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THERMAL POLLUTION
ITS EFFECTS AND TREATMENT

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THERMAL POLLUTION

ITS EFFECTS AND TREATMENT

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A Working Paper presents results of investigations which are to some extent limited or incomplete. Therefore, conclusions or recommendations--expressed or implied--are tentative.

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INTRODUCTION

Thermal pollution is not a new concept here in Minnesota. Effects of waste heat discharges to the Mississippi River in the Twin City area were discussed by the University of Minnesota in its first major report on the "Pollution and Recovery Characteristics of the Mississippi River"[1] published in 1958. A pioneering effort in water temperature prediction was presented by the University in its 1961 report[2] on the same subject.

Nationally, thermal pollution has become an increasingly popular topic for conversation in water management and pollution control circles. With the approval of State-Federal water quality standards, the criteria and implementation plans for control of waste heat discharges have been established. The intensity of public concern over thermal pollution problems has had a noticeable effect on the power industry. Speaking before the American Power Conference in 1969, Mr. L. G. Hauser of Westinghouse Electric said: "...it is obvious...that the country faces a very real and serious problem in disposing of waste heat. It is equally obvious that this problem cannot be solved, in the long run, by increasing allowable temperature limits for the natural bodies of water or by receiving special deviations from established thermal regulation standards."[3] Similarly, Morgan and Bramer state that: "The (water quality) standards set for interstate streams and coastal waters...can only be expected to become more stringent in the future."[4] In my opinion, most Federal and State administrators in environmental resource and regulatory agencies wholeheartedly support these viewpoints.

In the following paragraphs I will present current information and thinking on several major aspects of thermal pollution. I have tried to select specific references, which I feel are most useful, from the available literature for presentation in the text. Many of these references can be made available upon request. The National Thermal Pollution Research Program, FWPCA, Corvallis, Oregon, is a valuable resource for special information and consultative services which may be obtained by writing to Mr. Frank Rainwater, Director.

POWER NEEDS

Industrial cooling water needs account for about 50 percent of all water used in the United States. In 1964 diversions for cooling water needs totaled over 50 trillion gallons;[5] 80 percent of this total was for the condensers of the electric power industry. By the year 2000, it is expected that the electric power industry will need 92 percent of the total industrial cooling water supplies.[6] The need for increased cooling water supplies will accompany rapidly increasing needs for electricity and an increasing number of nuclear power plants as a percentage of the total. In 1965 electric power generation totaled 1.06 billion kilowatt hours (KWH) and peak generation was 0.19 million KW; by 1990 the total is expected to reach 5.85 billion KWH, with a peak of 1.06 million KW. Table 1 shows predicted energy and peak generation requirements through 1990.[7]

TABLE 1

PREDICTED ELECTRICAL ENERGY REQUIREMENTS

	Contiguous U.S.		Total U.S.	
	Energy (10^6KWH)	Peak (10^3KW)	Energy (10^6KWH)	Peak (10^3KW)
1965	1058	188	1060	189
1970	1522	277	1527	278
1975	2187	396	2194	398
1980	3075	554	3086	556
1985	4247	766	4263	769
1990	5828	1051	5852	1056

These numbers are meaningless, of course, unless we understand their significance locally in terms of potential waste heat discharges to receiving streams. The essential ideas for this understanding are presented in the following paragraphs.

THERMAL ELECTRIC POWER GENERATION AS A WASTE HEAT SOURCE

All major thermal electric power plants in the United States operate on the Rankine cycle and all follow the general pattern schematized in Figure 1.[8] As can be seen from Figure 1, the primary difference between fossil-fueled and nuclear-fueled power plants is in the heat source for steam generation. Typical, modern fossil-fueled boilers provide steam at 3000 psi and 1000°F.

Because of reactor safety requirements, the current generation of nuclear-fueled reactors of the boiling water or pressurized water types produce steam at about 600 °F and about 1000 psi or 2000 psi, respectively.

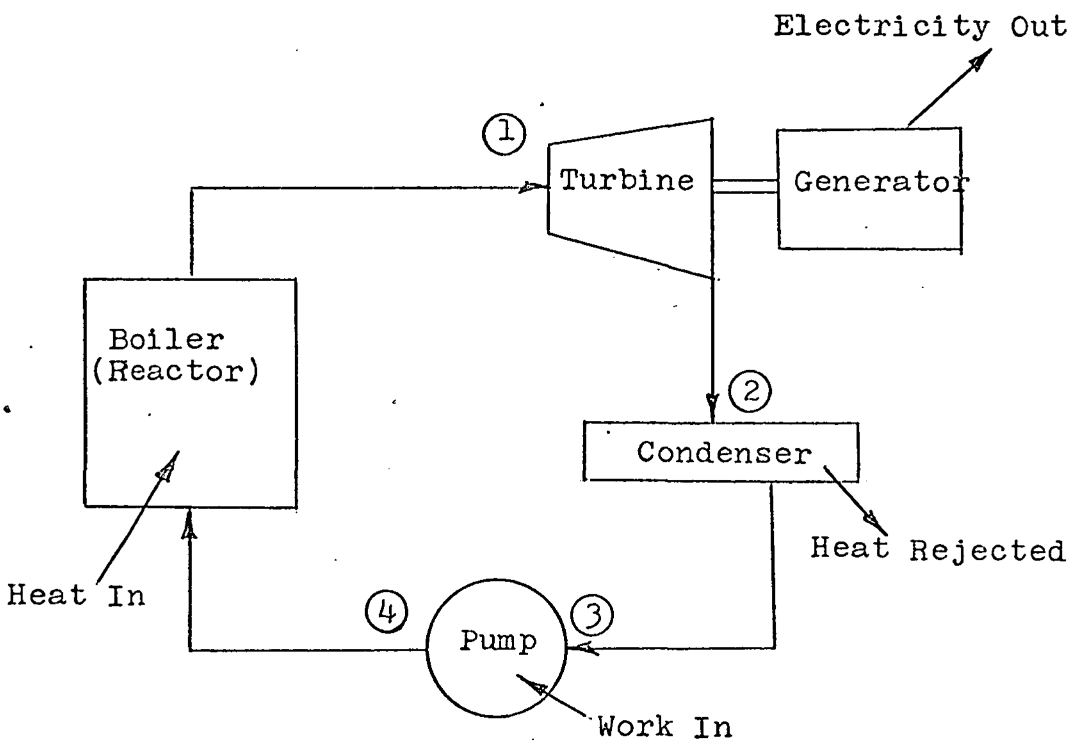

FIGURE 1. Schematic of Basic Rankin Power Cycle.

Figure 2 shows the basic Rankine cycle. Inputs and outputs are labeled according to the functional parts of the power plant diagram in Figure 1 as follows:

(3) to (4) is the work input provided by the feed water pump to the boiler;

(4) to (1) is the thermal input provided by the boiler;

(1) to (2) is the conversion of thermal energy to mechanical/ electrical energy by the turbine-generator units.

(2) to (3) is the heat rejection incurred by condensing spent steam to water for recycling.

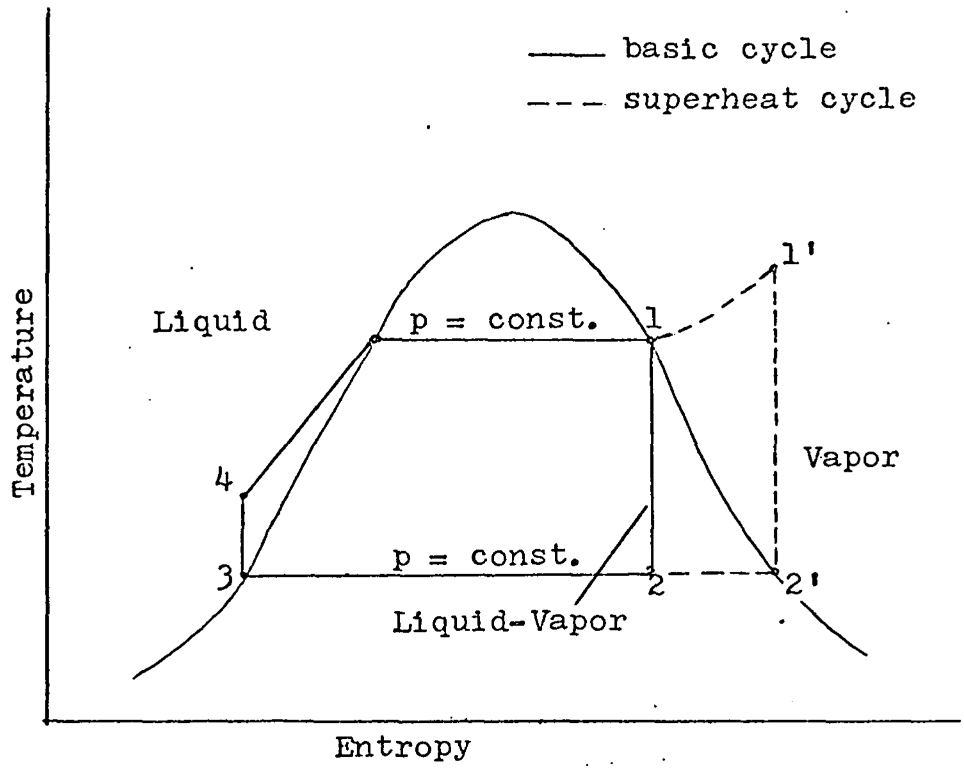

FIGURE 2. Temperature-Entropy Diagrams of Rankine Cycles.

Thermal efficiency of the basic Rankine cycle is calculated as the quotient of the work output divided by the thermal input as follows:

$$E_{th} = \frac{W_{Turbine} - W_{Pump}}{Q_{in}} = \frac{(h_1-h_2) - (h_4-h_3)}{(h_1-h_4)}$$

where h is the enthalpy, or heat content, of the respective points on the Rankine cycle. The maximum efficiency of this cycle, corresponding to present fossil-fueled power plant design, is about 42 percent and presumes superheating the steam as shown in Figure 1 by the dashed line extension of points (1) and (2). Maximum thermal efficiency of the present generation nuclear power plants is only about 33 percent. An alternative relationship for calculating thermal efficiency is to divide the thermal equivalent of electrical energy output by the thermal input as follows:

$$E_{th} = \frac{\text{Electricity Output}}{\text{Thermal Input}} = \frac{3413 \text{ BTU/KWH} \times 100}{3413 \text{ BTU/KWH} + \text{Waste Heat (BTU/KWH)}}$$

The denominator of this efficiency equation is called the "heat rate" of a plant and represents the average amount of heat required to produce one kilowatt-hour of electricity. Not all of the "waste heat" is discharged to the receiving stream, however. Some of the waste heat in fossil-fueled plants, about 10 percent, is discharged with the "stack" emissions; an additional 5 percent is wasted within the plant as radiation and other losses. Inplant losses for nuclear power plants are estimated at 5 percent.

On this basis, then, waste heat discharged with the condenser cooling water can be calculated as follows:

Fossil-fueled plant:

Heat to cooling water = (0.85 x heat rate-3413)BTU/KWH

At 40 percent efficiency

$$\text{Heat rate} = \frac{3413}{0.40} = 8533 \text{ BTU/KWH}$$

Heat to cooling water = (0.85 x 8533) - 3413 = 3800 BTU/KWH

Nuclear-fueled plant:

Heat to cooling water = (0.95 x heat rate - 3413) BTU/KWH

At 33 percent efficiency

$$\text{Heat rate} = \frac{3413}{0.33} = 10{,}340 \text{ BTU/KWH}$$

Heat to cooling water = (0.95 x 10,340) - 3413 = 6400 BTU/KWH

The difference in waste heat rejection to the cooling water between fossil-fueled and nuclear-fueled plants is obviously significant: 65 to 70 percent greater for the nuclear plants. The importance of this difference is driven home by the prediction that nuclear-fueled power plants will provide two-thirds of the thermal-electric energy requirements by the year 2000.[6]

Another obvious conclusion from the above numbers is that thermal-electric power generation is extremely inefficient, resulting in huge quantities of wasted energy. Improvements in fossil-fueled power generation efficiency are limited by available steam conditions in the Rankine cycle as described above. Modern fossil-fueled plants are approaching the practicable limit on thermal efficiency.

Nuclear-fueled plants can and will be more efficient with third and fourth generation power reactors, using gas or liquid metal for primary coolant instead of water. Maximum efficiency of the high temperature gas/metal power reactors is still limited, however, by the Rankine cycle at about 42 percent.

There are several alternatives to the conventional Rankine cycle, which are in various stages of development and use. Included among the alternatives are electric power generation by magnetohydrodynamics (MHD) and fuel cells. None are projected to be of major importance in the foreseeable future. Gas turbines (jet engines) are being installed in power-peaking units and do not reject waste heat to water cooling systems. These units are relatively inefficient, however, and are not expected to replace conventional thermal-electric units for base power generation.

Because there appears to be little hope in minimizing, or even slowing down, the projected increase in waste heat rejection from thermal power plants, it is important to consider effects of temperature increases on the aquatic environment. In short, is thermal pollution a serious threat to existing and potential water resources and uses?

THERMAL POLLUTION EFFECTS

It is important at this point to dispel any notion that general temperature increases in the aquatic environment can ever be described as "thermal enrichment." Not that temperature increases under certain circumstances cannot be considered beneficial--they are. The danger in using a term like "thermal enrichment" lies in the hazardous conclusion that only excessive temperature increases are bad. While we argue over what constitutes an excessive temperature increase, disaster may strike in the form of fish kills, unwanted algal blooms, or unacceptable water supplies for specific municipal and industrial uses. With this in mind, the following paragraphs include examples of specific physical, chemical, and biological responses to thermal pollution.

Gas solubilities are inversely proportional to water temperature; the saturation level for dissolved oxygen (DO) is reduced 50 percent with a water temperature increase from 32 ^{o}F to 90 ^{o}F; almost 0.1 mg/l per 1 ^{o}F temperature rise. Dissolved nitrogen behaves similarly to small increases in water temperature and with lethal effects to fish under conditions of dissolved nitrogen supersaturation.

Water temperature increases have the same effect on a stream's dissolved oxygen resources as organic loadings from sewage treatment plants. The Ohio Basin Region, FWPCA, calculated this effect on the Ohio River as shown in Table 2.[9] From Table 2 it is seen, for example, that flow requirements to maintain 5.0 mg/l of DO increase about 50 percent between 80.6 ^{o}F and 86 ^{o}F. This adverse response to temperature increases is explained as a lopsided balance among accelerated decomposition of organic materials, decreased DO saturation levels, and increased surface reaeration rates.

TABLE 2

CALCULATED FLOW REQUIREMENTS
FOR VARYING LEVELS OF TREATMENT EFFICIENCY
AND WATER TEMPERATURE; OHIO RIVER

Treatment Efficiency %	Required Flows at Given Temperatures - cfs							
	68 °F		80.6°F		86 °F		91.4 °F	
	(1)*	(2)**	(1)	(2)	(1)	(2)	(1)	(2)
92	280	529	664	1282	919	1748	1216	2422
95	235	351	324	693	370	1063	585	1552
98	185	299	256	425	292	502	339	606

* (1) Minimum DO objective = 4.0 mg/1

** (2) " " " = 5.0 "

The interaction of these phenomena has been related mathematically by a number of researchers to show the response of receiving stream DO levels to water temperature-flow-organic loading conditions. In one of these studies, Dysart notes that "In a river basin which receives significant amounts of both heat and BOD, it is possible, for example, that increased overall economic efficiency might be attained by cooling thermal wastes to a greater extent than required simply to meet the stream's temperature standards, thereby decreasing treatment costs for organic wastes."(10)

Water temperatures influence algal populations directly according to the following temperature preferences:(11)

diatoms (Chrysophyta) - 59 to 77 °F

greens (Chlorophyta) - 77 to 95 °F

blue-greens (Cyanophyta) - 96 to 104 °F

The blue-greens are particularly unacceptable as a group; consequently, a shift in population dominance to blue-greens is considered adverse.

Most saprobic bacteria (responsible for decomposition of organic materials) and parasitic bacteria are below their optimum temperature ranges at normal water temperatures in the United States.[12] Parasitic bacteria, particularly, prefer temperatures from 86 to 104 °F. Consequently, water temperature increases favoring these undesirable bacterial forms must be considered adverse.

Temperature effects on fish and shellfish are numerous--too numerous to discuss in detail here--and can be categorized according to life stage and geographical distribution of individual species. In a presentation before the ORSANCO Engineering Committee, the National Water Quality Laboratory, FWPCA, Duluth, stated: "...a family of curves must be developed to represent annual temperature regimes and to identify desirable fish species able to thrive under each of these temperature regimes."[9] The Columbia River Thermal Effects Study, scheduled for completion this June, has coordinated 24 research studies on anadromous fish responses to temperature changes. This has been a cooperative program of the Atomic Energy Commission, the Bureau of Commercial Fisheries, and FWPCA under the leadership of the Northwest Regional Office, FWPCA.

In their recommendations for thermal pollution control in Biscayne Bay, the Hoover Foundation included arguments based on (1) avoiding disturbance of natural temperature changes resulting in potential "biological deserts;" (2) avoiding the disruption of delicate balances in the biotic food chain and predator-prey relationships; and (3) the slow, complex, insidious nature of many biological responses to water temperature changes.[13]

Finally, the National Technical Advisory Committee discussed available knowledge on water temperature requirements for specific users in their Water Quality Criteria Report of 1968.[14] These requirements, many of which are reflected in State-Federal Water Quality Standards criteria, are simply not compatible with indiscriminate discharges of cooling water from thermal-electric power plants. It is for the reason that waste heat treatment must be included as an integral function of most future power plants, and as an added function to many existing plants.

WASTE HEAT TREATMENT

For thermal-electric power plants located on inland fresh waters, there are only two practicable alternatives for waste heat treatment at the present time--cooling ponds and cooling towers. As implied above, direct discharge of condenser cooling water to receiving streams with inadequate dilution should not be considered as an acceptable alternative. In fact, in many locations, the cooling water cycle should be "closed" with no residual waste heat discharged to the receiving stream. Hauser concluded in his presentation before the American Power Conference that by the end of the 1970's the only once-through cooling sites available will be on the sea coasts, serving 30 percent of the projected power needs. Therefore, 70 percent of new baseloads at that time will require some form of waste heat treatment.(3)

Cooling ponds can be a relatively low cost, effective, multi-purpose mode for waste heat treatment. Generally speaking, cooling ponds can be specifically designed impoundments for this purpose or result from effective utilization of existing impoundments. In either case, they can serve other functions, including recreation, sports fishing, and flow regulation for downstream users. In terms of overall impact on the environment, cooling ponds are definitely recommended.

Cooling ponds specifically designed for this function should be channelized to maintain "flow through" circulation, thereby taking advantage of the exponential relationship of heat dissipation to water surface temperature. Required surface area for these "flow through" cooling ponds can be estimated as follows:(15)

$$A = \frac{Q}{k} \ln \frac{(\Delta T_o)}{(\Delta T_d)} \quad ; \text{acres}$$

where

Q = cooling water flow; AF/day

k = heat transfer coefficient (2.0 ft/day, for example)

ΔT_o = temperature rise across the power plant; ^oF

ΔT_d = temperature difference between pond discharge and plant intake; ^oF

For a 1000 MW power plant (Q = 2000 AF/day, ΔT_o = 30 ^oF and an acceptable residual temperature (ΔT_d) of 3 ^oF, the calculated surface area is 2300 acres. This is close to a commonly used yardstick estimate based on two acres per MW, or 2000 acres total for a 1000 MW plant.

For comparison, the required surface area for a completely-mixed pond (uniform temperatures throughout) can be calculated as follows:

$$A = \frac{Q}{k} \quad \frac{(\Delta T_o)}{\Delta T_m} - 1$$

where ΔT_m = difference between pond temperature and plant intake temperature; ^oF

Calculated surface area for the same 1000 MW plant would be 9000 acres; consequently, the recommendation to design for "flow through" circulation insofar as possible.

For most cooling ponds, the circulation patterns will be somewhere between "flow through" and "completely mixed." Theoretically, then, the average cooling pond should be larger than 2000 acres for a 1000 MW plant. In fact, however, the design engineers may compensate to some extent for pond circulation pattern handicaps by concentrating power plant discharges at the water surface. The heated surface layer takes additional advantage of the exponential temperature-heat dissipation relationship. Induced stratification offers a second advantage of permitting cooler water withdrawals at power plant intakes located on the pond bottom.

Where adequate land is unavailable for cooling ponds, wet-type cooling towers are an acceptable, moderate cost alternative for waste heat treatment. The functional parts of wet cooling towers used in large power plant installations include (1) inlet water distribution system; (2) a "packing" layer to increase water-air contact surface area; (3) inlet air louvres; (4) "drift" (carry-over of water droplets with tower vapor) eliminator vanes; (5) cooled water basin; and (6) air movement equipment. Mechanical draft towers regulate air flow by means of large fans. Natural draft towers (commonly hyperbolically shaped) induce air flow by density differences between the air-water vapor mixture inside the tower shell and ambient air.

Both mechanical and natural draft towers, with numerous variations, can be designed to effectively "treat" power plant cooling water. (8), (12), (16)

Of special interest to us at this point are the costs of waste heat treatment, particularly in response to allegations that economical arguments preclude effective thermal pollution control. The most comprehensive document available at the present time on environmental considerations of waste heat treatment is "A Survey of Thermal Power Plant Cooling Facilities."[17] The survey participants concluded that properly designed and operated cooling ponds and towers do not contribute significantly to ground fogging or icing conditions; overall environmental effects are entirely acceptable. Their conclusions were generally supported in a report by power company officials entitled "Field Investigations of Environmental Effects of Cooling Towers for Large Steam Electric Plants."[18]

The cost of waste heat treatment alternatives has been widely reported on. (3), (8), (19) Tichenor summarizes the cost calculations in the most meaningful form...estimates of increased cost to the consumer.[19] Table 3 shows that the increase in cost of electricity to the consumer for waste heat treatment over once-through cooling with fresh water will range from 1 to 3 percent. Hauser concludes that: "The economic penalties associated with alternative cooling systems will not deter the electrical generation growth in this country."[3] From the increased costs shown in Table 3, I believe this to be a reasonable conclusion.

TABLE 3

AVERAGE U. S. CONSUMER COST INCREASE
FOR WASTE HEAT TREATMENT
OVER ONCE-THROUGH COOLING WITH FRESH WATER (%)

Cooling System	Consumer Type: Industrial	Commercial	Residential
Once-through with salt water	0.34	0.16	0.14
Cooling ponds	0.94	0.43	0.39
Wet-mechanical draft towers	3.17	1.41	1.28
Wet-natural draft towers	1.48	0.68	0.62

Of course, the idealistic approach to thermal pollution control is through waste heat utilization as discussed below.

WASTE HEAT UTILIZATION

Potential uses of nuclear waste heat were presented and discussed in a report of the AUA-ANL Engineering Practice School, Argonne National Laboratory.[20] Existing uses included regulation of water temperatures in fish hatcheries and warm water irrigation. Potential uses included space heating with steam or hot water; refrigeration; desalination; food processing; chemical processes; metallurgical processes; agriculture; sewage treatment; and heat engines. The overall prognosis of this study group for large scale waste heat utilization was not very optimistic. The usual problems included poor quality of the available waste heat; unfavorable geographic limitations; conflicts in power plant and "user industry" load factors; and limitations of individual industries to handle such large quantities of heat and/or volumes of water.

Warm water irrigation is the subject of study and experimentation in the Northwest. The Eugene Water and Electric Board has initiated studies using hot water from a Weyerhaueser pulp mill for multi-crop experimentation on six separate farms. Cold water "control" plots serve as the basis for judging effects of heated water over water at natural temperatures. Results to date have been encouraging, but inconclusive. Oregon State University scientists are experimenting with the effect of soil heating (electrical cables 6 ft. apart at 3 ft. depth) on growth rate and quality of tomatoes, strawberries, sweet corn, field corn, alfalfa, bush beans, lima beans, and soy beans. Compared to unheated control plots, the heated plots yielded healthier, more uniform plants and faster growth rates.

Joyner discusses the advantages and potential for utilizing waste heat for the promotion of shrimp and lobster production in Puget Sound.[21] Again, the prognosis for large scale benefits from this type of waste heat application is not promising.

A comprehensive discussion of waste heat utilization can be found in the Office of Science and Technology Report, "Considerations Affecting Steam Power Plant Site Selection."[22] Detailed presentations are included on multi-purpose plant siting including power reactors in combination with desalination plants, major industrial processes, and agro-industrial processes.

Overall, it must be concluded that waste heat utilization will not alleviate thermal pollution problems significantly in the foreseeable future. Research and development in this direction is continuing, however, and is a commendable effort.

THERMAL POWER PLANT SITING CRITERIA AND PROCEDURES

At this point it is clear that the problem of pollution from thermal-electric power plants must be faced--squarely and effectively; ignoring this problem or delaying positive action is certainly inadvisable. We have several considerations to summarize from the above sections:

1. The rapidly expanding need for thermal-electric power;
2. The huge quantities of waste heat rejected by fossil and nuclear-fueled power plants;

3. The limited need for waste heat utilization;
4. The dramatic, albeit insidious, effects of thermal pollution on the aquatic environment;
5. The availability of economic means for waste heat treatment;
6. The approved State-Federal water quality standards criteria and requirements for implementation.

Obvious conclusions to be drawn from these considerations include:

1. Thermal power plants must be located, designed, and operated to assure protection of existing and future water resources and uses;
2. Indiscriminate discharge of "untreated" cooling water to inland streams is generally incompatible with standards criteria and should be avoided.
3. Power planners should consider environmental effects and constraints early in their site studies to avoid unnecessary loss of time and money spent on sites and plant designs unacceptable to the responsible regulatory agencies.

Because of the appropriateness to this presentation, the following quotations have been extracted from the paper by Morgan and Bramer:(4)

> "When several alternative sites are being evaluated... thermal pollution considerations might be of great importance in final selection of a site."
>
> During pre-site selection surveys..."Present and projected availability and quality of water for generation and cooling, as well as site suitability for reservoirs, cooling towers, etc., should be determined."

> "It is not necessary, of course, that pollution abatement requirements be economically justified..."

> "It is apparent...that the average fisherman...is not likely to be much impressed by increased electric costs due to pollution abatement. The required 1.3 billion dollar investment in thermal effluent control does not appear to be excessive if any substantial increase would thus be realized in a seventeen billion dollar annual business."

> "Baseline ecological and engineering studies should precede land acquisition or construction planning."

The subject of power plant siting is presented in broad perspective in "Considerations Affecting Steam Power Plant Site Selection."(22) A specific problem discussed in this report is the lack of Federal licensing authority with the responsibility for assuring compliance with interstate water quality standards criteria on temperature. Pending legislation in Congress (S7 and HR 4148) would compensate for this deficiency by requiring: "Any applicant for a Federal license or permit...shall provide...certification from each State or interstate water pollution control agency... that such activity will not reduce the quality of such waters below applicable water quality standards." Properly implemented, this requirement would provide the needed vehicle for minimizing damage to the aquatic environment from thermal pollution.

A final word of caution. Experience to date has shown that the power companies are not taking full advantage of the available State and Federal resources in preliminary power plant site studies. Power companies are too often committing themselves on site selection, including land acquisition, before consulting with the environmental and/or regulatory agencies on the environmental acceptability of a site. This can and should be avoided by soliciting from the responsible agencies a recommended list of information needed by the agencies in their evaluation of proposed power plant sites. The utilities would then satisfy themselves that the needed information is compiled and made available to the regulatory agencies before committing themselves on a site selection. With this information, the responsible agencies can act promptly and fairly in arriving at their decisions on site acceptability based upon the criteria of established water quality standards.

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