 this regulatory function is under the Nuclear Regulatory Commission - NRC).

Finally, the Federal Water Pollution Control Act Amendments of 1972 have the purpose of eliminating discharges of pollutants, including waste heat, into the nation's waters by 1985, except under the terms of a Federal or State permit. To obtain such a permit the burden on the applicant is to demonstrate that "the protection and propagation of a balanced indigenous community of shellfish, fish and wildlife in and on the body of water into which the discharge is to be made" is assured. In addition to thermal prediction, this stipulation establishes the need for water quality monitoring, including thermal monitoring, to establish the relative changes between the pre-operational and the operational stage of a power plant project.

Recently, perhaps in recognition of the economic penalties of the "zero-discharge" concept, the regulatory pendulum has begun to return from the full swing of the early 1970's. The direction is toward site-specific impact evaluation. Thus, for a particular site, the process is to determine the environmental impacts of various design options, to evaluate the alternatives and to make a decision. This insures maximum attention to the tailoring of the waste heat disposal scheme to the hydrographic and ecological characteristics of the site. It requires cooperation between ecologists, engineers and planners, representing regulatory authorities, the general public and the energy facility proponents. The disadvantages of this approach lie in inherent differences in site-specific bargaining processes in that local evaluations may be deficient in maintaining a uniform perspective between energy needs, energy conservation and environmental protection.

1.4 Conversion Efficiency

The efficiency of electric power production by either fossil or fission fuels is governed by the thermodynamics of the heat cycle. The ideal or Carnot efficiency is determined by the temperature of the heat source and by the temperature of the surrounding air or water which acts as a heat sink. The ideal efficiency is given by

$$E_i = \left\{1 - \frac{T_{sink}}{T_{source}}\right\} 100 \qquad (1.1)$$

where the temperatures are measured on an absolute scale. In all mechanical and thermodynamic processes, the actual efficiency is less than the ideal. With the present technology of the steam-electric cycle, the actual efficiency is about 60% of the ideal.

The basic components of steam-electric generating systems by either fossil or nuclear fuel are shown in Figures 1-1 through 1-4. The components to the right of Section A-A in Figure 1-1 are common to all steam-electric systems and these will be described first.

Steam, at high temperature and pressure, enters a turbine where energy in the form of shaft-work is removed. The turbine shaft is coupled to a generator which produces electricity, and the spent steam at low temperature and pressure, enters a condenser. In the condenser, the steam is converted to the liquid phase (water) by the continual removal of heat by means of a separate condenser water circulating system.

When waste heat carried by condenser cooling water is discharged into an adjacent water body, transfer to the atmosphere occurs over relatively large areas by evaporation, radiation, convection, and conduction. When cooling towers are used, heat is rejected directly to the

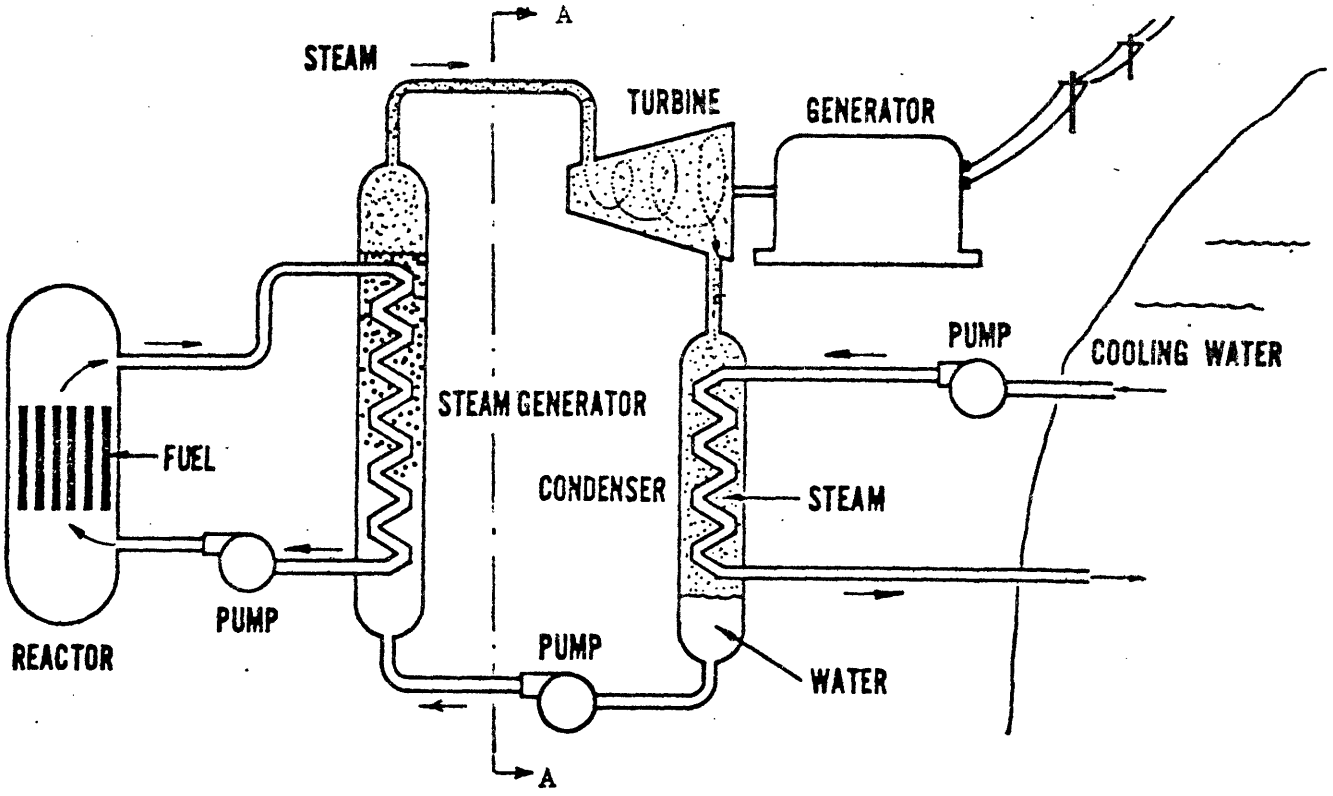


Fig. 1-1 Power Generation - Pressurized Water Reactor (PWR)

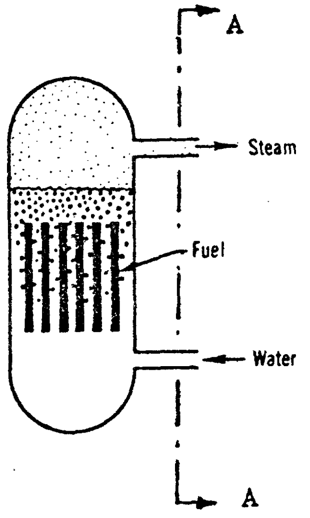


Fig. 1-2 Boiling Water Reactor (BWR)

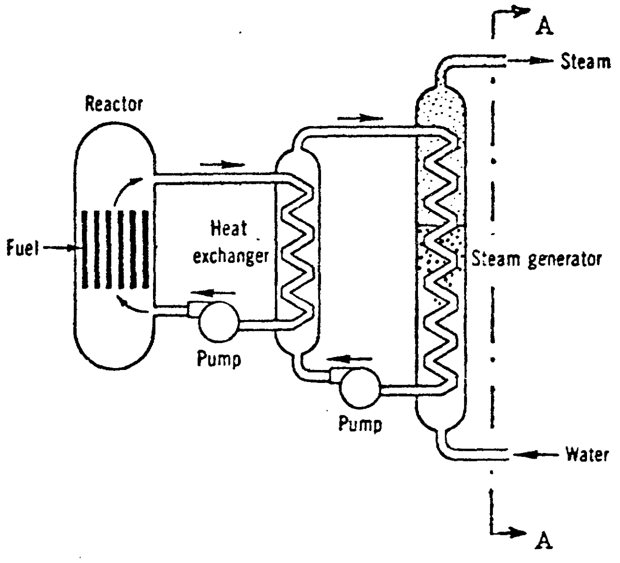


Fig. 1-3 Liquid Metal Breeder Reactor (LMBR)

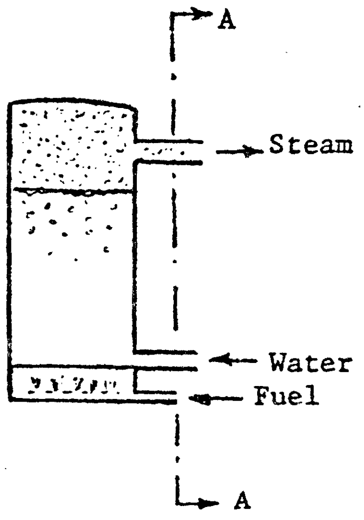


Fig. 1-4 Fossil Fuel Boiler

atmosphere, primarily by evaporation in wet cooling towers and by convection in dry cooling towers.

The components to the left of Section A-A in Fig. 1-1 represent a light water nuclear power plant with a pressurized water reactor (PWR). Heat from the reactor is transferred to a steam generator by means of water in a closed circulating system under a pressure of about 2300 psi. This high pressure prevents boiling of the water in the reactor circuit. Fig. 1-2 shows the components to the left of Section A-A in a boiling water reactor (BWR). In this type of nuclear plant, steam is generated directly in the reactor vessel. Both water and steam are at a pressure of about 1000 psi. In either the PWR or the BWR, the maximum temperature is limited by the heat transfer characteristics at the surface of the fuel rods.

Assuming a mean annual temperature of the heat sink at 60°F (520°R) and the heat source temperature at 600°F (1060°R), the ideal efficiency is 51% and the actual efficiency (at 62% of the ideal) is 32%.

Fig. 1-3 shows the left-side components of a liquid-metal breeder reactor (LMBR). This type of reactor has been under development but is not in commercial use. It requires one more closed loop circulating system than the PWR and two more than the BWR. Liquid metals such as sodium or a combination of sodium and potassium are used in the reactor coolant loop and in the intermediate loop to the steam generator. Because of the better heat transfer characteristics of liquid metal, in contrast to water, temperatures of the order of 1100°F can be obtained within the reactor vessel. Thus, the thermal efficiency of the LMBR will be higher than that of the BWR or PWR. In addition, the breeder principle implies that nuclear fuel is produced as a by-product. This comes about by providing fertile materials in the reactor coolant. Free neutrons produced by the fission reaction are absorbed by the fertile material to produce new fissionable material. The conversion efficiency of the LMBR is in the range of 40 to 42%.

Fig. 1-4 shows the left side components of a fossil fuel steam-electric generating plant. In terms of components it is the same as the BWR except that steam is produced in a boiler by the burning of coal, gas or oil. A significant difference is that steam temperatures in a modern fossil fuel station are approximately 1000°F with pressure of 2400 psi. With a heat sink at 60°F (520°R), the ideal efficiency is 64%. New fossil fuel stations achieve about 60% of the Carnot cycle efficiency for an overall thermal efficiency of 37 to 38%. Higher boiler temperatures, up to 1100°F, have been used and efficiencies of 40% have been achieved. However, the operating experience at these higher temperatures and pressures (3500 psi) have not been satisfactory.

A summary of the conversion efficiency of present and future electric generating sources is shown in Fig. 1-5 (Dieckamp, 1971) as a function of the temperature of the heat source. As indicated, the ultimate high efficiency energy source is the fusion reactor. However, commercial use is not foreseen in this century.

1.5 Heat Rejection to Condenser Water Cooling Systems

In order to quantify the heat rejection process, it is appropriate to review the basic units of energy and power.

ENERGY: Watt-hr (WH) = unit of energy, electrical
Foot-lb (ft-lb) = unit of energy, mechanical
British Thermal Unit (BTU) = unit of energy, thermal

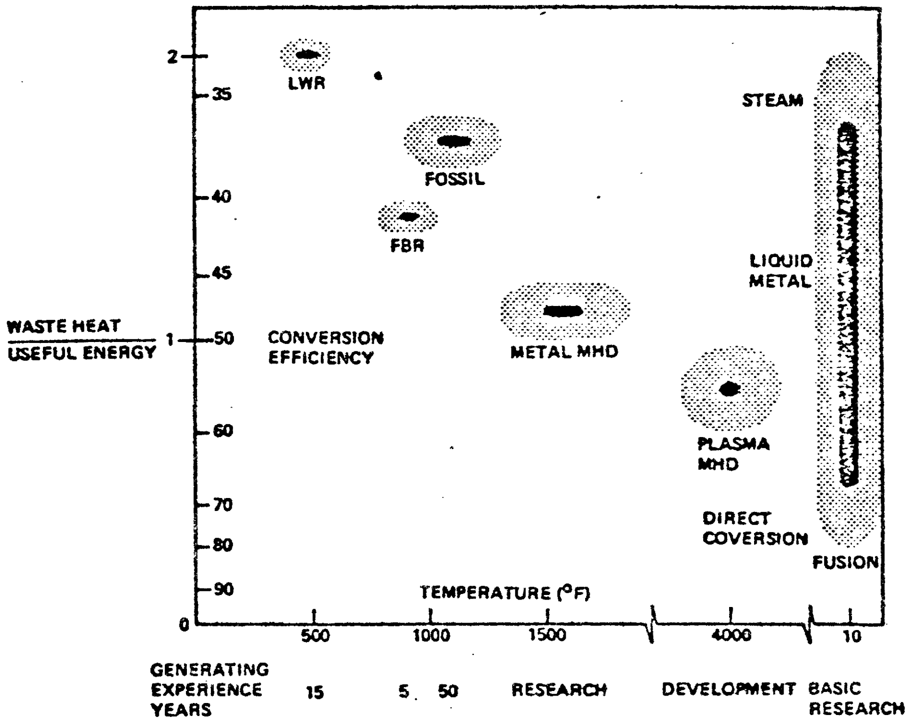


Fig. 1-5 Conversion Efficiency of Present and Future Electric Power Sources (after Dieckamp, 1971)

Joule (J) = unit of energy, thermal

The BTU is the quantity of heat required to raise the temperature of one pound of water from 60°F to 61°F at atmospheric pressure.

The relations between the other units of energy are as follows:

1 BTU = 778 ft-lb

1 BTU = 2.93×10^{-4} KWH = 1.055×10^{3} Joule
(where KWH = kilowatt-hr = 10^{3}WH)

1 KWH = 3,413 BTU

POWER: Watt (W) = unit of power, electrical [Note: 10^{3}W = 1 KW and 10^{6}W = 1 MW (megawatt)]

Foot-lb/sec = unit of power, mechanical [Note: 1 HP (horse-power) = 555 ft-lb/sec)

BTU/hr = unit of power, thermal

The relations between the other units of power are as follows:

1 KW = 3,413 BTU/hr

1 BTU/hr = 778 ft-lb/hr

The overall thermal efficiency E_t of a steam-electric plant is given by

$$E_t(\%) = \frac{\text{Electrical Output}}{\text{Thermal Input}} \times 100 \qquad (1.2)$$

or

$$E_t(\%) = \frac{3413 \text{ BTU/KWH}}{3413 \text{ BTU/KWH} + \text{Waste Heat (BTU/KWH)}} \times 100 \qquad (1.3)$$

The denominator of the above efficiency equation is known as the "heat rate" of a plant. This is defined as the average amount of heat required to produce one kilowatt-hour of electrical energy.

The heat rejected in the condenser cooling system is somewhat less than the "waste heat" portion of the efficiency equation because of in-plant and stack losses. If it is assumed that these are a constant fraction (represented by δ) of the fuel heat content, then the heat to be disposed of by condenser cooling is given by

$$\text{Heat rejection in cooling water } (MW_c) = MW_e(1-E_t-\delta)/E_t \qquad (1.4)$$

where MW_e = electrical output, in megawatts

In a 1000 MW_e nuclear (BWR or PWR) plant, E_t = 32% and in-plant losses are approximately δ = 5%, thus, MW_c = 1970 MW. This is equivalent to 6.7×10^9 BTU/hr. or 7.1×10^{12} Joule/hr.

In a 1000 MW_e fossil plant, E_t = 38% and in-plant losses are estimated at δ = 15% (because of additional heat loss through the stack); thus, MW_c = 1240 MW or 4.2×10^9 BTU/hr, or 4.5×10^{12} Joule/hr. Therfore, the condenser water heat rejection of the conventional nuclear plant is about one and one-half times larger than an equivalent fossil plant.

A typical condenser water flow rate for a 1000 MW_e unit is about 1500 cubic feet per second (675,000 gallons per minute) or 3.4×10^8 pounds per hour. The temperature rise for the water passing through the condenser is obtained by dividing the heat rejection rate in BTU per hour by the water flow rate in pounds per hour. On the basis of the above numbers, the temperature increase through the condenser is 12°F for the fossil unit and 20°F for the nuclear unit. These figures are based on the current state of technology; however, most authorities see little likelihood of a significant increase in steam power cycle efficiencies within the next decade or two.

1.6 Heat Rejection Systems

Heat is transferred within the power plant to cooling water as it passes through the condenser. If a continual supply of new water from an adjacent water body is available to the condenser intake, the process is called once-through cooling. If the cooling water is recirculated and the heat is removed from it through some auxiliary mechanism, the process is called closed-cycle cooling. The need for a large natural supply of cooling water for once-through cooling has usually been a prime factor in power plant site selection. The economy of scale for both nuclear and fossil units and the concern with the environmental effects of water temperature changes, combine to limit the locations that can use this form of heat dissipation. However, good engineering design together with predictions of the temperature field and an assessment of biological effects will enable once-through cooling to remain a viable cooling process for stations sited on major rivers, reservoirs, large lakes, and coastal waters. Excess heat will dissipate from the water surface and return to its natural temperature within a reasonable distance from the location at which the heat is added. This distance depends on the amount of dilution of the heated condenser water by the receiving water.

1.6.1 Once-Through Cooling

Heat is transferred from a water surface by evaporation, radiation and conduction. The percentage of the total heat transferred by evaporative transfer increases as the temperature of the water surface increases above its natural state. Since evaporative heat loss involves water loss as well, the consumptive water use of once-through cooling is proportional to the percentage of the total heat transfer by evaporation. For a water surface at 5°F above equilibrium, the heat loss by evaporation is about one-third of the total. For this case, the consumptive loss is about one per cent of the cooling water flow rate in a once-through cooling unit.

Changes in the way heated water is discharged - and thereby in the temperature distribution in the receiving water - can minimize the biological impact. Design possibilities range from complete stratification to complete mixing of the heated effluent. In stratification, the heated water is "floated" onto the receiving water in a relatively thin layer from a surface discharge. Heat dissipates to the atmosphere at a maximum rate and there are no temperature changes at or near the bottom of the receiving water. Because the heated surface layer spreads due to buoyancy, it must be prevented from re-entering the condenser water intake. Under certain conditions, a skimmer wall with an intake opening at the bottom may be used to control recirculation at the intake.

Thermal discharge regulations that prescribe a maximum surface temperature increase in the receiving water usually prohibit highly stratified surface discharges. However, to achieve a lower surface temperature, the velocity at the exit of the surface discharge channel can be increased, thereby entraining more of the receiving water into the heated discharge.

Complete mixing of the heated discharge with the available flow past the site is at the other extreme of possibilities. The condenser water is conducted through a diffuser pipe and discharged through nozzles or ports near the bottom of the waterway. Entrainment of surrounding water into the high velocity jets produces a rapid dilution. This discharge provides the most rapid temperature reduction within the smallest area, but more heat is stored in the water body and the rate of heat dissipation from the surface is reduced.

Reservoirs that were originally constructed for hydroelectric development are major sources of cooling water. Under certain conditions, the location of a thermal power plant on such a reservoir may improve the water quality. Because of solar heating at the water surface, reservoirs tend to stratify during the summer, and temperature differences of 35°F from surface to bottom are common. If the reservoir contains organic material loads, the cold hypolimnion (bottom) layers can become devoid of dissolved oxygen. The hydroelectric turbines usually take in water from near the bottom of the reservoir; thus, water quality in the river downstream can be impaired. A thermal power plant that withdraws water from the lower levels and discharges at or near the surface will bring hypolimnion water to the surface where it can be reaerated. This technique should not be used on small lakes or in reservoirs with a large number of cold-water fish or in which the heat could affect the thermal stability, delay the fall "overturn", and perhaps accelerate the eutrophication process.

Once-through cooling is important in coastal waters where auxiliary cooling alternatives are most limited. Except in shallow embayments, tidal and wind driven currents are generally available for rapid dispersion and dissipation of the added heat.

The primary advantages of once-through cooling are the low consumptive use of water, the ability to tailor the temperature distribution field in the receiving water to meet biological objectives, and the dispersal of heat dissipation to the atmosphere over a large area.

The disadvantages of once-through cooling are related to the possible damage to aquatic life from higher water temperatures. Biochemical processes, including the rate of use of oxygen, increase with rising water temperature; the ability of water to hold dissolved oxygen in solution, however, decreases. Laboratory and field experiments have established the temperatures beyond which there is death or an impairment of biological functions for fish and other components of the food chain. Indirect effects, which are more difficult to measure and evaluate, include the possibility of increased susceptibility to disease and increases in predators or less desirable species. Precautions must also be taken to prevent damage to fish by trash racks and screens at the condenser water intake. Extensive efforts such as the development of moving fish screens and limitations on intake velocities have greatly reduced fish kills. Smaller organisms such as zooplankton pass through the intake-condenser-discharge system. The effects of their passage depend upon both the temperature rise and the time of exposure.

Water temperature increases which approach the sub-lethal range of impaired biological activity should be avoided. Regulatory agencies limit maximum temperatures and specify allowable temperature rises (from 1-1/2° to 5°F) for various types of receiving waters. There is no general agreement among aquatic biologists as to whether temperature increases in these magnitudes from waste heat are harmful. Natural daily temperature changes in most bodies of water are in the same range.

1.6.2 Closed-Cycle Cooling

Closed-cycle methods of heat dissipation include cooling ponds, spray ponds and canals, mechanical and natural draft evaporative cooling towers, and mechanical and natural draft dry cooling towers. In each case, water is recirculated between the condenser and the heat dissipator.

Cooling ponds are used widely in regions where extensive land areas are available for surface heat dissipation. A 1000 MW station requires about 1000 acres of water surface. Spray systems can be added to increase the heat dissipation. However, the water loss from evaporation and drift can be significant. In addition, the performance of clusters of spray modules has not been as good as the performance predicted on the basis of individual unit measurements.

Cooling ponds and spray canals have also been used in conjunction with once-through cooling schemes. In this manner, a portion of the heat may be dissipated in the pond before the cooling water is discharged to an adjacent body of water.

Most cooling towers constructed for power plants above 500 MW have been of the natural draft wet, or evaporative type -- large hyperbolic towers that cool by creating a natural draft of air which passes through water droplets sprayed by nozzles within the tower. Cooled water collects in a pool at the base of the tower. The lowest water temperature in these towers will always be above the wet-bulb temperature of the surrounding air. A natural-draft tower for a 1000 MW nuclear unit would be 600 feet at the base and 500 feet in height.

A source of make-up water must be available to replace that lost by evaporation and drift and to provide blow-down water to prevent buildup of chemical residue by evaporation. Since the cooling is primarily by evaporation, evaporative cooling towers consume more water than once-through cooling processes; about 3 percent of the total amount circulated must be replaced. A typical 1000 MW nuclear unit requires about 30 million gallons per day for make-up and blow-down.

Cooling towers may pose environmental problems in certain areas. Fresh water supplies, especially in coastal regions, may not be large enough to replace water lost. Sea-water has been used as the coolant in certain instances, but the transport of water droplets out of the cooling tower, known as drift loss, is estimated to be in the range of one-tenth of one percent of the amount of water circulating. For a 1000 MW nuclear unit, the drift loss could be as much as 1 million gallons per day. As sea-water contains about 30,000 parts per million of dissolved salts, the production of salt after evaporation would amount to 125 tons per day in the plume downwind of the tower. Even if the drift loss is reduced by a full order of magnitude, the deposition of more than 10 tons of salt per day downwind may still be unacceptable.

Mechanical-draft wet cooling towers are generally 50 to 75 feet in height. Air is forced through the spray by large motor-driven fans. Capital costs are appreciably lower than for the natural-draft towers, but much higher operating costs must be considered in comparing the two types. There are other problems; the low, moisture-laden plume can cause fog and ice espacially in cold, humid climates, and the recirculation of heated air between tower exit and intake may be troublesome.

Dry cooling towers, whether natural or forced draft, avoid the difficulties of evaporation and drift loss as well as of fog and ice production. They transfer waste heat to the air passing through a fin-tube heat exchanger through which the cooling water is circulated in an enclosed system. The minimum cooling water temperature will always be higher than the ambient dry bulb air temperature. This may pose a severe penalty on the thermal efficiency in warm areas. Dry towers must be appreciably larger than wet towers and cost estimates are generally from three to five times larger.

1.7 Effect of Heat Rejection System on Thermal Efficiency

The function of a power plant cooling system is to reject the heat in the steam condenser. It is desirable to reject the heat at the lowest possible temperature since the ideal efficiency increases as the temperature of the heat sink decreases as shown in Eq. 1.1. The cooling system operating temperatures are closely related to the steam condensing temperature and turbine exhaust pressure. A lower exhaust pressure means that more useful work is produced by the turbine. The factor that expresses the relationship between the steam condensing temperature and the temperature of the warm circulating water leaving the condenser is called the condenser terminal temperature difference (TTD). This is a measure of the heat transfer efficiency of the condenser.

Two factors are important for the performance of a condenser cooling water system: 1) the static response under constant atmospheric and environmental conditions, and 2) the dynamic response (thermal inertia) to rapid changes in meteorological conditions. A plot of the steam condensing temperature as a function of temperature and turbine exhaust pressure is shown in Fig. 1-6 (Budenholzer, et al, 1971) for various types of heat rejection systems.

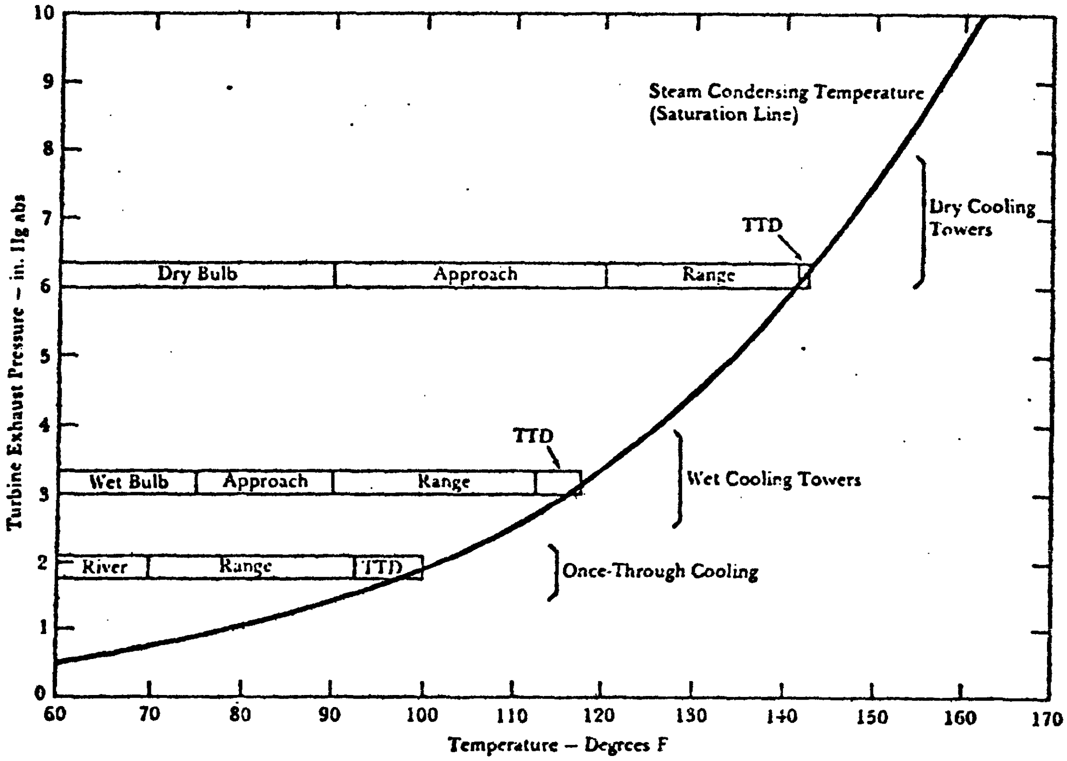


Fig. 1-6 Effect of Heat Dissipation Scheme on Turbine Exhaust Pressure (after Budenholzer, et al, 1971)

The steam condensing temperature, T_1, for a <u>once-through</u> system under static conditions is

$$T_1 = T_a + \Delta T_r + TTD \tag{1.5}$$

where T_a = ambient water temperature. ΔT_r is the temperature range of the condenser and is related to condenser flow as discussed in Section 1.5. The thermal inertia of a once-through system is very high, and in large bodies of water only seasonal changes in meteorological conditions will be felt.

An important difference between a once-through system and a cooling pond is the limited volume of the latter. Hence, under steady state operation the temperature of the cooling pond will be raised until an equilibrium between waste heat input and heat emission from the water surface has been reached. The steam condensing temperature is then

$$T_1 = T_i + \Delta T_r + TTD \tag{1.6}$$

T_i is the condenser intake temperature under given waste heat load and meteorological conditions. In order to evaluate T_i, a mathematical description of the hydrodynamic and heat transfer characteristics of the cooling pond must be formulated. The thermal inertia of a cooling pond is related to the water depth in the pond and is typically on the order of several days.

In wet cooling towers, the waste heat is directly emitted to the atmosphere. The theoretical minimum temperature to which the water can be cooled is the wet bulb temperature, T_{wb}. Under practical conditions, T_{wb} can only be approached within a certain limit, ΔT_{ap}, the approach.

$$T_1 = T_{wb} + \Delta T_{ap} + \Delta T_r + TTD \tag{1.7}$$

The thermal inertia of cooling towers is very small, which means that the steam condensing temperature follows closely any changes in meteorological conditions.

For dry cooling towers, the principal heat transfer mechanism is heat conduction between ambient air and the cooling water through the heat exchanger surfaces. The temperature minimum is in this case the dry bulb temperature, T_{db}, hence

$$T_1 = T_{db} + \Delta T_{ap} + \Delta T_r + TTD \tag{1.8}$$

The differences in steam condensing temperatures, as expressed in the above equations, have important implications on the operating characteristics of a power plant and on energy conservation. For a typical evaluation of these differences, including transient effects, a simulation example is given in section 2.4 of this report.

1.8 The Importance of Water

Estimates of water usage for steam-electric power generation are compared with estimates for other types of energy conversion and refining processes in Figure 1-7 taken from Davis and Wood (1974). In Table 1-2, the total national water use (withdrawal and consumption) by steam-electric power plants in the U.S. is shown for 1975 and projections are shown for the years 1985 and 2000. These forecasts are derived from the Water Resource Council's (1977) capacity and generation estimates for steam-electric plants according to mode of cooling. (See Table 1-3 below.)

Clearly the availability of water is one of the most important issues in the selection of a cooling system. Figure 1-8 depicts the approximate average and minimum river flow rates necessary to operate a

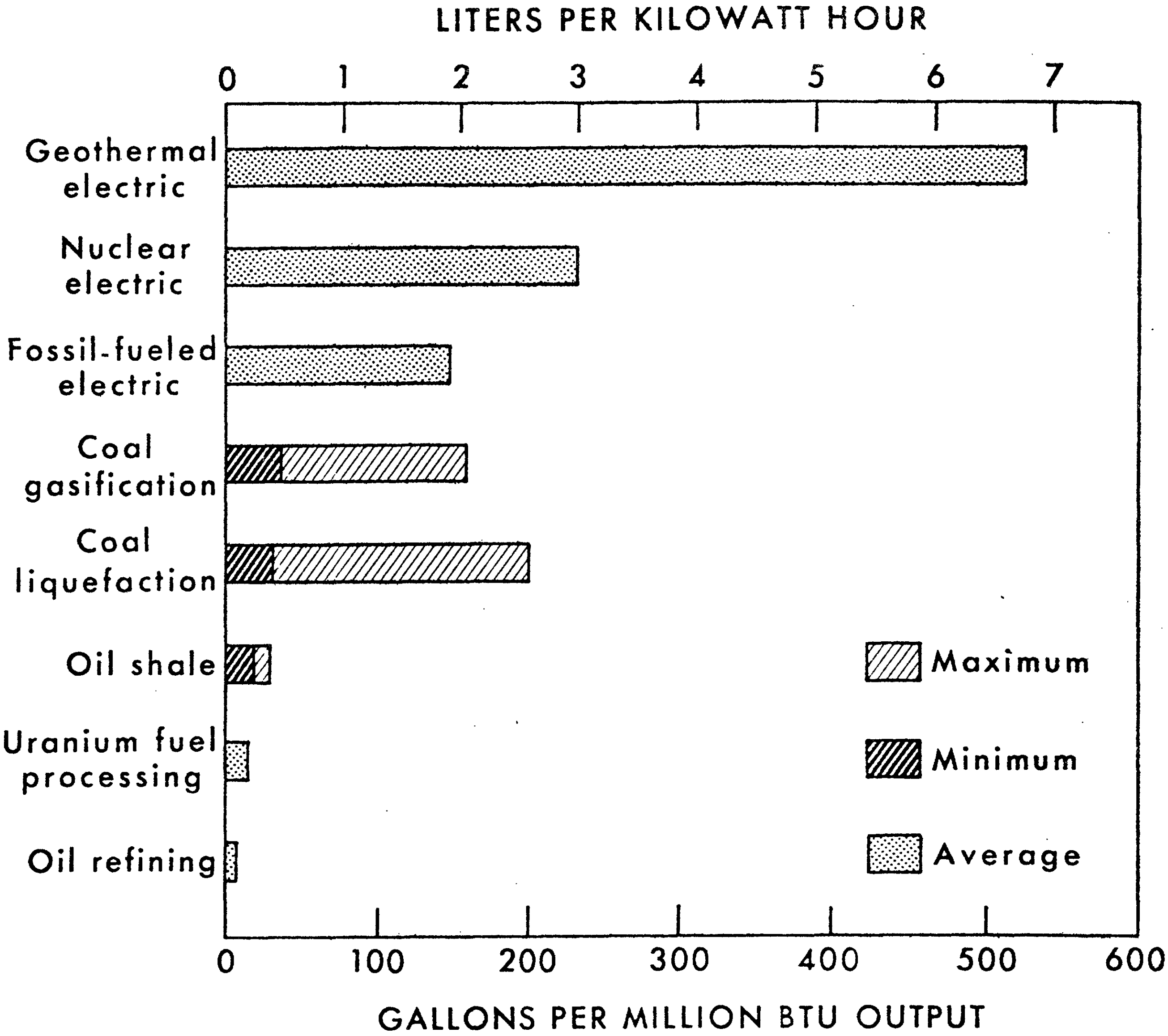


Fig. 1-7 Water Usage for Various Types of Energy Conversion and Refining Processes (after Davis and Wood, 1974)

Table 1-2

WATER USE BY STEAM-ELECTRIC POWER PLANTS

	WITHDRAWAL (MGD)			CONSUMPTION (MGD)		
	Fresh	Saline	Ground	Fresh	Saline	Ground
1975	92,342	46,683	259	1,208	326	811
1985	86,547	78,653	357	3,491	785	157
2000	69,912	93,815	151	9,061	2,320	87

Table 1-3

Present and Future Steam-Electric Generating Capacity by Cooling System Type[1]

(Capacity in MW)

	1975	2000
Once Through	249,000	322,000
Cooling Ponds	54,000	218,000
Wet Towers	79,000	1,312,000
Dry Towers	23	67,000
Combination	10,000	37,000
TOTAL:	392,000	1,956,000

[1] Source USWRC, Energy and Related Water Requirements, Appendix H, April 1977, Table A-3, p.A-27.

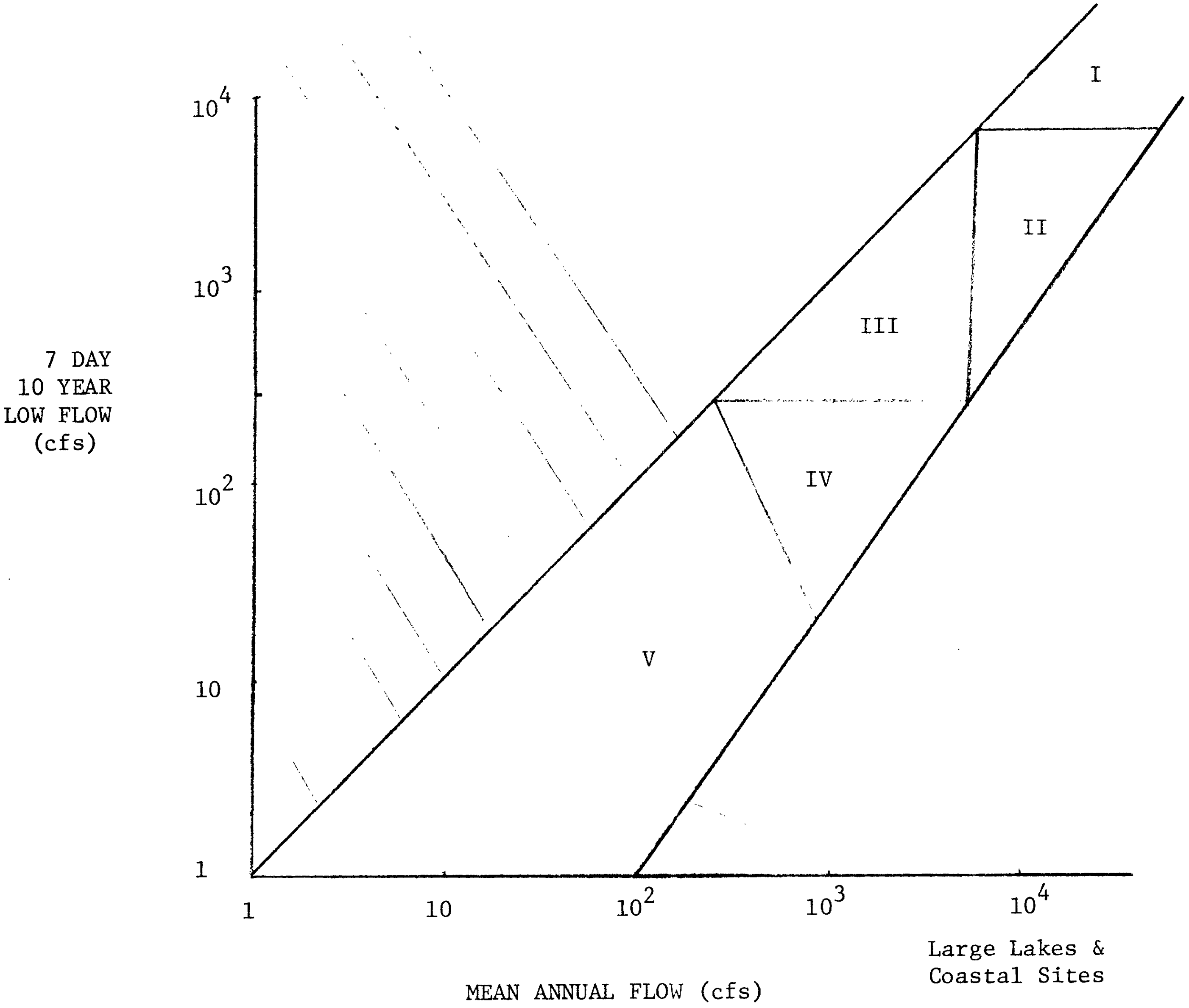


Fig. 1-8 Cooling Mode Alternatives as a Function of Water Supply for a 1000 MWe Plant

KEY

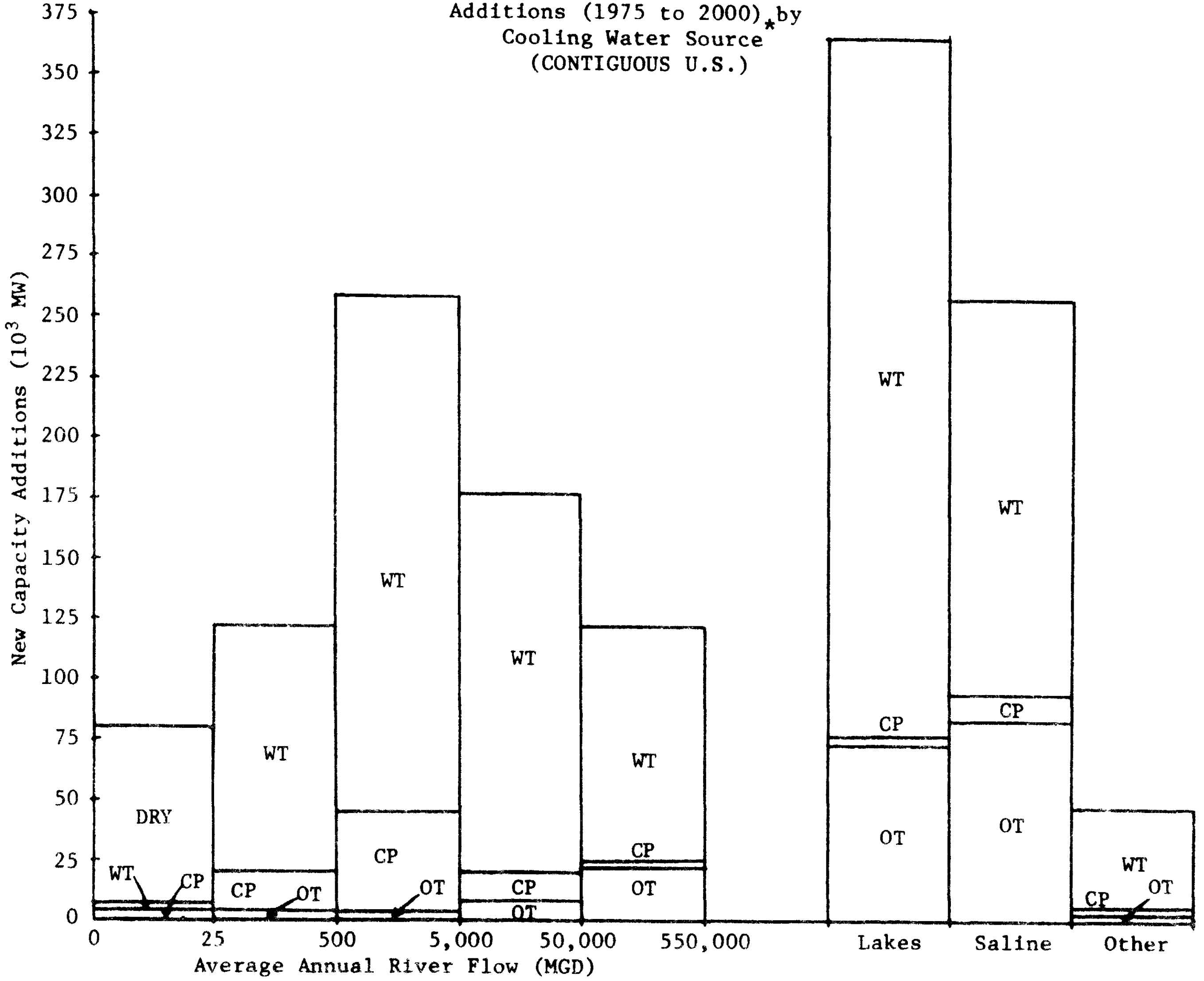
I	Once-through Cooling
II	Once-through Cooling and Supplementary Cooling
III	Evaporative Cooling*
IV	Evaporative Cooling and Storage*
V	Dry and Wet/Dry Cooling

* Assumes 10% of low flow may be used for cooling

1000 MWe station with various cooling systems. It is assumed that once-through cooling is technically feasible at all coastal sites and on the largest lakes and rivers. Figure 1-9 indicates those rivers in the contiguous U.S. where once-through cooling is feasible based on the 7-day 10-year low flow criterion of Figure 1-8. At sites where this flow is not possible, recourse must be made to closed cycle cooling (regions III, IV and V of Fig. 1-8). Evaporative cooling (towers, sprays, lakes and ponds) requires an average make-up water supply on the order of 30 cfs for a 1000 MWe plant. Where storage is not considered this must be supplied on a continuous basis, i.e., the minimum flow rate available for cooling must exceed the make-up and blow-down water requirements (region III). If storage is possible (e.g., by use of a cooling lake or pond or by constructing a storage pond to supply a cooling tower) the make-up water can be supplied on an intermittent basis and it is only necessary that the average flow rate exceed the make-up requirement (region IV). (The averaging interval will depend on the amount of storage.) When the make-up supply for evaporative cooling cannot be met in this way then recourse must be made to non-evaporative cooling, either in combination with wet cooling (wet/dry towers) or exclusively through dry towers (region V). These water availability considerations have, in fact, constrained the utility industry's planning with regard to cooling system selection for their proposed new generating capacity. Table 1-3 presents data compiled by WRC (1977) on present (1975) and anticipated (year 2000) electrical capacity organized by cooling systems, and figure 1-10 shows how the added capacity (difference in the figures of Table 1.3 plus anticipated retirements minus upratings) will be distributed according to

Figure 1-9 Location of Rivers in the United States where Once-Through Cooling could be Installed for a 1000 MW Fossil Steam Electric Plant According to Criteria Described in the Text

Fig. 1-10
Distributions of Proposed Capacity
Additions (1975 to 2000)*by
Cooling Water Source
(CONTIGUOUS U.S.)



WT = Wet Towers, OT = Once Through, CP = Cooling Ponds, DRY = Dry Towers

* Compiled from data provided by U.S.W.R.C., 1977. Only proposed steam electric plants ≥500 MWe are considered.

the size and type of cooling water body. This data brings out several interesting points.

First, the use of once-through cooling, which accounted for approximately 65% of the cooling in 1975, will account for only 16% by 2000. This change can be attributed to several factors, including the decreasing availability of suitable sites on large bodies of water, and the influence of state and federal water quality standards which discourage use of once-through cooling. While once-through cooling will still be the second most popular system, the new sites employing this mode will be located almost exclusively on the Great Lakes and coasts.

Second, the vast majority of closed cycle cooling, as presently proposed, will be by natural and mechanical draft evaporative (wet) towers. Other forms of evaporative closed cycle cooing such as on- or off-stream cooling ponds or various types of mixed modes show relatively minor increases due largely to complexities governing their design (as compared to modularized construction of mechanical draft towers) and due to the endorsement of wet towers by EPA as "Best Available Technology".

Third, a small but significant fraction of new plants are slated to employ dry cooling, either by itself, or in combination with wet cooling.

1.9 Outline of MIT's Research

The research program at MIT has been designed to help broaden the mix of feasible cooling system beyond that outlined in Fig. 1-9 above. A motivation for this research is the recognition that the ability to design and predict the performance of once-through and wet cooling tower systems is well developed as a result of intensive research, development and operating experience over the past decade. In contrast, the use of dry and wet/dry towers, cooling ponds and mixed modes have been constrained by design, performance and cost uncertainties. In addition, there appears to have been very few previous attempts to provide a common framework for optimal design, prediction of performance (in terms of efficiency and power availability) and cost evaluation for the entire spectrum of cooling system alternatives.

The research program at MIT has been an attempt both to provide such a common framework and to examine modes of cooling presently attended by performance uncertainties. The completed portion of the research can be divided into five parts. The first three deal with the cooling system alternatives described above including (1) the use of dry and wet/dry towers for closed cycle cooling, (2) the use of artificial (off-stream) ponds for closed cycle cooling and (3) the intermittent use of evaporative cooling towers to supplement once-through cooling for purposes of meeting environmental constraints. In part (4) of the study, design codes for dry and wet/dry towers, and for cooling ponds were used with existing codes for once-through and evaporative towers to provide a comparison of economic, environmental and resource comsumption trade-offs for these systems. Finally, in part (5), these results were used along with various scenarios of energy demand to estimate the incremental costs, and the water and fuel consumption, which would result from future thermal discharge controls.

It should be pointed out that these research activities, while related, are designed to be independent and not merely a series of components leading to a single set of conclusions and/or bottom-line implications. Technical reports describing these activities have been provided. The following section of this report outlines very briefly the major results to be found in each report.

II SUMMARY OF COMPLETED WORK

2.1 Design and Optimization of Dry and Wet/Dry Cooling Towers

Cooling systems for power plants located in arid regions must be designed to minimize water consumption. Because the use of dry cooling towers, either by themselves or in combination with wet towers, substantially increases both the capital and operating cost of a power plant, the economics of such systems must be carefully considered. In the present study several research areas that address this problem have been examined.

The interaction of cost and power plant performance has been carefully analyzed for the case of an all dry mechanical draft tower by refining an optimization program which was originally developed in the Mechanical Engineering Department at MIT (Andeen *et al*., 1972, 1973). The program considers ambient temperature variations throughout the year for the site in question. Rather than using predesigned dry modules, the module design is also optimized, e.g. by determining air velocity, tube length, etc., so that the average yearly cost of power generation of the plant-cooling tower combination is minimized. Recent refinements to the model include optimization of the surface condenser and the water distribution system between the condenser and the tower so that the optimum range and pipe sizes for the system can be determined.

A major economic penalty associated with the use of dry towers is the loss of generating capacity at high ambient temperature, especially for a utility with a peak demand during the summer. How to assess this penalty has been of concern to both utilities and tower designers. The M.I.T. study explored various options for replacing lost capacity ranging from use of gas turbines devoted exclusively to the task to total replacement by purchase of electricity at elevated costs per kilowatt hour. The effect of each option on the economic optimization of the plant-cooling system has been documented. A major conclusion is that the optimal tower size can be significantly decreased, thus reducing both capital and total production costs if a utility is able to purchase peak power. (see Figure 2-1).

The optimization program has also been modified to facilitate examination of wet/dry systems. Evaluations have been performed to determine the minimum cost system for a given yearly water consumption constraint (see Figure 2-2). The optimization is performed in consideration of detailed tower and water distribution designs and methods of accounting for lost capacity. This approach differs from that undertaken by others (e.g., U.E.&.C., 1976) who base their optimization on predesigned tower modules.

Finally, a study of MIT's hybrid wet/dry system (Curcio, et al., 1975) has been made. This design uses a modified fill in essentially a wet cooling tower to increase the ratio of sensible to latent heat transfers. Since the new design does not require a conventional dry surface, it should be easier to employ than a conventional wet plus dry and in addition the reduced relative humidity of the exhaust air is always low enough to preclude the formation of visible fog plumes. Figure 2-3 plots the operating cost of the hybrid system as a function of make-up water requirements indicating that, over a wide portion of

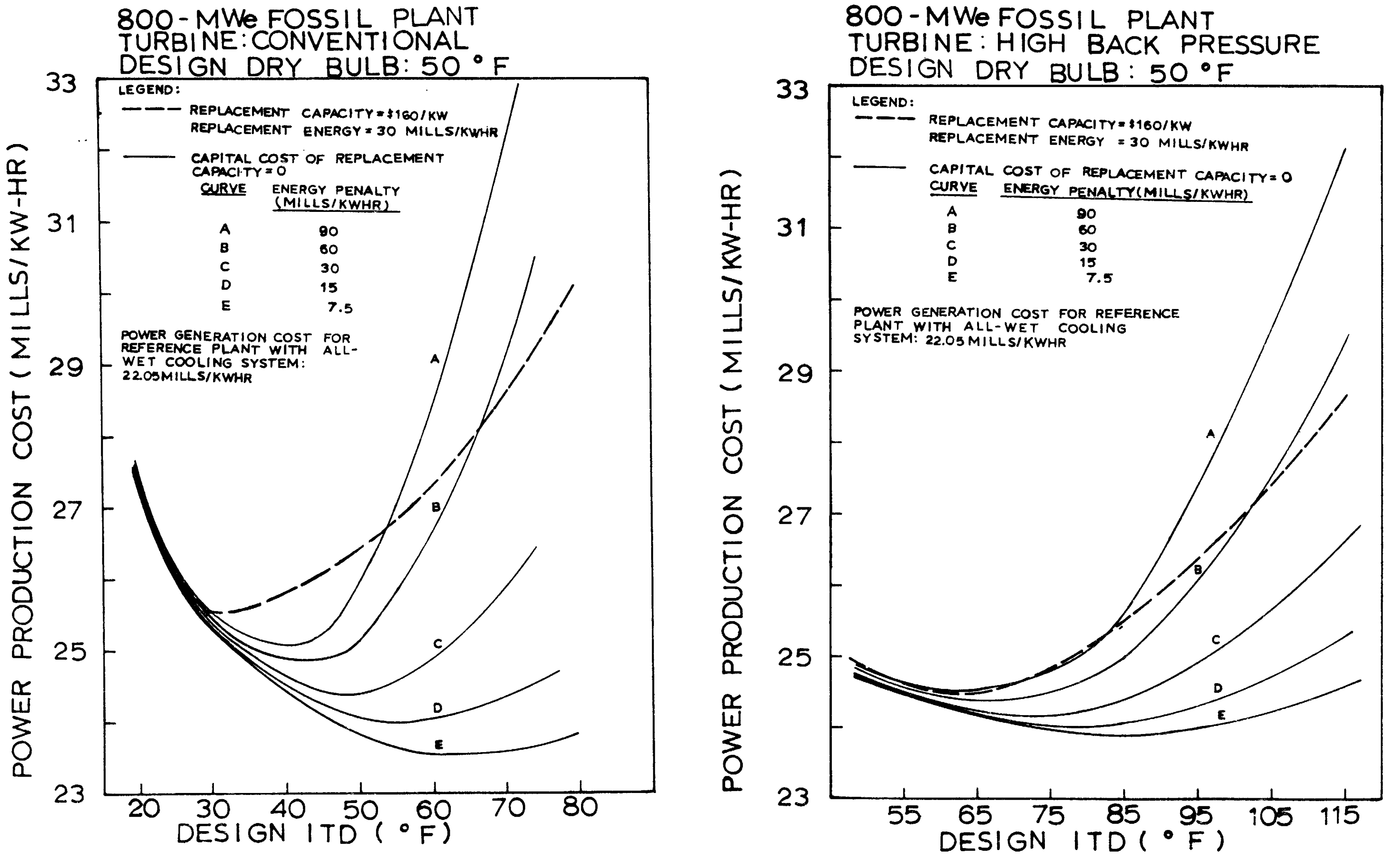


Fig. 2-1 Sensitivity Study of the Effects of Using Different Methods of Replacing Lost Capacity on the Economics of Dry Cooling Tower System in 800-MW Fossil Plant.

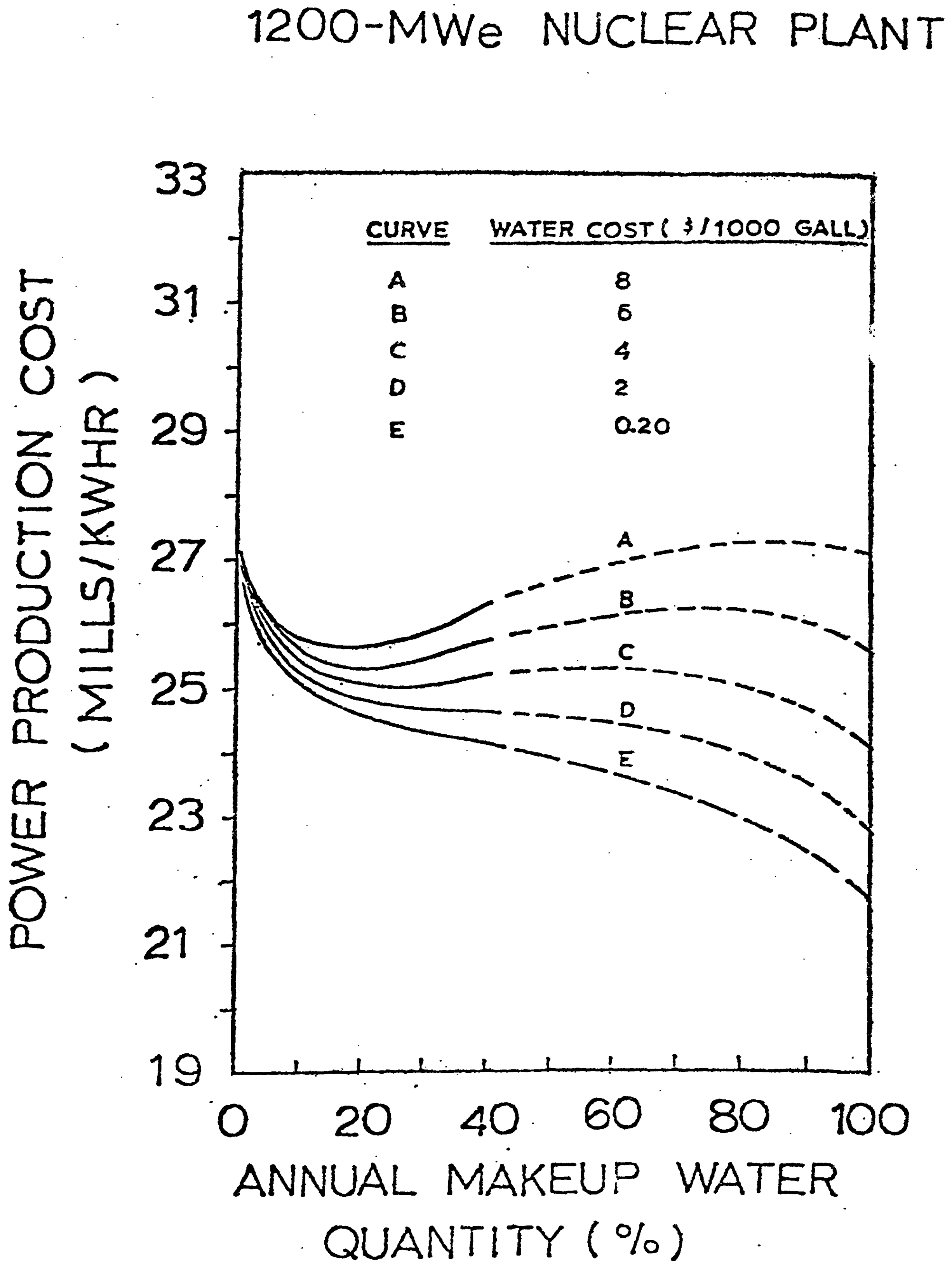


Fig. 2-2 Sensitivity Study of Wet/Dry Cooling Tower Costs to the Cost of Water

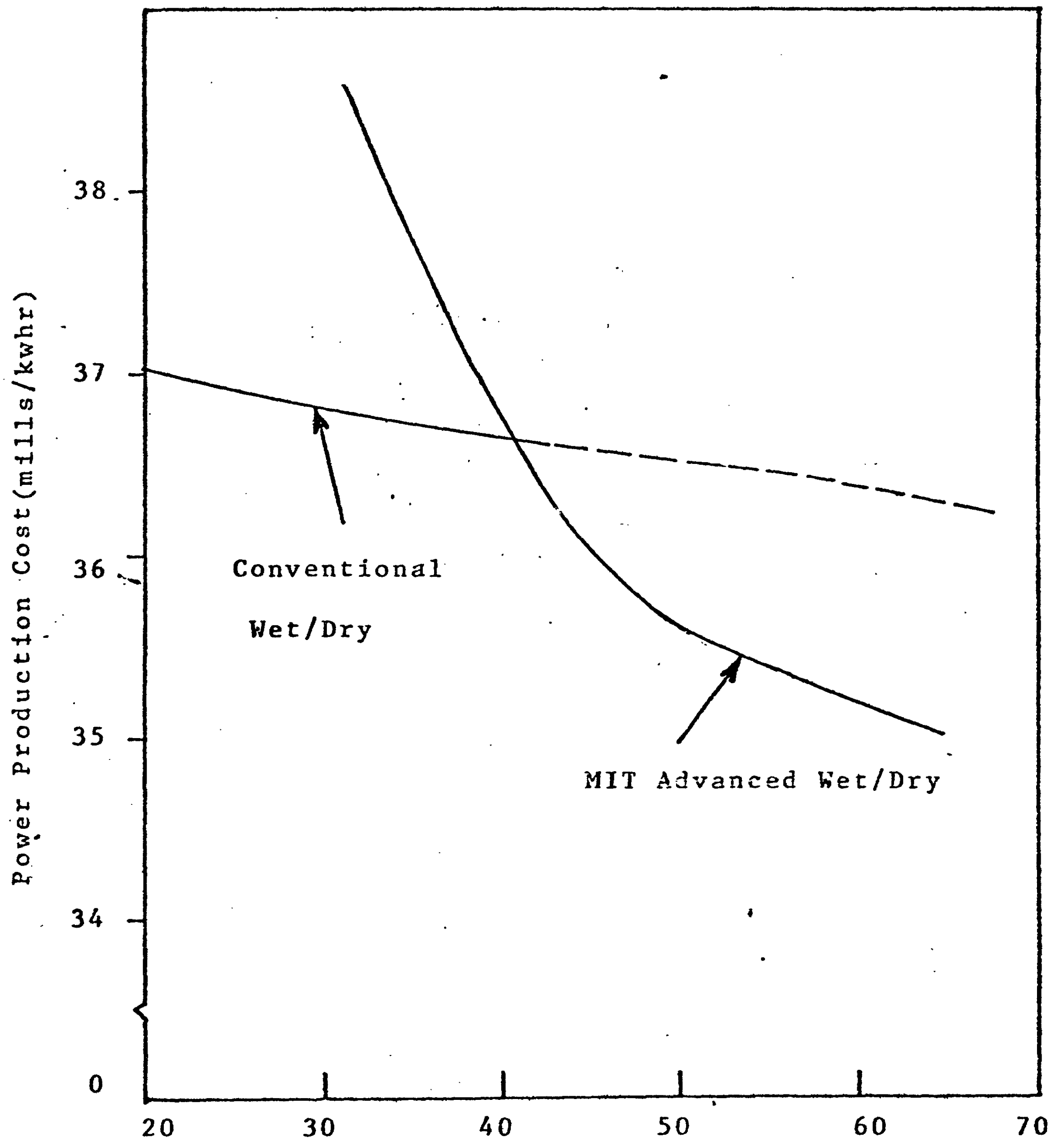


Fig. 2-3 Comparison of MIT Advanced Wet/Dry Tower and Conventional Wet/Dry Tower

the range, the hybrid system is less expensive than conventional wet plus dry. (Note that the economic parameters used in this analysis differ from those used in producing Figures 2-1 and 2-2, thus leading to differences in absolute generating costs.)

2.2 Design and Optimization of Recirculating Cooling Ponds

Cooling ponds are large, artificially constructed, water bodies used for closed-cycle dissipation of power plant waste heat. While there are areas of the country where cooling ponds have been widely used (e.g. Texas and Illinois), their use has been restricted by the relatively poor state-of-the-art in predicting cooling pond performance (e.g. relative to that of wet towers). This difficulty is created by the complex circulation patterns found in a pond and by the highly transient response of a pond to time-varying meteorology. As a consequence of past difficulties in simulating performance of a given pond, there have been few established guidelines for the design (optimization) of ponds. Existing guidelines are based on very simple, usually steady state, hydrothermal models.

Over the past years the Ralph M. Parsons Laboratory of the Department of Civil Engineering at MIT has been engaged in the development and application of mathematical models to study the hydro-thermal performance of cooling ponds and lakes (Ryan et al., 1973; Watanabe et al., 1975; Jirka et al., 1977; and Jirka et al., 1978). The object of the present effort has been to synthesize information from these models in order to develop a rational cooling pond design methodology. The specific tasks which have been undertaken are described below.

A computer program and user's manual to simulate the transient performance of cooling ponds of different classifications including deep, shallow-dispersive, and shallow-recirculating has been completed. (The development of the individual sub-models and the initial integration of the sub-models was performed under different sponsorship. It was necessary, however, to complete the integration as well as to make modifications for the present purposes.)

Using these transient models, predicted pond performance (statistical distribution of intake temperatures) was evaluated for a range of pond design parameters including range across the condenser, pond area, depth, and pond shape (density of baffles). The evaluation was based on one year of meteorological data from Moline, Illinois.

For the purposes of preliminary design, a quasi-steady model was developed to correspond to the transient model for the most efficient design - the shallow dispersive pond. Input to the quasi-steady model consists of time-averaged values of equilibrium temperature and surface heat loss coefficient. The appropriate averaging interval is selected as a function of pond depth to represent the thermal inertia inherent in the transient model. By assembling the averaged meteorological valuables into a cumulative (bi-variate) frequency distribution, the long term pond performance (e.g. cumulative distribution of intake temperature) can easily be evaluated in much the same way as is done for cooling towers. This technique is suggested as a means of screening for acceptable pond designs. Subsequently, a long term fully-transient analysis can be performed to test the selected design(s).

The various operating and capital costs which influence the economics of power plants cooled with ponds were considered. These costs include, primarily, circulating water pumps, land purchase and preparation, water consumption and lost generating capacity. Based on their simulated performance, the total production cost of each design was expressed as a function of these costs, in order to allow the evaluation of optimal designs. Figure 2-4 presents an example illustrating cooling pond costs versus land area for various land costs.

A major consideration in the choice of a cooling pond is water consumption. Evaporation losses from a 1200 MWe nuclear station using a cooling pond have been compared with similar losses from plants using cooling towers at a number of locations in the U.S. Figure 2-5 is one example of this comparison and indicates, for ponds, both natural evaporation (that loss which would occur in the absence of artificial heat input) and forced evaporation (that which is due to artificial heat input) components. Figure 2-6 shows, for the same site, the annual forced and total pond evaporation rates as a function of pond area. Several conclusions can be drawn from these figures: (1) forced evaporation from ponds is generally less than evaporation from wet towers, while total evaporation rates are comparable; (2) ponds exhibit greater monthly variation than do towers in both forced and total evaporation, and (3) total pond evaporation increases with pond area (over the range of areas

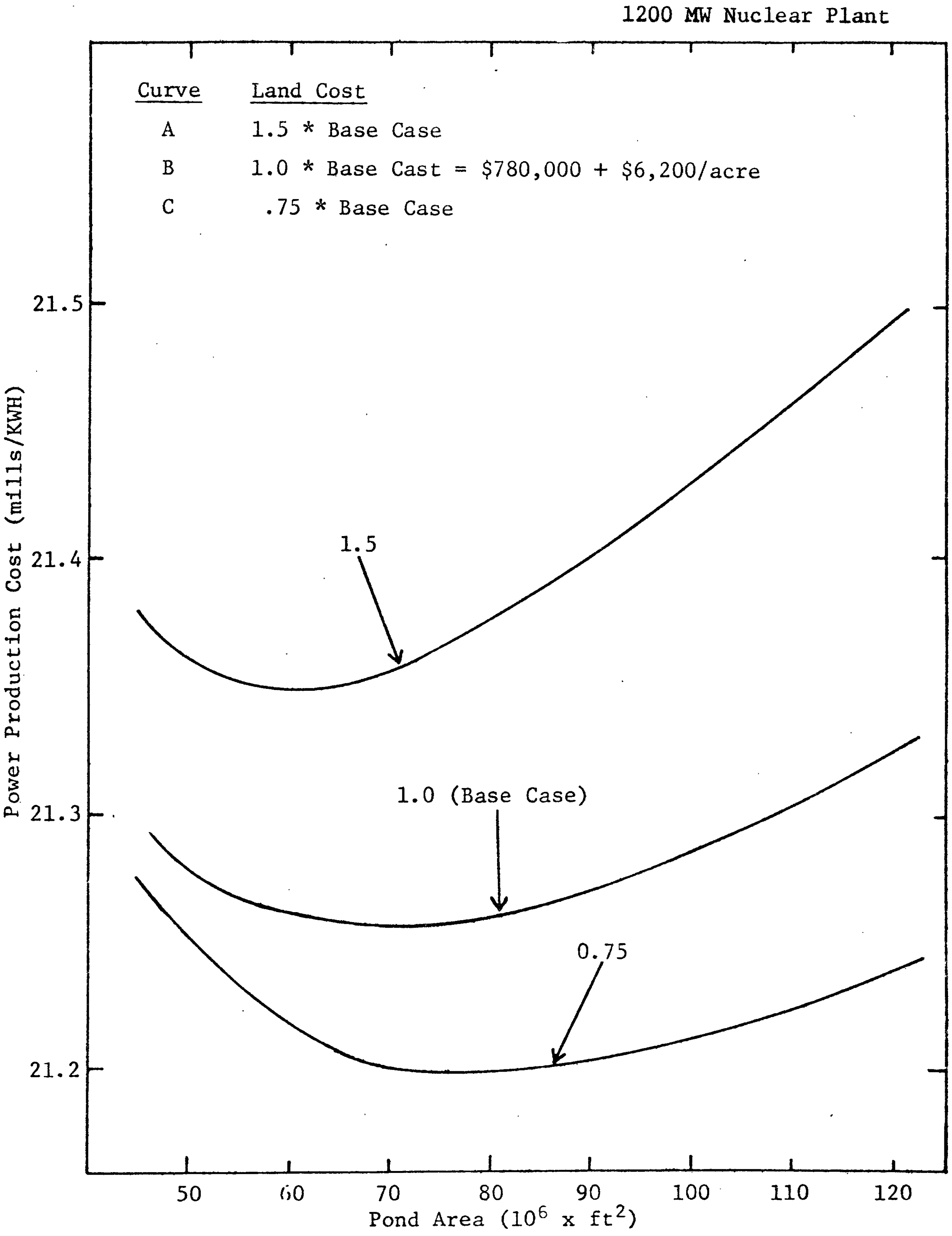


Fig. 2-4 Sensitivity Study of Cooling Pond Cost to the Cost of Land and Land Preparation

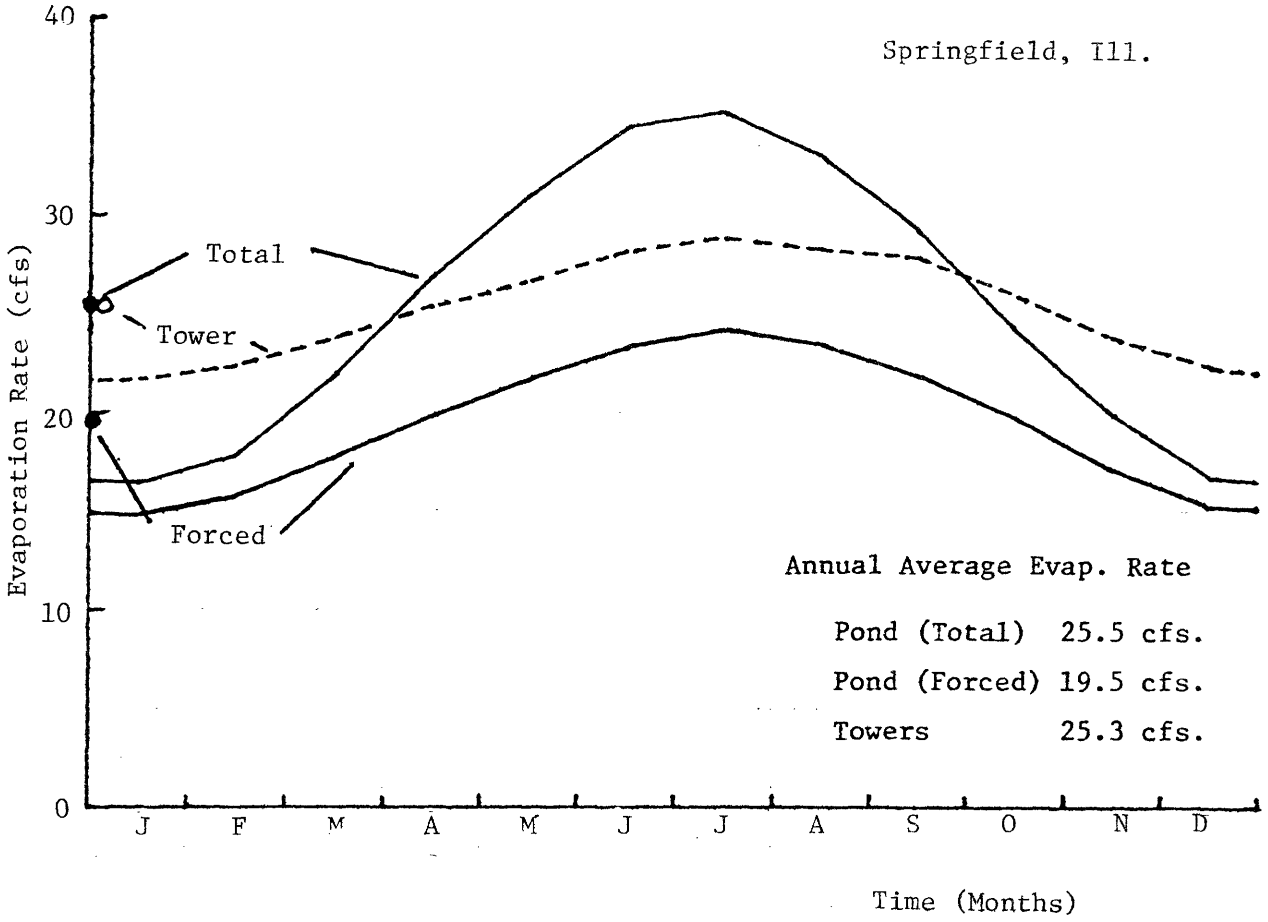


Fig. 2-5 Comparison of Pond and Tower Evaporation for Springfield, Illinois

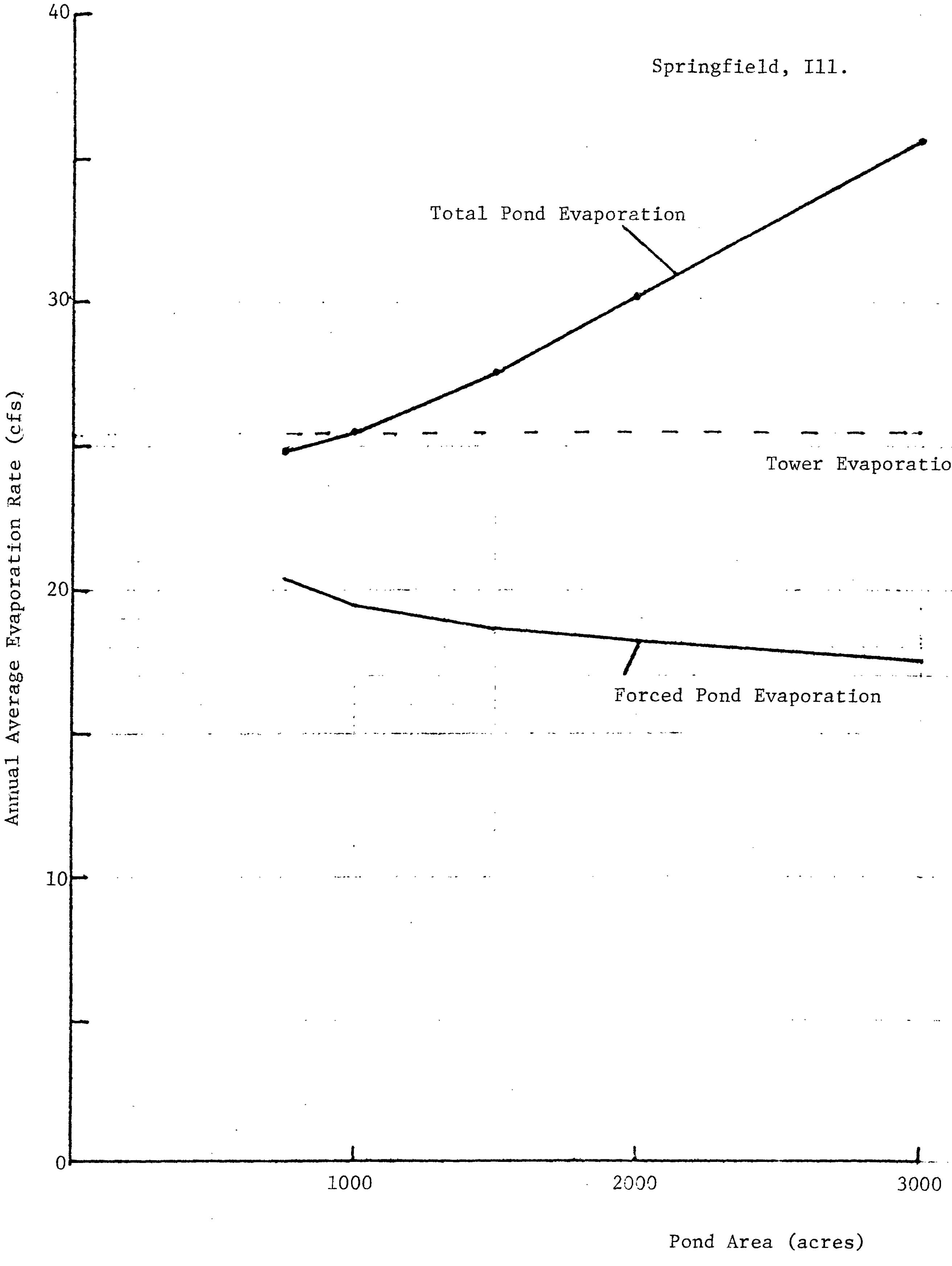


Fig. 2-6 Sensitivity of Evaporation Rate to Pond Area

considered) suggesting the desirability, from both water consumption and land use points of view, of building the smallest cooling pond where engineering performance is still within an acceptable margin of safety.

2.3 Development of Control Technologies for Supplementary Cooling Systems

At sites where the supply of cooling water is sufficient for once-through cooling supplementary cooling systems (e.g. cooling towers) may be required in order to meet environmental constraints on induced water temperature changes. At many of these sites it may be feasible to design a mixed mode cooling system which operates in either the open, closed, or helper (once-through but with use of the cooling tower) modes. Such systems may be particularly economical where the need for supplementary cooling is seasonal or dependent upon other transient factors such as streamflow. With a mixed mode system, the use of cooling towers on either the helper or closed mode would be based upon real-time continuous measurements of water temperatures in much the same way as supplementary control systems for air quality control respond to ambient monitor readings.

The design and operation of mixed mode cooling systems involves a number of issues, all of which directly influence the loss of net generating capacity resulting from the use of cooling towers. First, the design of the open cycle components of the condenser cooling system determines the limiting environmental conditions for open cycle operation.

Second, the cooling tower design must reflect a balance between the capital cost of tower construction and the loss of net plant capacity during tower operation. Third, the location, operation, and interpretation of the temperature monitoring system will be major factors in determining the frequency of cooling tower usage. Of particular importance in this regard is the influence of natural temperature variations which may mask the true impact of plant operations. Finally, the specification of the environmental temperature standard itself will directly affect the percentage of time cooling tower use is requried.

The design and operational issues detailed above have been examined in the context of a case study involving TVA's Browns Ferry Nuclear Plant. The large quantity of available site-specific data reflecting both pre-operational and post-operational conditions has made possible realistic simulations of plant operation and investigation of the sensitivity of plant capacity losses to design and operational parameters. Figure 2-7 shows such a simulation. The most important findings of the study are:

(1) The capability to switch cooling modes results in only 10% of the capacity losses experienced by a totally closed system.

(2) The cooling tower related capacity loss is extremely sensitive to the specified limit on induced temperature increases. A decrease in the allowable temperature rise from 5°F to 3°F produced a 300% increase in lost capacity.

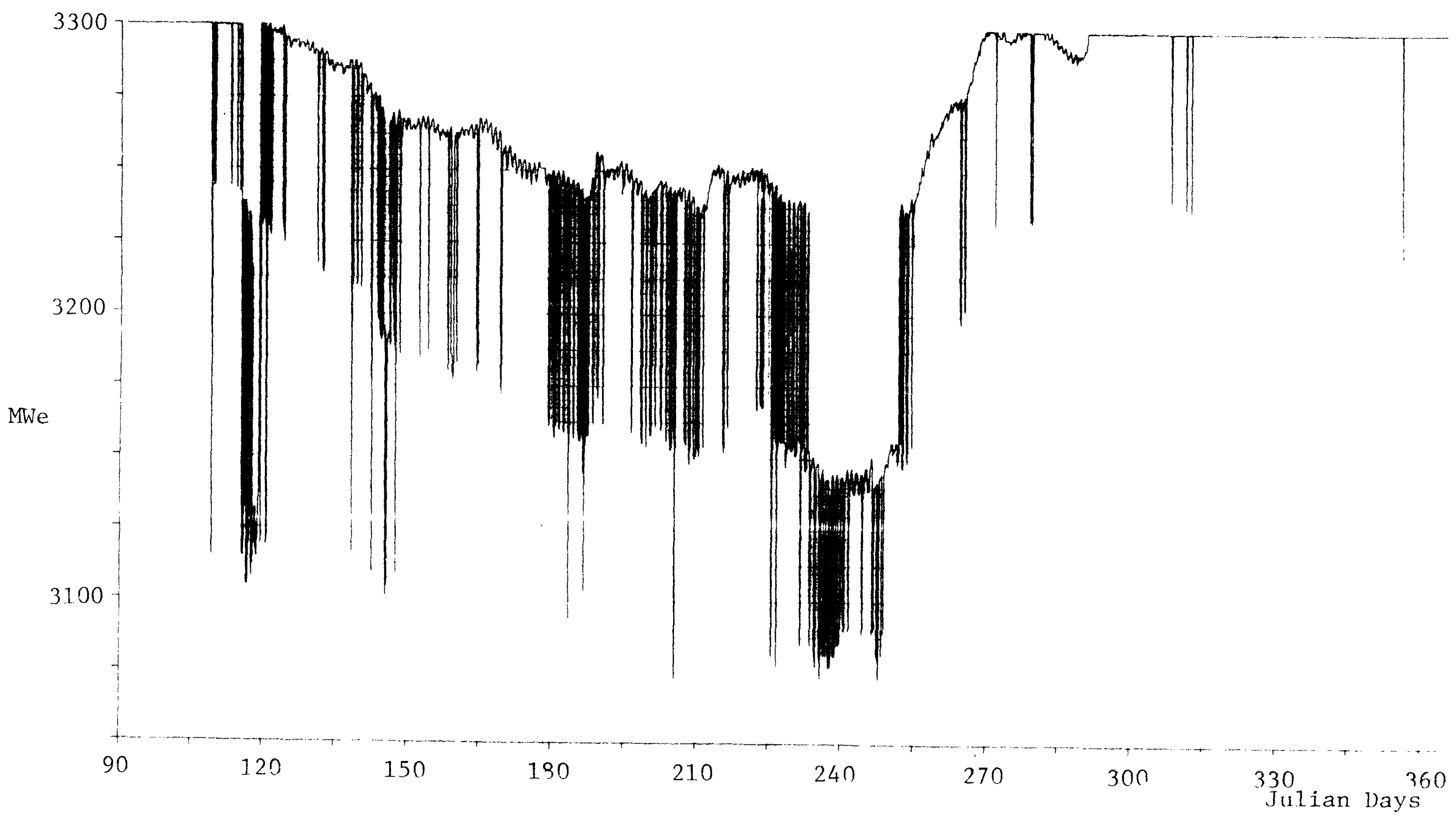


Fig. 2-7 Example of Power Output Using Optimal Mixed Mode

Compared to the influence of the environmental standard, changes in plant design, such as cooling tower size or open cycle diffuser mixing, have significantly less influence on plant capacity losses.

(3) About one third of the capacity loss incurred using a mixed mode system is the result of natural temperature variations that are interpreted as plant induced effects by the monitoring system. This unnecessary loss may be cut in half by the use of a predictive model for natural temperature variations developed by this study. Further reduction may be obtained by spatial and temporal averaging of temperature monitor measurements.

2.4 An Environmental and Economic Comparison of Cooling System Designs for Steam-Electric Power Plants

The engineering research efforts on cooling ponds and dry towers generated information that allows a comparison with other cooling system types - specifically, once through systems and both natural and mechanical draft wet towers. Such a comparison was made for a hypothetical 800 MWe fossil station and a 1200 MWe nuclear station located at a midwestern site on the Mississippi River. Design and simulation codes for cooling ponds and dry towers along with similar codes for open cycle and evaporative towers were used to establish optimally-sized cooling systems of each type based on a 10 year cumulative distribution of the appropriate meteorological and hydrological data. For once-through cooling, design options ranging from a surface discharge canal (least cost, greatest thermal impact) to submerged diffusers of different lengths and discharge velocities were evaluated. Figure 2-8 shows a simulation of power output during summer months for a station using four different cooling systems.

The cooling systems were then compared for a range of economic parameters including:

- capital cost of the power plant
- cooling system capital cost
- fuel cost
- cost of water consumption and water treatment
- cost for replacement capacity and for replacement energy
- capacity factor
- annual fixed charge rate

The comparison included present-valued incremental costs, power production costs, fuel and water consumption, and various environmental impacts. Tables 2-1 and 2-2 show parts of this comparison for the case of the nuclear and the fossil fuel plants.

2.5 Economic and Resource Allocation Implications of Open Versus Closed Cycle Cooling for New Steam-Electric Power Plants. A National and Regional Survey

An examination of Figure 1-10 indicates that most new generating stations are slated to use wet cooling towers, despite the fact that many plants will be located on coastal, Great Lakes or large river sites. According to a recent UWAG study [UWAG, 1978], over one half of these stations are proposing wet towers only because of state or federal water quality laws while an additional one-third have chosen wet towers for a

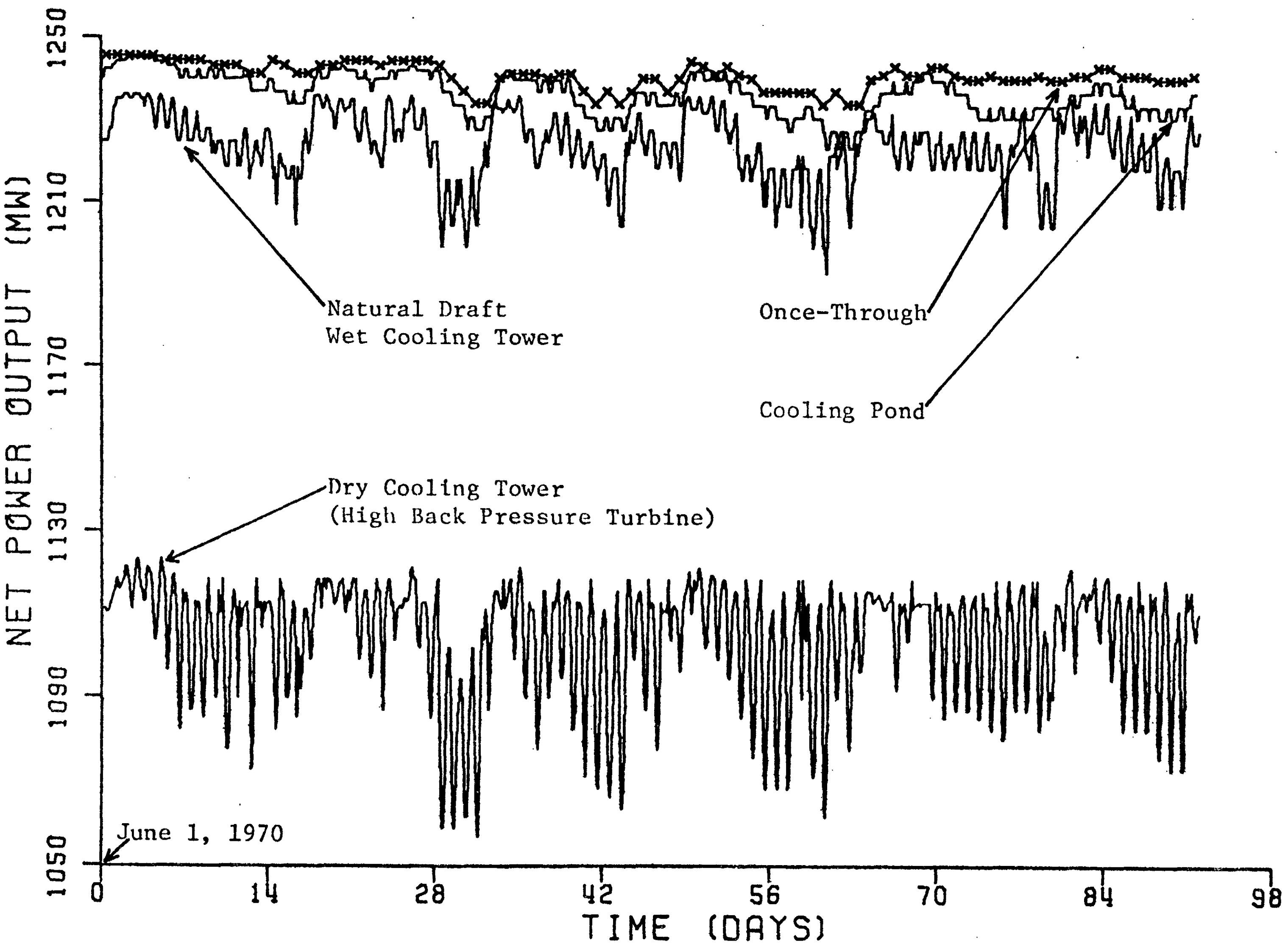


Fig. 2-8 Cooling System Transient Simulation (summer 1970)

	Once-through: Surface Canal	Once-through: Multiport Diffuser	Cooling Pond	Natural Draft Wet Tower	Mechanical Draft Wet Tower	Mechanical Draft Wet/Dry Tower *	Mechanical Draft Dry Tower
Power Production Cost (mills/KWH)	20.93	21.13	21.26	21.63	21.56	24.45	26.21
Cooling System Capital Cost ($ x 10^6)	18.48	27.31	27.53	34.46	27.52	73.49	108.59
Total Fuel Cost ** (mills/KWH)	4.87	4.88	4.91	4.97	4.96	5.29	5.64
Maximum - Minimum Power Production (MW)	13.3	13.5	28.8	44.6	37.2	60.0	81.1
Water Withdrawal Rate (cfs)	1500.	1500.	41.2	38.7	33.7	10.1	∿
Water Consumption (cfs)	16.8	16.8	27.7	27.8	23.5	7.1	∿

a) 1200 MWe Nuclear Plant

	Once-through: Surface Canal	Once-through: Multiport Diffusers	Cooling Pond	Natural Draft Wet Tower	Mechanical Draft Wet Tower	Mechanical Draft Wet/Dry Tower *	Mechanical Draft Dry Tower
Power Production Cost (mills/KWH)	21.62	21.76	21.84	22.03	22.05	23.81	24.43
Cooling System Capital Cost ($ x 10^6)	11.89	16.20	14.57	15.33	13.84	36.92	48.08
Total Fuel Cost ** (mills/KWH)	7.92	7.93	7.94	8.00	8.03	8.11	8.53
Maximum - Minimum Power Production (MW)	12.8	12.9	20.4	23.8	18.6	26.0	43.7
Water Withdrawal Rate (cfs)	840	840	18.9	16.1	14.8	4.4	∿
Water Consumption (cfs)	7.7	7.7	12.5	11.6	10.6	3.2	∿

b) 800 MWe Fossil Plant

* design make-up water requirement of 30% (of fully wet tower)

** sum of fossil fuel cost and replacement fuel cost

TABLE 2-1 Cooling System Comparison

TABLE 2-2 Comparison of Environmental Effects

Cooling System Effect	Once-Through	Cooling Ponds	Mechanical Draft Wet Towers	Natural Draft Wet Towers	Dry Towers
Thermal Impact	Potentially large depending on site. May be minimized through outfall design.	Generally small. Restricted to blowdown heat. Could be significant on small streams but blowdown can be stored during critical periods	Generally small. Restricted to blowdown heat. Could be significant on small streams.	Generally small. Restricted to blowdown heat. Could be significant on small streams.	None
Intake Impacts	Potentially large depending on site.	Generally small due to modest make-up requirements. Could be significant on small streams.	Generally small due to modest make-up requirements. Could be significant on small streams.	Generally small due to modest make-up requirements. Could be significant on small streams.	None
Groundwater Impacts	Negligible	Potential contamination from seepage. Potential water table changes.	Usually negligible	Usually negligible	None
Blowdown - Chemical and Low Level Radioactive Wastes	Generally small. Large water bodies and no recycling imply low concentrations.	Potentially significant. May require low cycles of concentration or treatment. Ponds can store blowdown during low flows.	Potentially significant. May require low cycles of concentration or treatment.	Potentially significant. May require low cycles of concentration or treatment.	None

Table 2-2 Comparison of Environmental Effects (cont'd)

Cooling System / Effect	Once-Through	Cooling Ponds	Mechanical Draft Wet Towers	Natural Draft Wet Towers	Dry Towers
Water Consumption	Considerable - About 0.4 gallons per KWH through forced evaporation. However, generally small fraction of water withdrawal.	Considerable - About 0.6 gallons per KWH through natural and forced evaporation. May vary considerably due to addition of seepage and subtraction of precipitation depending on site and accounting scheme.	Considerable - About 0.5 gallons per KWH through forced evaporation and drift.	Considerable - About 0.6 gallons per KWH through forced evaporation and drift.	None
Fogging, Icing and Visible Plume	Usually negligible due to relatively small water temperature rise.	Potentially significant depending on site. However large area (diffuse vapor source) and remote siting minimize impact.	More significant than ponds due to concentrated low level vapor source. May prevent siting in certain areas.	Higher release point minimizes ground level fog and ice but may affect visibility.	None
Drift	None	Negligible	Potential contamination to local soil and vegetation and corrosion of nearby structures.	Similar to mechanical draft but less significant due to higher release point.	None

Table 2-2 Comparison of Environmental Effects (cont'd)

Effect \ Cooling System	Once-Through	Cooling Ponds	Mechanical Draft Wet Towers	Natural Draft Wet Towers	Dry Towers
Land Use	Relatively small area required but land may be highly desireable for other uses due to its proximity to water.	Very large area required - typically 1-2 acres per MWe. Spray modules may reduce requirement by about a factor of 10.	Considerable area required though considerably less than ponds. Typically .012 acres per MWe.	Considerable area required. Typically .007 acres per MWe.	Considerable area required. Typically .020 acres per MWe.
Siting	Not very flexible. Must be located near large water supply.	Moderately flexible. Requires large open land area with suitable soil conditions and make-up water supply.	Moderately flexible. Requires reliable make-up source. (May require storage pond on unregulated rivers) Fogging, and icing may preclude some sites.	Moderately flexible. Requires reliable make-up source. Not suitable in hot arid climates or regions with hurricane potential.	Highly flexible. Negligible water requirement allows siting near fuel source or load center.
Noise	Generally small	Generally small	Potential annoyance from splashing on fill and fan operation.	Potential annoyance from splashing on fill.	Potential annoyance from fan operation.
Aesthetics	Cooling system least noticeable but plant may be highly visible due to nature of site.	Multiple use of pond may enhance aesthetics.	Small impact from visible plume.	More visible than mechanical draft due to tower height and size.	Relatively large structure but no visible plume.

combination of reasons including environmental regulations.

The large projected decrease in the use of once-through cooling (relative to wet towers) invites a number of questions concerning costs, environmental impact and natural resource requirements. In this part of the study several of these questions were addressed by estimating, regionally, the financial, energy and fresh water savings which could occur if more new plants were to employ once-through cooling than current plans suggest.

A first step was to estimate required new generating capacity for each of the 18 U.S. Water Resources Council (WRC) regions through the year 2000, as a function of projected national energy demand. One estimate is based on data supplied by electric utilities for stations scheduled to be in operation by 1996, and extrapolated by the F.E.R.C. to the year 2000 (U.S.W.R.C., 1977). Figure 1-10 is based on this data. Since this is generally regarded as a high estimate of demand (it corresponds to an overall energy demand of 163 quads in 2000), a lower estimate (corresponding to 130 quads, or about two-thirds of FERC's projected growth) has been derived from ERDA forecasts (Williamson, et al., 1976).

For each of the two energy demand scenarios, the percentage of plants which could utilize once-through cooling was estimated for several siting patterns. A base case siting pattern refers to the cooling systems reported by FERC (U.S.W.R.C., 1977). Other patterns of once-through cooling capacity are based on maximum allowable temperature rises (defined by minimum streamflows or specified surface areas for lake or coastal sites), historical patterns of cooling system selection, or both. Table 2-3 shows the percentage of new plants which could employ once-through cooling for each of five different siting patterns based on the high energy demand.

Table 2-3 Percentages of New Capacity Expected to be Installed Between 1975 and 2000 that could use Once-Through Cooling (High Energy Demand Scenario)

Water Resource Council Region	With Current Thermal Regulations	With Relaxed Thermal Regulations Alternative Siting Patterns: One	Two	Three	Four
One	25.3	91.0	67.1	75.6	100.0
Two	13.9	59.0	42.1	66.4	94.1
Three	11.2	26.0	39.3	57.9	64.5
Four	7.0	81.0	70.1	100.0	100.0
Five	3.2	62.0	16.7	24.6	24.6
Six	2.6	61.0	15.2	47.8	47.8
Seven	0.9	78.0	13.4	28.3	33.0
Eight	42.5	100.0	61.1	71.8	88.8
Ten	8.2	54.0	24.8	33.1	33.1
11-17	15.6	36.0	27.8	46.3	47.3
Eighteen	43.1	78.0	47.2	77.3	100.0
Contiguous U.S.	12.9	54.0	35.6	54.0	60.9

The cooling system design codes which were assembled in part (4) of this study were used to evaluate mechanical draft wet towers and open cycle systems in terms of cost, water, and fuel consumption. Evaluations were made for each of the 18 WRC regions taking into consideration regional variations in cost and meteorology. The evaluations were combined with the scenarios of energy demand and once-through cooling availability to provide regional estimates of cost and resource consumption for each siting pattern. By comparing the results for different siting patterns, estimates can be made of the incremental effects of different "standards" of thermal control. For example, Table 2-4 compares the base case siting pattern with alternative siting pattern one (cooling systems selected on the basis of historical trends, subject to a minimum river flow). The former pattern represents the current projected mix of cooling systems while the latter pattern reflects, roughly, the extent to which utilities would employ once-through cooling were environmental restriction concerning thermal discharges not an overriding concern.

While the absolute additional costs, water consumption and fuel consumption are all large on an absolute basis, it is helpful to look at these figures on a relative bases as well. In this regard, the figures for water consumption seem most significant. For instance, nationally, the additional water consumption due to thermal controls would account for between 10% and 14% of the projected growth in all non-agricultural water uses between 1975 and 2000 (U.S.W.R.C., 1978). In comparison overall consumption from the steam electric power industry will represent the leading sector in new demands, accounting for roughly 42% of the growth in non-agricultural water consumption.

	Incremental Change in Units of:		
Region	Additional Annual Cost (Millions of 1977 Dollars per year)	Additional Fresh Water Consumption (MGD)	Additional Energy Consumption (10^6 Barrels of Oil Equivalent per year)
1	143	259	4.8
2	284	678	8.9
3	191	223	6.4
4	448	374	14.9
5	387	374	12.7
6	97	80	3.4
7	399	366	14.9
8	193	187	7.5
9	0	0	0
10	125	125	5.3
11-17	325	428	11.9
18	82	223	2.4
Total U.S.	2,674	3,317	93.1

Table 2-4 Incremental Effects in Year 2000 of a Change from the Base Case Siting Pattern to Alternative Siting Pattern One for the High Energy Demand Case

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