25 January 1980, Volume 207, Number 4429 SCIENCE

Power Plant Cooling Systems: Policy Alternatives

John Z. Reynolds

Summary. Policies and pressures emanating from the 1972 Amendments to the Federal Water Pollution Control Act favor the installation of cooling towers, or closed-cycle cooling systems, in power plants. An assessment of the relative risks of alternative cooling system designs indicates that, in general, adverse environmental effects associated with cooling towers are more certain, are of larger scale, and are more likely to be irreversible than impacts associated with once-through cooling systems and cooling reservoirs. Adverse environmental effects associated with once-through cooling and cooling reservoirs are largely amenable to mitigation in the context of resource management principles. These factors, together with the greater costs associated with cooling towers, indicate that wherever the feasibility is demonstrated and there is minimal risk to aquatic ecosystems, once-through cooling systems or cooling reservoirs should be preferred.

The controversy regarding the environmental effects of power plant cooling systems has been shaped by many factors and events. In retrospect, the controversy probably has characteristics similar to many other public issues. On a technical level, erroneous information and faulty hypotheses continue to be factored into deliberations and tend to distort efforts to balance all available evidence. On an institutional level, organizations that were mobilized or developed to respond to nebulous or poorly defined problems tend to resist conceptual modifications that could lead to changes in direction. The "weight of evidence" approach to environmental assessment could help to rectify this situation by providing a clearer perspective of the relevant issues. This approach has increasing validity and utility as the state of the art increases and more advanced studies are directly responsive to established concerns. The limitations of resources and widespread skepticism regarding the legitimacy of many environmental claims, if one considers the relative costs and benefits, make it imperative that responses to environmental concerns transcend inappropriate constraints in balancing risks and environmental objectives (*1*).

Background

Conventional steam-electric generating stations require water to cool and thus condense the steam (*2*). The quantities of water necessary for this purpose are very large in comparison with most other water uses, and the temperature of the circulated water is typically raised 5° to 20°C above the intake temperature. For a given plant the total amount of heat rejected remains relatively constant, so that decreases in the temperature rise must be accomplished by increasing the flow of the cooling water.

Cooling systems are classified according to their basic components and types. The components, common to all types, include an intake, pumps, condenser, and discharge, all connected in series. The basic types are once-through, cooling lakes or reservoirs, and closed-cycle. For closed-cycle systems, cooling towers in a recirculating mode are usually used, although single-purpose cooling impoundments, spray ponds, and other systems closely connected with and optimized for plant operation may also be considered closed-cycle. Figure 1 shows the percentage of each type of cooling system in the United States by increments of capacity associated with various time periods since 1970 (*3*).

Prior to 1970 most power stations were constructed with once-through cooling systems. State pollution control agencies were typically given the authority to deny water use permits where significant environmental degradation would be expected to occur. In many instances, the maximum allowable temperature of the water in the receiving body was prescribed, with various criteria applied to the water in the mixing zone, that is, the area of interface between the water being discharged and the ambient water.

Federal oversight of state water quality standards was initiated in the late 1960's (*4*). One overriding concern was introduced into the standard setting process at that time, namely that temperatures in areas where biota may be exposed should be limited to levels that are proved not to be harmful to the subject organisms. This narrowly construed policy readily became a constraining objective to state agencies charged with achieving environmental protection and resource management goals in a broad context.

The difficulties this presented in administering state water temperature standards were apparently misinterpreted in the analysis of regulatory policy that led to the 1972 Amendments to the Federal Water Pollution Control Act (*5*). In addition to retaining the established format for water quality standards, the 1972 Amendments and subsequent regulations introduced two new concepts to

The author is director of environmental services, Consumers Power Company, Jackson, Michigan 49201; when this article was written he was a project manager for the Ecological Effects Program at the Electric Power Research Institute, Palo Alto, California 94303.

0036-8075/80/0125-0367$01.50/0

deal separately with other effects on aquatic life that may be caused by cooling systems. The 316(a) provision recognized that, in addition to the discharge temperature effect, organisms may be entrained in the cooling water and otherwise be affected by exposure to the power plant cooling system. Section 316(a) requires that an analysis be made of the thermal component of a discharge to assure that effects will not preclude the "protection and propagation of a balanced, indigenous population (community) of shellfish, fish and wildlife" of the subject water body if the use is to be allowed (*6*).

Through section 316(b) another constraint was introduced into system design to provide maximum protection for aquatic organisms that might be influenced by the intake. The highly visible aspects of fish impinged on intake screens was probably the motivating factor. In any event, this section requires that "the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact" (*7*).

The U.S. Environmental Protection Agency (EPA) has issued regulations and guidelines to implement these and other sections of the 1972 legislation. Closed-cycle cooling (cooling towers) was selected as "best available technology" for thermal effluent control in regulations promulgated on 3 October 1974 (*8*). (These were subsequently remanded by court action and have not been repromulgated to date.) Old units (any unit in service before 1 January 1971, or any unit less than 500 megawatt-electric in service before 1 January 1974) were exempt from this technology requirement.

These regulations have tended to obfuscate rather than clarify the planning needs for power plant cooling systems. For example, rigid limitations on discharge temperature may be counterproductive to controlling entrainment effects or meeting intake design criteria because reduced temperatures are most readily accomplished by increasing intake flow. In some cases, such as where ambient temperatures are near the lower thresholds, protection and propagation of various desirable species may be enhanced by power plant effects. Such benefits would not be allowed with the use of only hardware-based technology criteria developed without consideration of local conditions (*9*). And, although the state of the art of hardware development can be readily defined at any time, environmental associations are quite variable and are less predictable, and thus tend to be discounted as the most conjectural aspect of comparative assessments. Advances in both technology and assessment methodology can mean that evaluations conducted in the early stages of planning become outmoded during later stages of project development (*10*).

Overriding all of these considerations, theoretically, is the mandate of the 1969 National Environmental Policy Act (*11*). This act requires a consideration of all available alternatives in the context of protecting and enhancing the quality of the human environment. If one considers the contradictory aspects of the existing policy concerning cooling systems, and the relatively limited issues emphasized therein, it appears that a thorough reassessment of cooling systems policy in the context of this act is necessary.

The past decade has been a period of inquiry, debate, and consternation on the part of the electric utility industry and others attempting to address a succession of criticisms of the conventional methods of cooling system design. Recent annotated bibliographies on the subjects of thermal effects (*12*), impingement (*13*), entrainment (*14*), and chemical effects (*15*), list 3950, 657, 607, and 950 references, respectively, through most of 1977, and the bulk of these references are to studies conducted in the past 10 years. The resources that have thus been committed to studies of the environmental aspects of cooling systems amount to hundreds of millions of dollars. Although one may argue that many of these efforts were wasteful, poorly designed, poorly motivated, self-serving, or otherwise ill-conceived, they have,

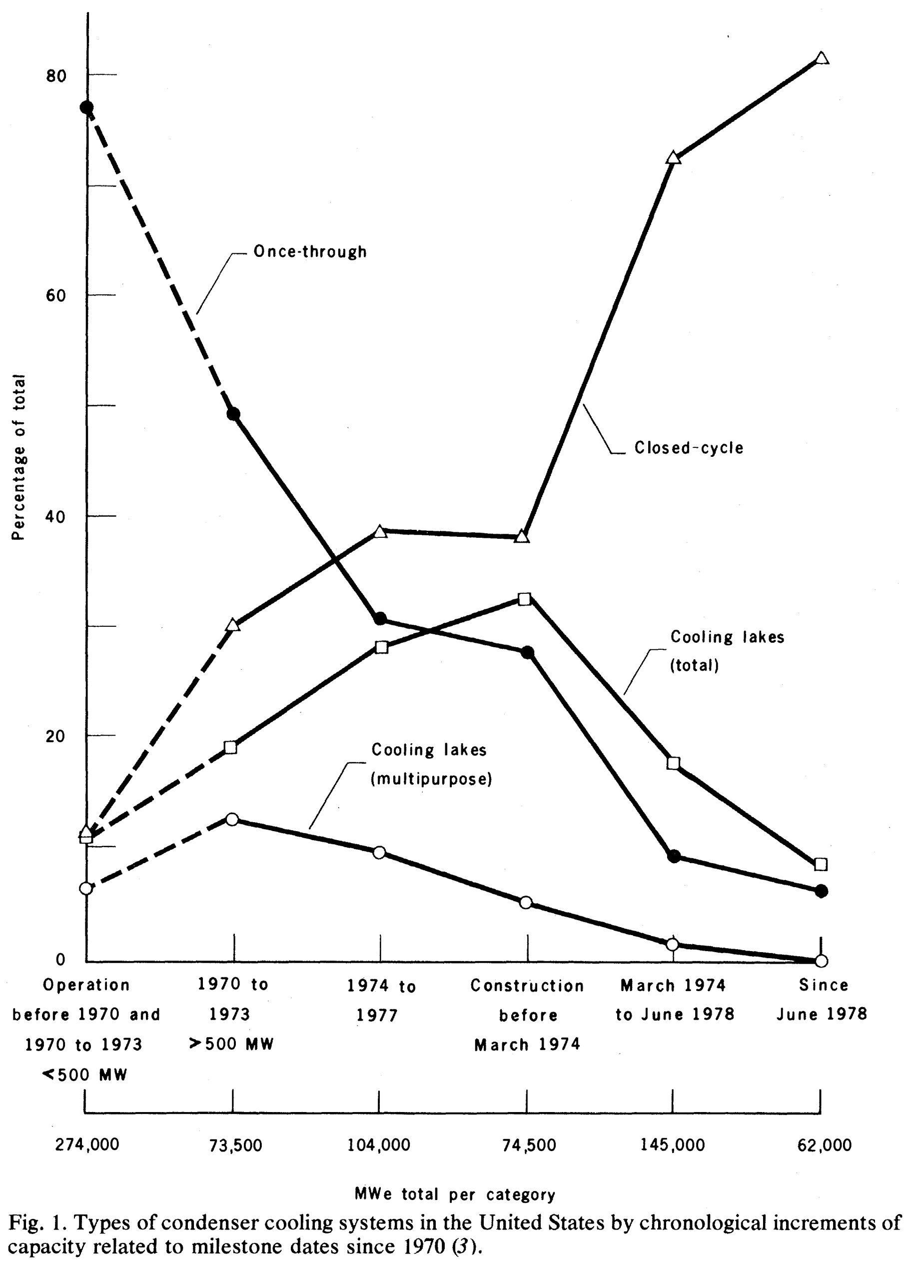

Fig. 1. Types of condenser cooling systems in the United States by chronological increments of capacity related to milestone dates since 1970 (*3*).

nevertheless, provided a substantial storehouse of information on which a more enlightened perspective may be based. In the following sections I address some of the key issues and suggest an alternative method for interpreting the weight of evidence.

Water Quality

Considerations of water quality have been prominent in the study of cooling system effects and in the development of cooling system regulations. When the first water quality standards were developed it was recognized that temperature changes in receiving water bodies could have profound effects on physical, chemical, and biological processes affecting water quality (*16*). Subsequent studies identified possible hazards to aquatic life associated with the release of toxicants discharged incidental to the cooling process, primarily biocides (normally chlorine) used to prevent fouling of intakes and condensers with organic matter (biofouling) and metals associated with corrosion and erosion of condenser tubes.

One type of water quality effect might be exhibited in dissolved oxygen and total dissolved gas concentrations, because of the direct effects of temperature on gas saturation values and on biochemical reaction rates and physical exchange processes. Secondary effects would involve relative differences in chemical oxidation states, such as increased oxidation of ammonia to nitrate. Comprehensive studies have demonstrated, however, that temperature effects on the common water quality variables will be insignificant where the discharge represents a relatively small fraction of the receiving water volume or flow (*17*). This is not surprising because, with dilution, the resulting water temperatures remain within the limits of natural variability.

The question of biocides and other toxicant effects is much less certain and involves the introduction of foreign substances. Chlorine gas or chlorine compounds have commonly been used to prevent biofouling of cooling system surfaces that would adversely affect flow or heat transfer and thus lower plant efficiency. The normal practice is to add chlorine intermittently, perhaps for 1/2 hour per day, with relatively greater amounts or frequency of application being required during warm-weather periods and in highly productive waters.

Regulations now limit the residual concentrations of chlorine as well as the duration of chlorine application, but it is in the interest of both the regulator and the utility to limit usage to the optimum level required for biofouling control (*18*). Although residual toxic effects in water bodies have not been observed at the levels of chlorine currently applied, concern about long-term toxicity, perhaps through the formation of halogenated organic compounds, will remain an issue. This matter should not, however, weigh heavily in an evaluation of alternative cooling systems. Other approaches are available to control biofouling, where necessary, and the need to control these growths is common to all systems (*19*). The control of biofouling of cooling towers is an additional problem, however, and the need for chemical treatment to control scaling and corrosion makes the question of ultimate disposal of residual chemicals more difficult for these systems.

Closed-cycle systems also result in the concentration of water contaminants that may be present in the source water body. Evaporation of water in these systems commonly results in concentration factors 2 to 10 times above ambient, with the result that many constituents in the discharge water may approach or exceed the recommended limits (*20*). This possibility is related to site considerations that cannot be controlled by the plant operator and, therefore, presents substantial uncertainties in the environmental comparison of alternative systems.

Intake Effects

In most instances, on the basis of the relative volumes required one would expect closed-cycle cooling systems to have less impact as a result of water withdrawal than alternative cooling systems. Make-up water volume to replace evaporation and other losses in closed-cycle operation is generally more than an order of magnitude less than that required for once-through cooling (*21*). Accordingly, aquatic life in the source water is less subject to risk of impingement or entrainment if the intake volume is minimized.

The total effect of each of these alternatives is not easy to define, however, and must ultimately be considered in conjunction with site and plant characteristics. For example, entrainment of organisms in a cooling tower represents a 100 percent loss compared to selective cropping of a lesser percentage of organisms, typically less than 30 percent, in a once-through system (*22*). In addition, intake designs are available to control or virtually eliminate losses through impingement, although not without substantial cost and possible operational difficulties (*23*).

Entrainment or impingement of any magnitude does not translate directly into impact on populations, aquatic communities, or ecosystems. Numerous approaches have been used to relate or place in perspective the relative significance of potential losses on aquatic resources (*24*). Losses of fish food organisms have often been compared to total available biomass or related to energy flow at the intertrophic level. Losses of fish have been translated by various population-production models to effects on available stock or harvest. These and similar approaches all involve judgments and assumptions that depend, at least partially, on the state of the art and thus soften the degree of objectivity that is possible.

The degree of confidence one may place on such assessments, however, is not as limiting as a rigorous appraisal of the state of the art might suggest. While the complexities of ecosystem behavior may be beyond our abilities of comprehension, the effects of cooling systems can be related to other effects in a resource management context. Models applied in this context can provide very useful insights into the relative effects of power plant interaction and, in particular, the relative significance of effects of alternatives and the directions of secondary responses. To the extent that conclusions can be thus derived, the need for deterministic solutions may be lessened.

In suggesting the resource management approach, it is assumed that the water bodies potentially affected are already significantly perturbed by development, water use, or some level of resource exploitation or management. Relatively pristine and remote water bodies would not normally be considered as likely candidates for cooling system water use in any case.

The resource management approach to evaluating the significance of environmental effects is not new and has consistently been applied in matters affecting terrestrial habitat and wildlife populations. Preference for a more deterministic, and normally more rigorous approach for evaluating the significance of aquatic effects is difficult to justify in view of the relative refinement of the available assessment methodologies (*25*).

One might argue that a minimal impact approach is preferable for highly utilized waters in the belief that within a reasonable period natural populations will be reestablished and virtually any unnatural perturbation would cause an undesirable shift. For most water bodies, however, this notion is untenable because of the irreversible nature of changes that have occurred and the improbable likelihood that, even under favorable, abiotic habitat conditions, any preexisting population structure could be restored. A positive approach, of course, could work to enhance the resource toward some desired condition.

Although there may be some theoretical basis for advocating the necessity to keep impingement and entrainment to a minimum, because incremental cropping may place finite populations at risk, zones of thermal effect and habitat modification cannot be considered in this context.

Thermal and Habitat Effects

The relative significance of thermal and habitat effects, because they involve artificial changes and perhaps result in the introduction of new populations, is related in substantial measure to functions of the scales of comparison. The many studies that have been conducted on thermal effects and habitat changes indicate that the resultant impacts are, in general, neither incompatible with the maintenance of existing populations nor likely to cause effects beyond localized areas (*26*). Such a sweeping generalization requires some qualification, and many scenarios can be described to dramatize adverse effects. The term scenario is used advisedly because, somewhat in the context of rare events, the sequence of effects, the duration of the offending conditions, and the probability of their occurrence are such that widespread repercussions are unlikely.

This is especially true when one considers thermal effects. Motile aquatic organisms, such as fish, are attuned to environmental temperature gradients and actively avoid adverse conditions and respond positively to conditions that are preferred. Whether or not this may be detrimental to the affected organism with regard to such factors as abnormal metabolism and reproduction, disease, predators, biocide exposure, and vulnerability to rapid temperature fluctuations, has been extensively debated. That such effects may occur has been demonstrated by controlled experiments, but the effects have rarely been observed in field studies, indicating that within the limits of field monitoring programs adverse effects in the natural environment may be difficult to identify.

Because individual aquatic organisms will be adversely affected under some conditions, and because habitat modifications may produce undesirable changes on a local scale, it is necessary to evaluate the potential impacts in the context of the resource base. Even though it may be possible to demonstrate that the effects of the power plant are relatively insignificant compared with other factors, the effects can be mitigated, if necessary, by operational changes, design modifications, or direct management intervention. The most efficacious approach is clearly dependent on site and plant conditions.

Cooling Reservoirs

In the foregoing discussion I alluded to certain aspects of laboratory and field studies that may be applied to the documentation of cooling system effects. Field studies involving relatively large water bodies and migratory populations are not practical for measuring impacts or quantitatively validating cause-effect relationships. Cooling lakes or reservoirs, in contrast, provide convenient field laboratories for examining effects that are impractical to investigate any other way. Many cooling lakes are sufficiently large to exhibit characteristics of typical lake ecosystems, but are self-contained to the point where population characteristics can be well-defined and interactions within and among trophic levels identified.

In most studies of cooling lakes the investigators have concentrated on assessing the status of fish stocks. Power plant operations have been shown to result in shifts in relative abundance of some species, but the net effect in projects designed to accommodate a fishery has usually been an enhancement of fish production (*27*). Comprehensive studies of cooling lakes have similarly shown shifts in species abundance at other trophic levels, but structural and functional aspects of the systems remain intact, in relative conformity to conditions in noncooling lakes (*28*).

Evaluation of cooling lake ecosystems under a variety of design and operating conditions, with differing relative intensity of use for power plant cooling, can provide data for extrapolation to once-through cooling water bodies. Conceptually, it can be argued that because cooling lake populations will experience all of the insults associated with once-through cooling, effects of a comparable plant on similar populations in a larger natural water body would be no greater than those observed in the cooling lake.

Any assessment of the impact on a cooling reservoir must also take into account other effects associated with site development. If a stream is flooded, the existing terrestrial and aquatic populations will be replaced or modified in accordance with the new habitat. These effects are commonly offset by provisions being made for the "resource" used for other purposes. In a recent survey of 108 cooling reservoirs in existence, under construction, or planned, the following multiple purpose features were identified: public access (70 percent), public recreation (63 percent), shoreline development (30 percent), municipal water supply (20 percent), industrial water supply (9 percent), irrigation supply (5 percent), flood control (20 percent), and hydroelectric power (8 percent) (*29*). Thus, to a large extent, cooling reservoirs can be designed and managed to accomplish many socioeconomic and resource enhancement objectives.

Terrestrial Impact

Of the various cooling system alternatives, cooling reservoirs clearly require the largest areas of land. Typically, for multipurpose developments, at least 1 acre of land must be inundated for each megawatt of electric capacity. The importance of this requirement is a function of individual site characteristics, and highly productive agricultural land and unique habitats are obviously valued differently than less productive areas.

The effects of cooling tower systems on land resources may also be substantial. The area required for construction may be as great as for other plant features and the material requirements for construction of towers, visual impact, and noise are not trivial. And, infrequently, damage to surrounding vegetation may occur as a result of chemicals in cooling tower drift and icing effects (*30*).

The use of cooling towers does not necessarily preclude development of a reservoir, because in many areas minimum stream flows are too low to allow continuous withdrawal for make-up, and storage must be provided for substantial periods. The reservoir design, again, would be a function of site- and plant-related characteristics, but the implications for environmental impact and effects on other entities may be comparable to a case involving a cooling reservoir.

Once-through cooling systems normally would require the least amount of land, that used being incidental to intake and discharge structures and related appurtenances.

Water Consumption

Water conservation is a theme that is gaining increasing prominence nationwide in the review of water-related projects and activities. As water development possibilities become more limited and competing demands more intense, the areas of the country considered "water-short" expand accordingly. Net water loss, or water consumption, has thus become an important consideration in the evaluation of cooling system alternatives.

All wet cooling systems ultimately rely on transfer of waste heat to the atmosphere. While once-through cooling systems and relatively large cooling reservoirs may reject but 40 percent of the excess heat through evaporation, cooling towers lose approximately 80 percent through evaporation (*31*). One must also take into account, however, water losses associated with natural evaporation, including those from storage reservoirs, in any comparison of site alternatives.

Energy Use and Generation Capability

The higher rates of heat dissipation through evaporation in closed-cycle systems are achieved through greater inputs of energy. Subsequent losses in efficiency caused by these greater energy inputs may also be reflected in losses in generation capability. Two principal factors account for these losses: auxiliary power requirements (pumps and fans, for example) and higher turbine backpressures (caused by the generally greater temperature of recirculated cooling tower water compared to once-through intake water).

Energy and capability losses for closed-cycle systems vary substantially, depending on cooling component design (for example, mechanical as opposed to natural draft tower), plant type (for example, base load as opposed to peak, fossil as opposed to nuclear), and whether the cooling system is retrofitted to an existing plant or optimized in plant design. Estimates of energy losses are in the range of less than 1 percent for new fossil unit alternatives to more than 4 percent for retrofitting a nuclear plant. Capability losses range from about 1.5 percent for new fossil unit alternatives to nearly 5 percent for retrofitting a nuclear plant (*32*).

On a percentage basis these penalties may appear insignificant, but together the impacts are substantial. For example, if one assumes 2 percent average energy and capability losses for a total affected capacity of 200,000 MWe, about 150,000 barrels per day of additional oil equivalent would be required and one complete unit would be needed for every 50 equivalent units constructed with closed-cycle cooling, simply to compensate for energy and capability losses. Environmental and socioeconomic effects associated with this additional energy use and plant construction are not trivial factors in weighing the policy alternatives.

Policy Assessment

The foregoing sections provide a capsulated view of how issues surrounding cooling system policy have developed. A suitable framework for assessing policy, in which the different risks of affecting the environment may be appropriately balanced, has been lacking. One approach might be to consider for each cooling system type, on a relative basis, the types of effects, the likely scale of effects, the certainty of impacts, and the probable irreversibility of impacts or lack of mitigation opportunities.

Cooling towers have, with a relatively high level of certainty, the greatest impact on water quality, water consumption, energy use, and loss of generation capability, with little potential for mitigation within the scale of site development. Cooling reservoirs have, also with a relatively high level of certainty, the greatest impact on terrestrial habitat, but the effect is confined to the local area. The relative impact of cooling reservoirs on aquatic life is less certain, but opportunities for mitigation and reversibility of impact are available and have been demonstrated.

The only area in which once-through cooling systems show a relatively high potential level of impact is that associated with aquatic effects. And, in spite of numerous studies, the relative uncertainty of impact on some aquatic populations will remain high, simply because of the complexity of ecosystem interactions. It is somewhat ironic that the lower the probability of significant impact, the more difficult it is to detect change; this leads to greater monitoring and study effort being required to measure smaller and more trivial levels of impact. In general, however, it has been shown that, where the relative water use is small, the probable impacts are readily reversible or can be mitigated, and the scale of effect can be defined in relation to the water body resource and natural variability of that resource (*33*).

The trends in cooling system installations are obviously not consistent with this appraisal (Fig. 1). Current policy imperatives are directed to the installation of closed-cycle systems and, in addition to the environmental trade-offs, are having substantial ancillary impacts on power plant development and resource management questions. For example, lack of acceptance of once-through cooling contributes to consolidation of capacity in large complexes because the economy of dispersed siting on natural water bodies, where once-through cooling may be feasible, is negated. Also, the inability to develop multipurpose cooling reservoirs means that the benefits they would contribute to other users may need to be provided by other resource management programs and facilities.

When one considers the multitude of site-related factors involved in the selection of cooling system alternatives, it is unlikely that rigid national policy can be responsive or fully responsible. National policy could, however, ensure that risks to environmental values are appropriately considered and that decisions reflect a balancing of these risks. The National Environmental Policy Act could provide an initiative for these types of assessments.

Present trends indicate that the weighing of risks is heavily prejudiced against balanced development of cooling system alternatives, with great potential cost in terms of water quality, water consumption, aquatic resources, energy, and capital. Correction of this imbalance will require policy imperatives that favor once-through cooling and cooling reservoirs where site conditions are reasonably amenable to these types of systems.

References and Notes

1. For contrasting views on environmental costs versus benefits, see "Has environmental regulation gone too far," *Chem. Eng. News* **57**, 24 (23 April 1979).
2. A statistical computer file of all planned and operating steam electric generating stations in the United States is maintained by Atomic Industrial Forum, Inc., 1016 Sixteenth St. NW, Suite 850, Washington, D.C. 20036. Called POWER Database, the file contains technical information on cooling system characteristics and may be searched on request for a fee.
3. Data from National Economic Research Associates, Inc., "Status of present and planned water intake and discharge systems for the electric utility industry: The results of a survey," submitted to the U.S. Environmental Protection Agency (Utility Water Act Group, Hunton and Williams, Richmond, Va., June 1978), table 1.
4. Water Quality Act of 1965, Public Law 89-234.

5. Federal Water Pollution Control Act, 1972 Amendments, Public Law 92-500.
6. Although section 316(a) in (5) limits consideration to effects of the thermal component of the discharge (taking into account the interaction of such thermal component with other pollutants), the EPA guidelines and regulations have required consideration of the integrated effects of cooling system exposure.
7. Although section 316(b) does not specifically require protection for aquatic organisms, the EPA guidelines and regulations have emphasized this aspect of environmental impact.
8. *U.S. Code Fed. Reg.* **40**, pt. 423.
9. The direct trade-off between flow requirement and temperature rise for a given rate of heat dissipation is readily apparent. Other localized effects tend to increase habitat diversity, provide refugia for various species, and otherwise favor certain populations. Discharge canals, for example, are commonly cited as harboring aquatic populations that would otherwise not exist in the region or would be unavailable for possible exploitation.
10. The time involved from initial planning to project operation is currently about 8 years for large fossil fuel plants and 12 years for nuclear plants.
11. National Environmental Policy Act, Public Law 91-190.
12. S. S. Talmadge, C. C. Coutant *et al.*, *Thermal Effects on Aquatic Organisms: Annotated Bibliography* (Oak Ridge National Laboratory, Ecological Sciences Information Center, Oak Ridge, Tenn., published annually since 1972). The number of citations is the cumulative total and does not include pre-1970 literature contained in the computerized data base.
13. M. S. Uziel and E. H. Hannon, *Impingement: An Annotated Bibliography*, Oak Ridge National Laboratory/Atomic Industrial Forum, project RP877 (Electric Power Research Institute, Rept. No. EA1050, Palo Alto, Calif., April 1979).
14. R. F. Carrier and E. H. Hannon, *Entrainment: An Annotated Bibliography*, Oak Ridge National Laboratory/Atomic Industrial Forum, project RP877 (Electric Power Research Institute, Rept. No. EA1049, Palo Alto, Calif., April 1979).
15. D. M. Opresko and E. H. Hannon, *Chemical Effects of Power Plant Cooling Waters: An Annotated Bibliography*, Oak Ridge National Laboratory/Atomic Industrial Forum, project RP877 (Electric Power Research Institute, Rept. No. EA1072, Palo Alto, Calif., May 1979).
16. It was not until the 1972 Amendments to the Federal Water Pollution Control Act that heat was defined as a pollutant, in somewhat the same context as conservative water contaminants. The act did, however, recognize the special nature of temperature considerations in the provision of the variance clause, 316 (a).
17. This question has been addressed in many power plant monitoring programs, particularly for nuclear plants that became operational in the early 1970's.
18. The EPA has proposed that, within limits, power plants restrict chlorination to the "minimum" levels required, and many utilities have conducted studies to accomplish this objective. Savings on chemical usage are achieved when dosage is reduced, but usually at some increased risk that severe biofouling will occur and cause degradation in plant performance.
19. One commonly used alternative involves continuous mechanical cleaning and, in some cases, has eliminated the need for chemical additions.
20. As an example, a significant fraction of water samples from natural sources are found to contain arsenic at concentrations of 10 to 100 micrograms per liter [D. F. Kopp and R. C. Kroner, *Trace Metals in Waters of the U.S.* (Department of the Interior, Washington, D.C., 1967). Proposed limits for arsenic concentrations are an average of 57 micrograms per liter over a period of 24 hours; a maximum of 130 micrograms per liter for the protection of freshwater aquatic life; and virtually zero for the protection of human health because of the expected carcinogenicity of arsenic compounds [see "Water quality criteria, request for comments" *Fed. Reg.* **44**, No. 52 (15 March 1979)]. The quantity of water discharged from closed-cycle systems (commonly called blowdown) varies widely and is determined by the control limits on concentration resulting from evaporation of mineral constituents in the water.
21. A hypothetical 1000-MWe nuclear power plant is estimated to withdraw 2152 cubic feet per second (61 cubic meters per second) for once-through cooling compared to 43 cubic feet per second (1.2 cubic meters per second) for closed-cycle with cooling towers [B. R. Parkhurst and H. A. McLain, *An Environmental Assessment of Cooling Reservoirs* (Oak Ridge National Laboratory, Environmental Science Division, Publ. No. 1042, Oak Ridge, Tenn., 1978), p. 5].
22. Lawler, Matusky and Skelly, Engineers, *Ecosystem Effects of Phytoplankton and Zooplankton Entrainment*, project RP876 (Electric Power Research Institute, Publ. No. EA1038, Palo Alto, Calif., April 1979).
23. S. S. Ray, R. L. Snipes, D. A. Tomljanovich, *A State-of-the-Art Report on Intake Technologies* (Tennessee Valley Authority, Office of Power, Chattanooga, Tenn., October 1976).
24. Lawler, Matusky and Skell, Engineers, "Biological effects of once-through cooling, principles of quantitative impact assessment" submitted to the EPA (Utility Water Act Group, Hunton and Williams, Richmond, Va., 1978).
25. D. H. McKenzie *et al.*, *The Application of Fisheries Management Techniques To Assessing Impacts*, prepared for Nuclear Regulatory Committee (Battelle Pacific Northwest Laboratory, Publ. No. NUREG/CR-0572, Richland, Wash., March 1979).
26. Lawler, Matusky and Skelly, Engineers, "Biological effects of once-through cooling, summary of findings and conclusions," submitted to the EPA (Utility Water Act Group, Hunton and Williams, Richmond, Va., June 1978).
27. C. D. Becker *et al.*, *Synthesis and Analysis of Ecological Information from Cooling Impoundments*, Battelle Pacific Northwest Laboratory, project RP880 (Electric Power Research Institute, Publ. No. EA1054, Palo Alto, Calif., April 1979). This study involved a systematic review of the ecological information available on cooling impoundments in the United States, with a detailed assessment of data from 14 selected impoundments with relatively high power plant heat loads per unit surface area.
28. R. W. Larimore *et al.*, *Evaluation of a Cooling Lake Fishery*, Illinois Natural History Survey, project RP573 (Electric Power Research Institute, Publ. No. EA1148, Palo Alto, Calif., July 1979), in press.
29. Espey, Huston and Associates, Inc., "Cooling impoundments, the use of surface water impoundments for cooling of steam electric power stations—II," submitted to the EPA (Utility Water Act Group, Hunton and Williams, Richmond, Va., June 1978). The figure in parentheses is the percentage of the total number of projects that incorporate the indicated multiple purpose feature.
30. J. J. Rochow, *Environ. Sci. Technol.* **12**, 1379 (1978). This study showed severe vegetation damage up to 92 meters from a pair of mechanical draft-cooling towers in a forest community near the shore of Lake Michigan.
31. Espey, Huston and Associates, Inc., "Cooling impoundments, the use of surface water impoundments for cooling of steam electric power stations—I," submitted to the EPA (Utility Water Act Group, Hunton and Williams, Richmond, Va., June 1978), table 6.2. Predictions of evaporation are quite variable because of complexities introduced by meteorological and operational differences and a lack of consensus on appropriate formulas. A hypothetical 1000-MWe nuclear power plant is estimated to evaporate 18 cubic feet per second (0.51 cubic meter per second) with once-through cooling, compared to 27 cubic feet per second (0.76 cubic meter per second) with cooling towers [see Parkhurst and McLain in (*21*)].
32. Stone and Webster Engineering Corporation, "Thermal control cost factors, report on the capital cost of closed-cycle cooling systems," submitted to the EPA (Utility Water Act Group, June 1978), tables 1-1, 1-3.
33. This concept is inherent in several approaches described in (i) W. VanWinkle, *Assessing the Effects of Power Plant-Induced Mortality on Fish Populations, Proceedings of a Conference* (Pergamon, Oxford, May 1977), and (ii) Lawler, Matusky and Skelly, Engineers, *Methodology for Assessing Population and Ecosystem Level Effects Related to Intake of Cooling Waters*, Project RP876 (Electric Power Research Institute, Palo Alto, Calif., in preparation).