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ENVIRONMENTAL IMPACT AND HYDRAULIC STRUCTURES - CURRENT AND PREDICTED

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DISSOLVED GASES - POSITIVE AND ADVERSE EFFECTS

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Introduction

Oddly enough, the problem to which this paper is addressed is separated into two distinct situations: both deficiency and excess of dissolved gases.

Deficiency of dissolved oxygen (DO) in streams, reservoirs, canals, and estuaries is rooted in the natural process of biological decomposition of organic materials. Manmade wastes have accelerated this action and hydraulic structures have sometimes compounded the problem by limiting natural reaeration processes, concentrating pollutants, etc.

On the other hand, hydraulic structures can be highly efficient aeration devices and in some cases have caused supersaturation of dissolved gases with the associated problem of gas embolism in fish.

In either event, water quality criteria present difficult challenges to hydraulic engineers.

Research in the effects of hydraulic structures on dissolved gases is active, but apparently inadequately supported in view of the magnitude of the problems. The Federal Interagency Steering Committee for Reaeration Research was formed in late 1971 for the purpose of coordinating Federal research in this

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field. This paper reflects conclusions reached by that committee as well as personal opinions of the author.

Dissolved Oxygen Deficiency

Hundreds, perhaps thousands, of miles of waterways are deficient in DO, as defined by water quality standards. Causes of this deficiency are mentioned above. Effects include reduced capacity for waste assimilation and impairment or destruction of sport and commercial fisheries.

Typical examples of the deleterious effect of hydraulic structures on the DO content of a waterway occur at numerous locations. Hypolimnion waters (bottom layer) of deep reservoirs often become nearly devoid of DO due to biological degradation of natural or waste organic matter on or near the bottom. Natural annual or semiannual turnover of a stratified reservoir normally replenishes the DO content in the hypolimnion. However, in some cases, a rapid rate of oxygen depletion may result in serious DO deficiency before the next period of turnover. In a few very deep reservoirs, concentrations of dissolved solids cause a sufficiently stable density difference to inhibit complete turnover even when the reservoir is isothermal resulting in a year-round condition of zero DO in the hypolimnion.

Oxygen deficiency in reservoirs reduces the extent and quality of the reservoir fishery. Furthermore, release of these low-DO waters from low-level outlets or turbines transfers the problem to the tailrace. Tranquil streams downstream from dams may never recover from this effect.

Treatment of either the reservoir or the tailrace thus becomes necessary to restore the DO to an adequate level.

Reservoir Reaeration

Several methods are available for reaeration of reservoirs (Ref. 4). artificial destratification has been widely used for reaeration of many small and a few moderate-size impoundments. Circulation of bottom waters to the surface by air diffusers (Ref. 1), mechanical pumps, or hybrid devices allows atmospheric replenishment of the oxygen supply. Unfortunately, the inherent low efficiency (less than 1 percent of the input energy is utilized in changing the stability of the reservoir) makes application of this technique to large reservoirs very expensive.

Bubble diffusers using either air or molecular oxygen may also be used for direct oxygen transfer. The use of molecular oxygen is presently being developed by TVA for application in a large reservoir.

Where it is desirable to maintain a cold-water release, complete dissolution of the bubble while still in the hypolimnion allows reaeration without destroying stratification. Special devices have been developed to allow oxygen transfer and circulation in only the hypolimnion (Ref. 7).

Tailrace Reaeration

Numerous devices and methods are available for this purpose (Ref. 4). Air or molecular oxygen may be injected in turbine penstocks or draft tubes (Ref. 5) with care taken to avoid rough operation and loss of efficiency of the turbines. Possible corrosive effects, particularly when using molecular oxygen, should be considered. Devices such as a downflow-bubble-contact system (Ref. 7) might be placed in the penstock or in a bypass to supersaturate a portion of the flow for later mixing with the main flow.

Within the tailrace channel, diffusion of air or molecular oxygen, mechanical surface aerators, and U-tubes may be considered.

Gates and valves (Ref. 2) and associated energy dissipators (Ref. 3) are often highly efficient reaeration devices and require no auxiliary power for operation. However, nitrogen supersaturation and its associated problem may occur as discussed below.

Supersaturation

Supersaturation of dissolved gases occurs when bubbles of air are subjected to pressures exceeding atmospheric pressure. For example, gas under an absolute pressure of 2 atmospheres (at sea level) would theoretically be supersaturated 200 percent with respect to the atmosphere. Thus, bubbles submerged only 3.4 (1.1 atmospheres) feet could theoretically be supersaturated at 110 percent.

In practice, these levels are not found because gas transfer is dependent upon time, temperature, dissolved solids, pollutants, and other factors. Furthermore, turbulence exposes the supersaturated water to the atmosphere and allows some of the dissolved gas to escape. In one Bureau of Reclamation test, an aerated jet plunging into a pool approximately 50 feet deep resulted in a supersaturation level of about 110 percent. The stilling pool was extremely turbulent with violent action on the surface. On the other hand, at the same location, air injected into a turbine and carried to a submergence of about 40 feet in the draft tube, then released into a tranquil tailrace, caused up to 130 percent supersaturation.

The supersaturation values expressed in the preceding paragraph are for total dissolved gases. The supersaturation levels of DO and dissolved nitrogen are normally equal to the total dissolved gas supersaturation level. Absolute concentrations are determined by the partial pressures and relative occurrences of the gases in air (78 percent nitrogen, 21 percent oxygen, and 1 percent trace elements).

The problem associated with dissolved gas supersaturation is gas embolism or gas-bubble disease in fish. Exposure to certain levels of dissolved gas supersaturation for required lengths of time causes bubbles to form in blood vessels. Fish affected by this disease exhibit bubbles in the mouth, in gills, and on gill covers and fins. Bubbles have also been found on internal organs. Movement of the fish to shallower or warmer waters compounds the problem by causing a condition similar to the bends experienced by divers. Though the disease has been commonly attributed to supersaturation of dissolved nitrogen, investigators now feel that the proper definition includes total dissolved gases.

Different species exhibit varying tolerances to dissolved gas supersaturation. Furthermore, symptoms of gas-bubble disease eventually disappear after death of the fish, sometimes making positive identification of the cause of death difficult or impossible. Exact levels of tolerance to supersaturation, time requirements for exposure, and behavioral patterns of the fish have not been completely identified. At one Bureau of Reclamation project, about 200 trout were killed during operation of an auxiliary outlet works, but a similar operation 2 weeks later failed to show any evidence of a fish kill. Nitrogen and oxygen levels were measured at up to 140 percent supersaturation during a controlled test some months later.

In the case of turbine air injection described earlier in this paper, no fish were found with symptoms of gas embolism with the exception of one live trout. These conditions of 130 percent supersaturation had existed in the river for about 1 year, and the river is considered as a high-quality fishing stream. Obviously, the present understanding of the problem of embolism caused by dissolved gas supersaturation is not adequate to completely define causes of and remedies to the problem. Nevertheless, dissolved gas standards are being set. A case in point is the Columbia River in the Northwest (Ref. 6) where considerable expenditures of Federal funds are being made for construction of corrective facilities under pressure of State water quality standards. The need to protect the fishery resource should not be argued; however, standards must be based on adequate definition of the problem.

Research

Federal agencies, universities, and private corporations are presently engaged in research emphasizing destratification, bubble diffusion of molecular oxygen, penstock or draft tube injection, and natural reaeration of streams. New or accelerated work is also needed in all of the areas mentioned above. Current and future research concerning dissolved gas supersaturation should emphasize further definition of the problem. For example, determination of the relationships among dissolved gas concentrations and other water quality parameters in establishing physiological effects on fish is necessary. Then, research to develop several alternative means of control should be stressed.

General Comments

The Federal Interagency Steering Committee on Reaeration Research has stated a need for accelerated research to allow identification, definition, and solution of oxygen deficiency, dissolved gas supersaturation, and other water quality problems before construction of hydraulic structures. Also, economical methods for modifying the operation or configuration of hundreds of existing structures need to be identified.

Furthermore, in the author's opinion, there is an apparent problem of implementation of standards and expenditure of public funds prior to adequate problem definition.

REFERENCES

1. Barnett, Richard H., "Reservoir Destratification Improves Water Quality," Public Works, June 1971

2. Elder, Rex A., et al., "Aeration Efficiency of Howell-Bunger Valves," Journal, Water Pollution Control Federation, April 1969

3. Holler, Albert G., Jr., "Reaeration of Discharge Through Hydraulic Structures," U.S. Army Corps of Engineers, Ohio River Division, December 1970

4. King, Danny L., "Reaeration of Streams and Reservoirs - Analysis and Bibliography," U.S. Bureau of Reclamation Report REC-OCE-70-55, December 1970

5. Raney, Donald C., and Arnold, Terry G., "Dissolved Oxygen Improvement by Hydroelectric Turbine Aspiration," preprint for the ASCE Annual Water Resources Engineering Conference, Atlanta, Georgia, January 1972

6. Smith, Hugh A., Jr., "N_2 - Threat to Pacific Northwest Fisheries?," Water Spectrum, Summer 1972

7. Speece, Richard E., "Hypolimnion Aeration," Journal AWWA, January 1971

DISSOLVED GASES - POSITIVE AND ADVERSE EFFECTS

KEY WORDS: aeration, environmental engineering, water quality, hydraulic structures, dissolved gases

ABSTRACT: Operation of hydraulic structures may result in either a deficiency or an excess of dissolved gases. Deficiency, particularly with regard to dissolved oxygen (DO), may occur due to decomposition of organic matter at or near the bottom of a stream or reservoir. Some hydraulic structures, such as stilling basins, may be highly efficient in reaerating the flow. Or, in certain cases, supersaturation of dissolved gases may occur with the possibility of resulting gas embolism in fish. Although water quality standards for dissolved gases are being introduced, the problem has not been adequately defined.

RELEASES FROM STRATIFIED RESERVOIRS

by

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Typically, the 60 reservoir projects located within the Ohio River Basin are thermally stratified from early or mid–spring through early fall. Releases from these impoundments have a definite influence on the water quality characteristics of the streams and rivers of the basin. These influences are observed in the immediate vicinity of the individual projects in terms of stream temperature, dissolved solids, and the response of the aquatic environment as well as at points far removed in terms of waste assimilation, water supply, and again, the aquatic environment.

A thorough knowledge of the physical, chemical and biological dynamics of each impoundment is an absolute necessity in managing the reservoir releases on a day–by–day basis to satisfy water quality control objectives. In spite of many similarities, each of the existing reservoirs tends to be unique in one or more water quality factors. These differences may constitute significant problems in comprehending the cause and effect relationships of chemical and biological reactions and their relationship to reservoir regulation. The more significant factors such as topographic, geologic, hydrologic, and land–use characteristics of the catchment and the morphometric characteristics of the reservoir are obvious and predictable. For example, the water impounded in a small reservoir, unless highly buffered, is extremely vulnerable to acid mine drainage. In other instances, the factors are so subtle or so complex that prediction or field measurement and evaluation are extremely difficult. To illustrate this point, consider a stream carrying industrial wastes that enters a stratified impoundment. The inflow will seek a level corresponding to its entering density which may be above, within, or below the metalimnion. The effect on chemical and biological dynamics will vary greatly depending on temperature, available light, availability of oxygen, types and concentrations of constituents in solution and suspension, and the kinds and numbers of organisms present.

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The initial reservoirs constructed in the Ohio River Basin were provided with only the capability to release water from the bottom of the impoundment. Biologists eventually pointed out that the aquatic environment was undergoing a radical change brought about by the release of cold water into a previously warm water stream. Other detrimental effects were also brought to light. The need to control quality as well as quantity of reservoir releases was recognized. An evolution of outlet works design aimed at providing reservoir management personnel with the capability to achieve water quality control has progressed over the years. The Corps has been extensively involved in evaluating and seeking to improve these designs.

Pre–impoundment water quality surveys are now essential to provide design criteria for selective withdrawal outlets as well as to formulate guidelines for reservoir regulation in terms of water quality management objectives. Heat budget analyses yield predictions of the temperature characteristics of impoundments which, in turn, provide the basis for design criteria and evaluation of the relationship of storage to tailwater temperature objectives. The thermal response of an impoundment is the foundation on which the study of all other physical, chemical, and biological reactions are based.

While thermal stratification has been studied in the oceans and in natural, freshwater lakes for many years, only recently has attention been given to man–made impoundments with the thought of controlling the quality of stored and released water. It has been observed that thermal gradients in impoundments may differ significantly from those observed in natural lakes. In fact two impoundments in close proximity to each other and having similar morphometric characteristics may differ significantly. The difference is explained in terms of the internal distribution of thermal energy. Water entering a stratified impoundment may spread over the surface, dive to the bottom, or occupy a discrete layer at a level of neutral buoyancy according to its temperature–density relationship. Furthermore, the outflow may be withdrawn from a high, intermediate, or low level. Obviously, a low–level withdrawal will result in the downward displacement of the warmer epilimnion water resulting in a more gradual thermal gradient than commonly found in the classic natural lake profile.

A well defined thermal gradient, because of the temperature relationship to water density, serves as a highly flexible diaphragm separating the epilimnion from the hypolimnion. The density gradient, although small in magnitude, is sufficient to form a barrier to the vertical transfer of thermal energy.

In addition to being an energy barrier, the density gradient effectively isolates the hypolimnion storage from the surface reaeration process. If there is even a moderate amount of organic matter suspended in the hypolimnion, oxygen depletion is swift once the vertical transfer of dissolved oxygen is blocked. As the dissolved oxygen concentration nears total depletion, facultative and anaerobic micro–organisms proliferate in and above the mud–water interface. Some of these organisms utilize mineral oxides, sulfates, and more complex inorganic compounds as a source of energy while others decompose organic matter. The mineral compounds are reduced to their more soluble state while the waste products of the decomposition process include carbon dioxide dissociates to form a weak acid. The pH is thus lowered thereby creating an even more favorable environment for solution of the reduced forms of iron, manganese, and sulphur compounds.

To achieve control of such factors, two areas of activity are being expanded to improve the design and operation of selective withdrawal structures. Laboratory investigations of density currents have been conducted to develop techniques for analyzing the features of the withdrawal zone. These investigations are continuing to provide a steadily improving knowledge of the complex hydrodynamic behavior of an impoundment. Mathematical models are also being utilized to simulate the thermal characteristics of impoundments.

The density current studies are yielding information pertaining to the vertical dimensions of the withdrawal zone, velocity distribution within the zone, and the relationship of intake port shape and location to these factors. The distribution of inflow is also being examined. The mathematical models are being continuously updated to better describe the physical processes involved. While excellent results are being achieved with one–dimensional models where appropriate, two– and three–dimensional models are in the initial development stages. Work is also being done by chemists and biologists to expand these models to describe or predict the chemical and biological dynamics within an impoundment.

Application of these procedures is being utilized on a routine basis to develop input to the design of reservoir projects. Existing projects are being examined to determine if the mode of operation can be improved in terms of water management objectives for stored and released water.

HYDROTHERMAL RELEASES IN ELECTRIC POWER GENERATION

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For each unit of energy generated by a modern steam electric generating plant one must supply approximately two or three times the energy equivalent in fuel. The difference cannot be recovered and is necessarily discharged to the environment. Although many facets of industrial cooling exist, electric power generation creates by far the largest demand on our water resources to satisfy cooling needs, and consequently draws the greatest attention in the assesment of the environmental impact of hydrothermal releases. The remarks in this paper are directed to this question.

The growing demand for power (doubling every 10 years) is being met by a comparable growth in installed capacity at a site. Unit sizes in the range of 900 to 1,100 megawatts are commonly being designed and station installed capacities approaching 3,000 to 4,000 megawatts are proposed. If a large source of water is available at the site, economic considerations often favor once-through cooling for part, if not all, of the condenser cooling requirements. Typical cooling water requirements for an 1,100 MWe nuclear unit with a 20°F rise across the condenser would be approximately 1,650 cfs, rejecting 7.5×10^9 Btu/hr to the water source.

In a period of great public awakening and awareness of ecology, water must be treated not only as an economic resource but also as the environment which supports a large community of living organisms. The strong public support that exists for the preservation of our environment has seen a great response in the funding priorities for scientific research as well as governmental action in establishing criteria to minimize environmental

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impact. In a consideration of alternative cooling concepts, either once-through or closed loop, neither choice is clear without a study of its environmental influence at the proposed power plant site. It is the opinion of this writer that the once-through cooling concept will and should continue to be retained as a strong candidate to meet both the needs of industrial cooling and the requirements of environmental preservation.

Thermal pollution of our waters is recognized to be a serious problem, but primarily one of concern near the heat discharge point rather than in the far field. Man's contribution to the total amount of incident energy on his world is comparatively small. The rate at which heat is rejected to a body of water cited in the above numerical example is approximately equal to the annual average rate of incident solar heat input to a two-square-mile area at latitude 41 degrees. Within this area, however, such amounts of additional heat may create an environment hostile to the aquatic community. In particular, the question that must be addressed is just how great will be the consequences of adopting a proposed design. If a climate favorable to the consideration of once-through cooling is to be maintained, three areas must be further developed.

1) An interdisciplinary research program within the life and the physical sciences should see active support -- a program directed toward furthering our understanding of aquatic organisms and their interaction with hydraulic structures.
2) The adoption of thermal discharge criteria which are flexible enough to allow for newly acquired knowledge to be readily applied to the design of cooling water systems should be encouraged.
3) The tremendous capability of mathematical modeling should be exploited to the fullest in order to provide accurate and

detailed temperature predictions.

The several biological problems which must be addressed when evaluating the impact of once-through cooling on the aquatic environment are conveniently grouped into four areas: impact of (1) construction, (2) intake, (3) entrainment, and (4) heat and chemical release. The impact of construction usually can be controlled with the provision that some care will be exercised in selecting or employing construction methods. Unless the area is unique or highly productive, the mortality due to construction has no widespread consequences, and recovery occurs in the construction area within a reasonable period of time. The large volume of water being circulated potentially creates problems in entrapment of fish and eventual impingement on intake screens. Entrapment can be minimized by the provision of low intake velocities, elimination of embayments in front of the intake, and the erection of a variety of barriers which tend to prevent fish from entering the intake structure. Impingement is either avoided by fish bypass schemes or by mechanical removal of fish from the screenwell. These problems have stimulated active research activity with the promise of better solutions to come. Biologists consider that the entrainment of planktonic forms and their subjection to stresses as they pass through the condenser to be the most serious of the problem areas. No satisfactory means has yet been, or can likely be, devised to avoid entrainment, and the impact on the ecology of the surrounding area resulting from mortalities as water passes through the condenser and discharge system is not completely understood. However, mathematical models designed to simulate the population dynamics of important planktonic forms are coming into use as a means of assessing this impact. In general, the advancement of our understanding of entrainment is a research area of critical importance. Finally, the consequences of the heat and chemicals returned to the water source must be considered. Surface discharges promote rapid heat exchange with the atmosphere and produce less disturbance to the benthos. Diffusers, which rely on intensive dilution at some depth in the receiving water body avoid creating regions of large rises above natural ambient temperatures, cause rapid dispersion of chemical wastes, and minimize recirculation. The best solution should be determined by a consideration of conditions at the site and guided by the products of research into the thermal effects on aquatic life.

Depending upon the jurisdiction, the power industry meets a wide range of regulatory requirements. For example, in issuing a State permit some states have sought to impose a uniform code of temperature criteria; others have attempted to retain flexibility in their requirements. In either case, the tendency has been to favor very stringent criteria wherever a comfortable margin of environmental protection is necessary because of our limited knowledge. However, in an era when scientific research is rapidly expanding the limits of pertinent knowledge, the most reasonable approach is to adopt flexible requirements which can reflect the present best judgement of the scientific and engineering community.

Uniformity tends to deny that each site is unique, that a certain fishery may need more, or less, protection, that biological research is apt to disclose significant new findings. Evaluation of thermal criteria on a site by site basis encourages justification based on a comprehensive biological field study, allows the latest research findings to influence judgements, and promotes a wider choice of design concepts to minimize environmental impact. An across-the-board relaxation of regulatory requirements is not being advocated. Rather, the recommendation is for flexibility to meet environmental needs as they become better understood.

The field of hydrothermal analysis has an abundant literature of mathematical models and algorithms for simulating the component process of once-through cooling. For example, the following sequence of models all contribute to the design of a diffuser: internal hydraulic calculations yield port discharge velocities; a single buoyant jet model proceeds to the point of mutual jet interference; a two-dimensional slot jet model approximates conditions to the free surface; a two-layer flow model simulates temperatures near the discharge structure; and a far-field model, accounting for advection, diffusion, and heat exchange with the atmosphere, simulates temperatures remote from the discharge structure and determines heat recirculation. In these and other cases, computer programs can be prepared which yield accurate approximations to the time-dependent spacial distribution of temperature. Beyond their capability of yielding valuable design information, mathematical models will continue to play a more and more prominent role in regulatory activities. Mathematical models are not without limitation, however, and confidence in predictions is understandably weakened if the model is driven by inadequate or questionable field data. The cost of collection of the necessary field data may exceed many times the cost of model development and operation. However, such field work is essential for model development and validation. Notwithstanding the cost of a field study program, mathematical models present perhaps the most effective means of responding to questions of environmental impact and demonstrating the justification for a discharge design concept.

In summary, once-through cooling remains as a valuable alternative to consider among various means of condenser cooling schemes. The continued acceptance of once-through cooling hinges on the active support of an interdisciplinary biological research program, the adoption of flexible thermal criteria which can accomodate the results of new research, and the exploitation of current capabilities in mathematical modeling.