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REAERATION AND CONTROL OF DISSOLVED GASES - A PROGRESS REPORT

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16. ABSTRACT

The research program, Reaeration and Control of Dissolved Gases, has emphasized destratification of reservoirs, biological effects of reaeration and destratification, dissolved gas levels at energy dissipator structures, conception of new methods and devices for reaeration, and corrosion by molecular oxygen. Destratification testing has occurred at Flaming Gorge Reservoir and Lake of the Arbuckles and is being planned for Lake Casitas. Research on biological effects at Lake of the Arbuckles is receiving support and a comprehensive state-of-the-art report has been issued. A dissolved gas level prediction method has been developed from data collected from a wide variety of types of energy dissipators. Laboratory testing on the corrosive effects of the use of molecular oxygen is underway. (28 ref)

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REAERATION AND CONTROL OF DISSOLVED GASES - A PROGRESS REPORT

by

Reaeration Research Program Management Team

March 1975

Division of General Research
Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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A subsidiary team, the Reaeration Methods and Devices Team (MAD), performed or directed much of the technical work. Persons who have served on this team are:

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PURPOSE

The purpose of this report is to review the program and describe progress made thus far on the research project, Reaeration and Control of Dissolved Gases.

CONCLUSIONS

1. Aspects of the research program plan which have been emphasized to date are: destratification of reservoirs, biological effects of reaeration and destratification, dissolved gas levels at energy dissipator structures, and conception of new methods and devices for reaeration. Research on corrosion by molecular oxygen has been added to the original plan.

2. Destratification testing was conducted at Flaming Gorge Reservoir using a diffused air system and at Lake of the Arbuckles using an "air gun." Although in both cases the devices were too small to produce readily measurable changes, particularly in the former case, there was evidence that both methods yielded a destratification efficiency of 1 percent or less, which is similar to earlier experience at very small reservoirs. In most cases, the energy requirement associated with these low efficiencies would deter application of these methods to very large reservoirs. Data were not adequate to allow calculation of the reoxygenation efficiency, although historically these devices have yielded 1 to 2 pounds of oxygen per kilowatt-hour of energy expended. Destratification studies are continuing at Lake of the Arbuckles, using a propeller-pump device, and are being planned for Lake Casitas.

3. A comprehensive state-of-the-art review of the biological effects of artificial destratification and aeration in lakes and reservoirs has been prepared which outlines research needs. A major study is underway to determine the biological effects of destratification operations at Lake of the Arbuckles.

4. Data have been collected from a wide variety of types of energy dissipators with the objective of determining their ability to reaerate and their tendency to supersaturate. General conclusions were drawn concerning effects of pressure, turbulence, and amount of air entrained. A more detailed analysis has developed a predictive capability so that various characteristics of the structure can be used to predetermine the dissolved gas level. Principles of gas transfer were used in developing a reaeration coefficient, related to bubble exposure time, for hydraulic structures.

5. A test facility has been constructed and tests are underway for investigating the corrosive effects of molecular oxygen on construction materials, particularly metals. The growing use of molecular oxygen for injection into reservoirs, streams, hydraulic machinery, and conduits prompted this investigation.

APPLICATION

The results reported herein can be applied to the solution of problems of dissolved oxygen deficiency and dissolved gas supersaturation in streams, reservoirs, and reservoir releases.

INTRODUCTION

Background

The Bureau of Reclamation became involved in the subject of reaeration in 1968 while considering a proposed high dam on the Snake River. Low-level releases would be required from the dam to maintain cold temperatures for spawning salmon. However, these releases would be essentially devoid of dissolved oxygen (DO). The problem then became one of raising the DO level from zero to saturation in a flow of 16,000 ft^3/s (453.1 m^3/s). The magnitude and difficulty of this task clearly showed the need for improving technical capabilities in reaeration.

One widely used technique for controlling downstream DO is selective withdrawal. This approach usually has minimal effect on reservoir DO levels unless a given layer is greatly depleted or eliminated by selective discharge, which might be the case in smaller reservoirs. Unfortunately, selective withdrawal or spillway operation to enhance downstream DO conditions also involves discharging warm water from upper levels of the reservoir, making the river downstream uninhabitable by cold water species of fish. Spillway operation at hydropower installations may also involve a loss in power revenues. Therefore, artificial reaeration is sometimes the only acceptable alternative.

Late in 1969, an in-house state-of-the-art review of reaeration research needs was made, a report was issued [14],* and in 1971 an interdisciplinary planning team was formed. During the review, an in-house seminar was conducted to familiarize staff members with the basic principles of reaeration. As a result of the planning team's efforts, a program management team was organized and is now managing and directing

*Numbers in brackets designate references listed at the end of this report.

the research program. All the regional offices are involved and are cooperating in the many team efforts.

To investigate reaeration and supersaturation problems and to coordinate Federal activities in this field, a Federal Interagency Steering Committee on Reaeration Research was formed in November 1971. Members are the Bureau of Reclamation, Tennessee Valley Authority, Corps of Engineers, Geological Survey, and the Environmental Protection Agency. The Bonneville Power Administration participates as an observer.

As the research program developed, the need became evident for a subsidiary technical team to study and develop methods and devices for reaeration. Such a team was formed in June 1972, following a survey of reaeration needs in the Bureau's seven regions, which was conducted during 1971 [10].

Objectives

The following specific objectives, considered to be of equal priority, were adopted by the Program Management Team (PMT):

1. Determine the reaeration capabilities of conventional hydraulic works.

2. Develop new methods and devices to achieve reaeration of reservoirs, reservoir releases, and streams; establish related design and operating characteristics.

3. Evaluate environmental and biological effects of reaeration.

4. Determine the relative performance of different methods and devices at various locations in a river-reservoir system.

5. Establish standard procedures for rating the reaeration efficiency and cost effectiveness of methods and devices.

6. Develop basic information and procedures, for use in planning and design for (a) determining needs, (b) selecting optimum methods and devices, (c) estimating costs, and (d) predicting the effects of reaeration.

Up to the time of this progress report, emphasis has been on reservoir destratification (including biological effects) and measurement of dissolved gases at conventional hydraulic works (particularly supersaturation). All work is aimed at satisfying Objective 6.

Research Program

Some of the objectives of the research program previously mentioned are further explained as follows:

Environmental and Biological Effects

The previously planned research program included an estimated funding requirement of nearly $500,000 over a 4-year period for investigation of environmental and biological effects. This amount was approximately half the requirement for the total program. Funding has occurred at a rate of about $50,000 per year for the total program. As a result, the program is being extended beyond the 4-year period and research on environmental and biological effects has received minimal support. Some assistance has been provided to investigators who have other, larger funding sources.

The effect of reaeration upon the environment, and synecological (studies of individual organisms or individual species) and autecological (studies of groups of organisms associated as a unit) aspects of the aquatic system must be evaluated. This evaluation should be made on all reaeration devices, structures, and related features investigated during the research program to determine the effects on the reservoir, stream, or a reservoir-stream system. The goal is to obtain generalizations which can be applied for prediction of effects. Two important aspects of the evaluation that should be considered are: (1) the rate and magnitude of changes, and (2) the relationship between physical, chemical, and biological factors.

Since it is vital to the evaluation to have substantial background data, the collection of data should begin 1 or more years prior to the actual test. The test period alone should be at least 2 years. It is assumed that the data will be collected during actual reaeration tests. The research team should determine the parameters that should be measured. The following list of parameters to be investigated should serve as a guide:

Physical

a. Temperature

b. Transparency

c. Hydrodynamics

d. Turbidity

Chemical

a. Dissolved oxygen—field test

b. Routine chemical analyses

c. Alkalinity—field test

d. pH, CO_2—field test

e. Biochemical oxygen demand (BOD)

f. Problem chemicals

g. Deposition and solution products

h. Other gases of interest

Biological

Fish, zooplankton, algae, bottom fauna:

a. Life history

b. Growth rates

c. Change in composition and numbers.

Nitrogen embolism.—Problem areas or potential problem areas should be identified. Contact should be maintained with the Columbia River studies.

Standard Method of Economic Comparison

Standardization of reaeration efficiency.—Objective: Formulate an empirical relationship to include all parameters which influence the reaeration efficiency of a method or device (such as oxygen deficit below saturation, oxygen deficit below desired level, initial DO level, temperature, pressure, concentration of contaminants, stream velocity, etc.)

For example:

Efficiency (pounds of oxygen per kilowatt-hour) = $KT^a p^b D^c$ etc.

Where: a, b, c, K = constants
T = temperature
p = total pressure at the point of measurement, and
D = oxygen deficit

From field measurements, a value for K could be determined empirically for determined standard conditions. For a given device at a specific location, the efficiency could then be computed.

Standard method for cost efficiency.—Objective: Develop standard procedures for estimating cost of reaeration equipment installation, operation, and maintenance; allow comparison between alternative methods or combinations of methods; and to become aware of possible side benefits, such as the value of byproducts, for example, hydrogen in oxygen production.

Methods and Devices for Reaeration

Research and development of methods and devices for reaeration should be concerned with the application of existing techniques to large volumes and flows; development of new methods and devices; evaluation of the reaeration capability of spillways and outlet works; identification of secondary effects (beneficial or adverse); and determination of relative efficiencies, optimum use, and limitations for various reaeration methods and devices. The problem may be divided into three parts: (1) reservoir reaeration, (2) release reaeration, and (3) instream reaeration. To maintain knowledge of the state of the art, the review of current literature and research reports should continue.

Reservoirs.—Three assumptions are suggested for use in approaching the problem of reservoir reaeration, namely:

1. Stratification considered to be desirable.

2. Destratification or homogenization considered to be desirable.

3. Either stratification or homogenization is satisfactory.

Reservoir stratification may be highly desirable when certain requirements are imposed. When a cold, high DO release is required, the reaeration of only the hypolimnion may be indicated. Mixing may be indicated under other conditions because of secondary beneficial effects. Requirements for temperature control may be so rigid that a combination of hypolimnion reaeration and selective withdrawal may be indicated.

Certain general studies may be needed to provide an adequate understanding of the hydrodynamics of reservoirs so that a rational selection of the method and/or device can be made, location of devices can be optimized, and operating criteria can be established.

Other general studies would involve effectiveness and operating characteristics of devices. Such studies would include:

1. Evaluation of efficiencies of devices within ranges of oxygen requirement deficit and driving force.

2. Evaluation of intensive (short-term, large input) use versus extensive (long-term, smaller input) use for various devices.

3. Evaluation of continuous versus intermittent operation.

4. Identification (not to include evaluation) of secondary effects (biological, chemical, physical) associated with certain methods and devices.

The types of devices that should be included in the research studies are:

1. Devices for hypolimnion reaeration:

   (a) Diffusers (air, molecular oxygen)

   (b) Pumps and pumps combined with other devices

   (c) Other devices which may be developed.

2. Devices for full reservoir reaeration:

   (a) Bubblers, hydraulic guns, helixors, etc.

   (b) Pumps

   (c) Other devices which may be developed.

Evaluation of reaeration methods and devices should include laboratory testing and prototype testing as appropriate.

Releases.—Reaeration of releases from reservoirs involves high and low energy flows. The problems associated with these two flow conditions are distinctly dissimilar. The high energy flow condition may be utilized to draw air into the flow without an external source of energy. This may be done by gates and valves, jet diffusers, energy dissipators, flip buckets, or spillway chutes. There is an opportunity to evaluate most of these devices using existing structures. Low energy flow situations involve, to some extent, the expenditure of energy from an external source. The U-tube aerator, molecular oxygen injection at hydraulic turbines, and afterbay reaeration are examples of methods that should be studied. Weir drops in an outlet channel and some turbine draft tubes may serve as reaerators without an external energy source.

Research in reaeration of releases should be centered around the problems associated with large flows; comparisons of devices and methods with respect to effectiveness within certain desired ranges of percent saturation, including supersaturation; effectiveness when releases are high in BOD; and limitations of various devices because of nitrogen supersaturation. Specific research areas should include the following:

1. Prototype evaluation of reaeration characteristics of, and possible modifications to, existing works including:

   (a) Gates and valves,

   (b) Energy dissipators,

   (c) Chutes and other conveyance structures, and

   (d) Turbines.

2. Laboratory development of jet aspirators to determine applicability to closed flow conditions.

3. Prototype evaluation of devices with respect to nitrogen supersaturation. Establishing limitations and development of modifications to reduce nitrogen saturation.

4. Large scale, perhaps prototype, modeling and evaluation of the U-tube aerator.

5. Evaluation of molecular oxygen injection at an existing turbine.

Streams.—Reaeration of natural streams has been the object of considerable research, but additional studies may be warranted especially with regard to those streams which flow into reservoirs and those which carry reservoir releases. Reaeration of inflows to reservoirs in some cases may be more desirable, and perhaps less expensive, than reaeration of the water that is impounded. It is also possible that a combination of inflow reaeration and reservoir reaeration may produce optimum results. Likewise, reaeration of water in the natural stream below a dam may be a desirable and efficient alternative or adjunct to reservoir reaeration. Objectives should include:

1. Development of criteria for evaluating reaeration of reservoir inflow and outflow streams as a

substitute or an adjunct to reservoir and reservoir release reaeration.

2. Evaluation of instream reaeration devices; taking into account stream geometry, discharge, and BOD; for the purpose of determining minimum reach to achieve desired DO levels and relative efficiencies of devices.

SURVEY OF REAERATION NEEDS

During 1971, a questionnaire survey was made of Bureau of Reclamation regions and the Engineering and Research (E&R) Center offices to determine the extent of problems in Bureau and other reservoirs, streams, canals, and aquifers resulting from the lack of dissolved oxygen. The previously described research plan was based on the needs so identified. The results were described in a summary report [10] to the PMT.

The following major problems were identified:

1. Low DO levels in reservoirs due to local areas of bottom deposits with high BOD; eutrophication, ice cover, and stratification inhibiting atmospheric reaeration; dissolved iron and manganese; and high concentrations of nutrients and warm temperatures with associated algae blooms.

2. Low DO levels in streams resulting from heavy BOD loading, inadequate waste treatment, high nutrient levels, and low DO releases from reservoirs.

Research needs were determined in order of priority as follows:

1. Develop methods and procedures for improving the quality of hypolimnion waters and, accordingly, low-level releases into streams and canals.

2. Evaluate the application of destratification in comparison with other reservoir water quality control measures.

3. Develop and evaluate more efficient methods for preventing winterkill in small reservoirs.

4. Develop high-efficiency devices for in-stream reaeration.

More than 27 reservoirs and 8 streams were listed where problems existed because of low DO. Thus, each of these sites presented an opportunity for reaeration research.

The problem of supersaturation of dissolved gases was not identified as being a major concern at the time the survey was made. However, this concern developed later and became a major part of the research program.

DESTRATIFICATION OF RESERVOIRS

Background

Work in this subject was pioneered by Symons and his associates in the U.S. Public Health Service. Although their work was limited to very small impoundments, they developed a method for calculating destratification efficiency which has universal application [23]. An example calculation is given in table 1. Also, under Symons' leadership, a survey was conducted

TABLE 1.—*Example calculation of reservoir stability*
From reference [23]

Layer, ft	Volume, acre-feet	Weight, 10^6 lbs	Moments about surface, 10^{10} ft-lbs	Distance from center of layer to isothermal C. G., ft	P.E. gained or lost by moving layer to C. G., 10^{10} ft-lbs	Mult. factor, 10^{10} ft-lbs	Temp. profile, °C	Specific gravity factor	Stability, 10^{10} ft-lbs
0-10	700,000	1,902,700	951.35	−11.8	−2245.19	−2,245	23	−0.00250	+5.6
10-20	400,000	1,087,257	1,630.89	− 1.8	− 195.71	− 196	20	−0.00180	+0.4
20-30	300,000	815,443	2,038.61	+ 8.2	+ 668.66	+ 669	19	−0.00170	−1.1
30-40	200,000	543,628	1,902.70	+18.2	+ 989.41	+ 989	18	−0.00140	−1.4
40-50	100,000	271,814	1,223.16	+28.2	+ 766.50	+ 767	15	−0.00090	−0.7
	1.7×10^6	4.621×10^{12}	7.747×10^{13}		− 16.33				+2.8

Isothermal center of gravity (C. G.):

$$\frac{7.747 \times 10^{13}}{4.621 \times 10^{12}} = 16.8 \text{ ft. from surface}$$

P.E. = Potential Energy

Max. stability = 2.8×10^{10} ft-lbs which provided general and approximate information on destratification efficiency and costs for reservoirs up to nearly 500,000 acre-feet (617 x $10^6 m^3$) in volume [24].

In 1962, Koberg and Ford [15] of the Geological Survey also performed some basic work with an air-bubbling system at Lake Wohlford in California, 2,500 acre-feet (3.08 x $10^6 m^3$).

The Geological Survey at Lake Cachuma in California, 205,000 acre-feet (253 x $10^6 m^3$), met with little success because of inadequate sizing of the diffused-air system [9].

Since 1968, a successful diffused-air destratification system has operated at Lake Casitas in California, 254,000 acre-feet (313 x $10^6 m^3$), under the direction of the Casitas Metropolitan Water District [6]. The system was intended to maintain a minimum DO level of 1 mg/l near the municipal intake, maintain a DO level of greater than 5 mg/l in the upper zone of the reservoir to support existing aquatic life, establish a maximum allowable temperature of 64° F in the lower zone of the reservoir, and enhance the reservoir fishery by increasing the habitable reservoir volume.

In recent years there has been interest in applying the concept of destratification to increasingly larger reservoirs. In 1968, the Corps of Engineers installed a 300-horsepower diffused-air system at Lake Allatoona in Georgia, 367,500 acre-feet (453 x $10^6 m^3$). In 1971, the Corps also installed a diffused-air system at Table Rock Reservoir in Missouri, 2.7 million acre-feet (3,330 x $10^6 m^3$).

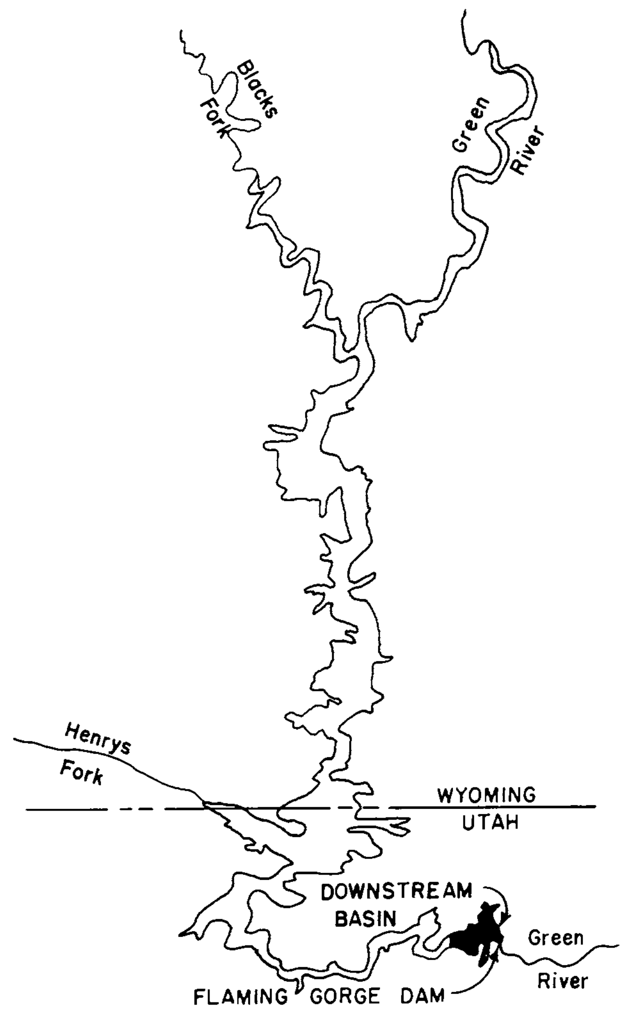


Figure 1. Flaming Gorge Reservoir

Flaming Gorge Reservoir

In 1972, small-scale pilot tests were conducted at Flaming Gorge Dam in Utah (fig. 1) to determine the feasibility of using destratification as a method of controlling the temperature of releases through the powerplant [5].

During the years required to fill Flaming Gorge Reservoir to near-maximum operating levels, the tail-water fishery has followed a pattern of development previously noted on other large reservoirs with single-level release facilities. With low-level diversions in operation during filling of the dead storage pool, little change occurred in the quality of releases. As the reservoir reached intermediate levels, silt was retained in the reservoir, summer release temperatures were controlled to a 50° to 55° F range, and an ideal trout habitat was created downstream. As the reservoir continued to rise toward upper operational levels with penstock entrances at considerable depth, summer release temperatures dropped below optimum ranges, the trout growth rate decreased, and the quality of the tailwater fishery was materially reduced. A typical summer temperature profile is shown in figure 2.

In May 1972, regional representatives of the Bureau of Reclamation and the Utah Division of Natural Resources met to discuss possible remedial measures to control release temperatures. The metal trashracks at the penstock entrances were considered to be too limited in height and situated at too great a depth to make them amenable to quick modification for selective withdrawal. Consequently, to secure higher release temperatures, major consideration was given to using an air-diffusion system to mix the water near the dam. Use of the ice-prevention system on the penstock and outlet trashrack structures (fig. 3) to secure indicative

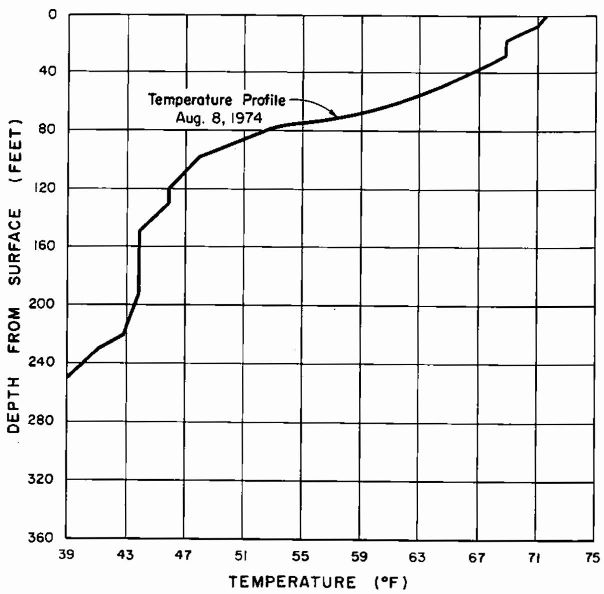


Figure 2. Typical summer temperature profile at Flaming Gorge Dam.

data which might be used in designing a subsequent system was discussed. Following the meeting, the Denver Engineering and Research Center was requested to study the problem at Flaming Gorge, and to initiate preliminary destratification testing and data collection during the summer of 1972.

Use of the trashrack ice-prevention system for test operations appeared to be the most feasible approach for the following reasons:

1. The system could be placed in operation with a minimum of modification and cost, soon enough to assure valuable data acquisition in 1972 as requested.

2. The existing system was extensive and ideally segmented which would allow a range of experimentation horizontally and vertically.

3. It appeared desirable to fully investigate the capabilities of the existing system before proceeding to design a completely new installation.

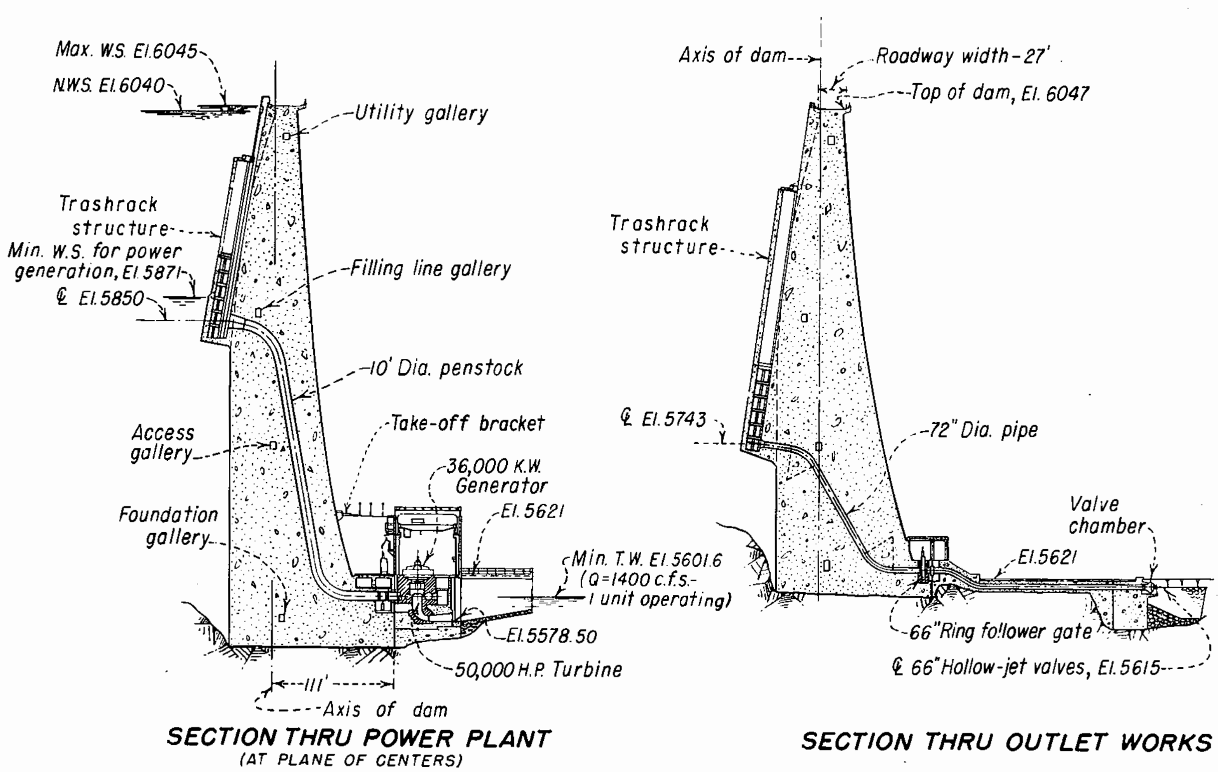


Figure 3. Penstock and outlet works structures—Flaming Gorge Dam.

4. Although it was anticipated that use of the existing systems would not greatly affect release temperatures because mixing would be restricted to elevations above the penstock entrances, it was believed that sufficient change in the temperature profile near the dam would be noted, which would be an aid in future design.

The 1972 pilot testing, as expected, produced no measurable effect on powerplant release temperatures. However, a limited volume of water near the dam above the level of the intakes appeared to be affected. Monitoring data obtained were valuable in designing and estimating a conceptual prototype destratification system, and will also aid in the design of alternative temperature control systems.

Some factors that made identification of effects of the diffuser pilot testing operation difficult were:

a. Lack of adequate background data prior to the start of the operation.

b. Natural, long-period perturbations in the temperature profile caused by variations in release, wind, and changes in storage.

c. An inadequate number of stations for measurement of temperature profiles in the immediate zone of testing because of limited manpower.

d. The very small energy input and low destratification efficiency of the air diffusers.

e. The proximity of the diffusers to the dam and the zone of influence of the penstock intake flow nets.

f. Poor timing of the tests; the pilot operation was not started until the reservoir had reached peak stratification.

It is believed that the efficiency of the 1972 pilot system, estimated at 0.02 percent, was severely limited by size and location. Results of a previous laboratory study suggested that below a certain critical limit of energy input, the destratification effect would be essentially negligible.

Prototype testing by the Corps of Engineers at Lake Allatoona in Georgia (a reservoir comparable in size to the downstream basin at Flaming Gorge and with similar power generation releases) increased water temperatures at a depth of 140 feet (42.7 m) by 10° F under midsummer conditions. Efficiency of this system varied from 0.3 to 0.7 percent.

Using the reasonable assumption that a diffuser system with an efficiency of 0.5 percent could be designed, power requirements for destratifying the downstream basin at Flaming Gorge (fig. 4) to a depth of 200 feet (61 m) would be 320 horsepower. The power requirement for the entire reservoir using 0.5-percent efficiency and under similar conditions would be 6,120 horsepower, which is obviously impracticable. It was estimated that the capital cost of an air-diffuser installation adequate for control of the downstream basin would be approximately $200,000. In addition, the annual operating costs for this installation, including power, would be $70,000 to $90,000. The annual cost of necessary monitoring would be $6,000. The cost of a one-season full-scale prototype test was estimated at $283,000, which includes full capital cost plus 1 year's operation. Anything less than prototype scale testing would probably be inconclusive.

Previous experience with the use of diffused-air systems suggests rather conclusively that the destratification efficiency is on the order of 1 percent or less. Therefore, this technique would seem to be limited, for reasons of economics, to relatively small impoundments. However, an alternative approach would be to destratify only a portion of a reservoir, near the intake for example, or to partially destratify only to the degree necessary to control a specific water quality problem. Example calculations are shown in table 2. The success of these latter two approaches depends greatly on the resulting reservoir hydrodynamics, which require further study.

Because of the uncertainties and high costs of destratification at Flaming Gorge Reservoir, selective withdrawal was chosen as the most economical and reliable method for controlling temperatures below Flaming Gorge Dam.

Current Studies

Lake of the Arbuckles

The major thrust by the Bureau in destratification research is at Lake of the Arbuckles in Oklahoma, figure 5. Arbuckle Dam and Reservoir were constructed on Rock Creek in south-central Oklahoma in 1966 by the Bureau to provide municipal and industrial (M&I) water supplies to the towns of Ardmore, Davis, Sulfur, and Wynnewood, and a major oil refinery near Wynnewood. The project was transferred

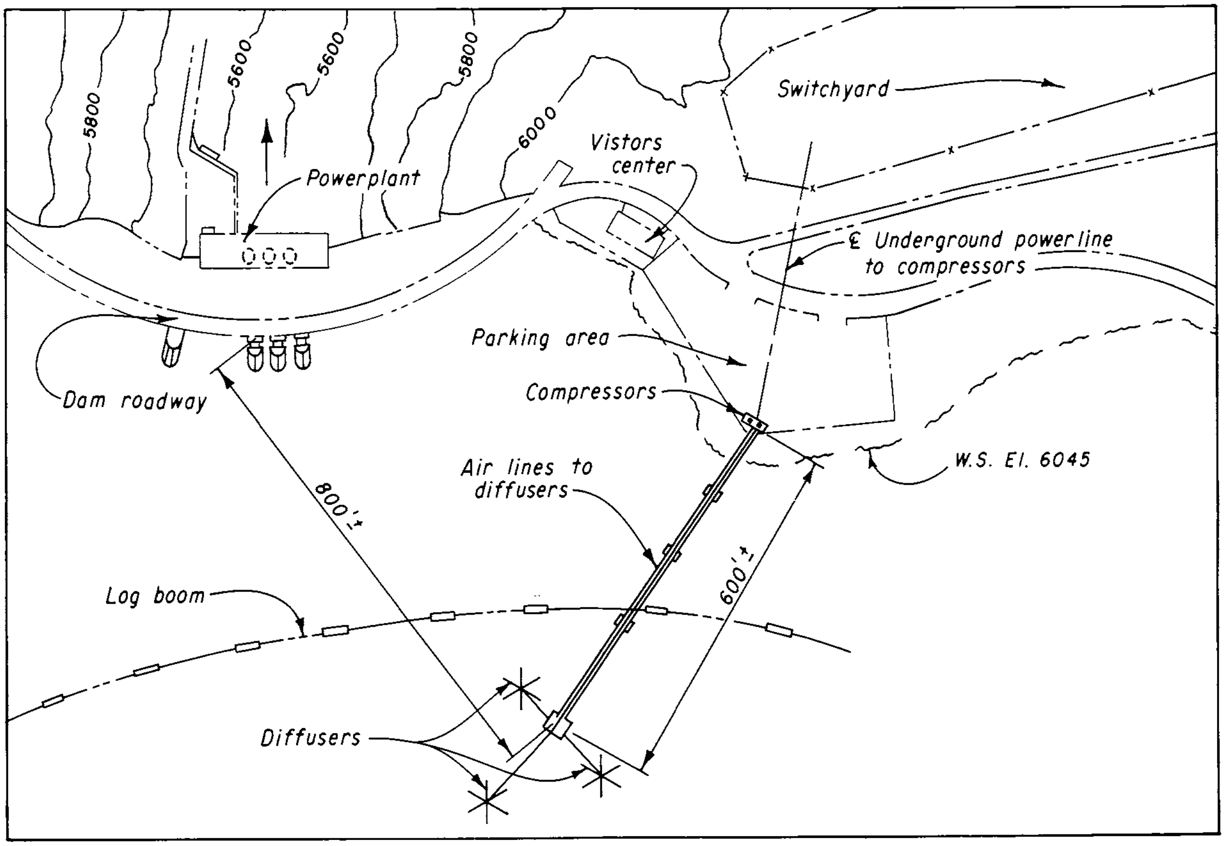


Figure 4. Hypothetical air-diffuser system for downstream basin—Flaming Gorge Reservoir.

TABLE 2.—*Example destratification calculation*

Total max. stability = 2.8×10^{10} ft-lb

Assume that the stability increases linearly from zero on April 1 to 2.8×10^{10} ft-lb on July 1, then decreases linearly thereafter to zero on November 1.

By starting destratification on April 1, continuous mixing could be maintained with a power input of:

$$\frac{2.8 \times 10^{10} \text{ ft-lb}}{(91 \text{ days})\ (24 \text{ hour/day})} = 1.282 \times 10^{7} \text{ ft-lb/hour,}$$

then:

$$\frac{1.282 \times 10^{7} \text{ ft-lb/hour}}{1.98 \times 10^{6} \text{ ft-lb/hp-hour}} = 6.5 \text{ horsepower (hp)}$$

Assuming an efficiency of 0.5 percent for a diffused-air system:

$$\text{Compressor size} = \frac{6.5 \text{ hp}}{0.005} = 1{,}300 \text{ hp}$$

Assuming that destratification of only one-fourth of the reservoir is necessary:

$$\text{Compressor size} = \frac{1{,}300 \text{ hp}}{4} = 325 \text{ hp}$$

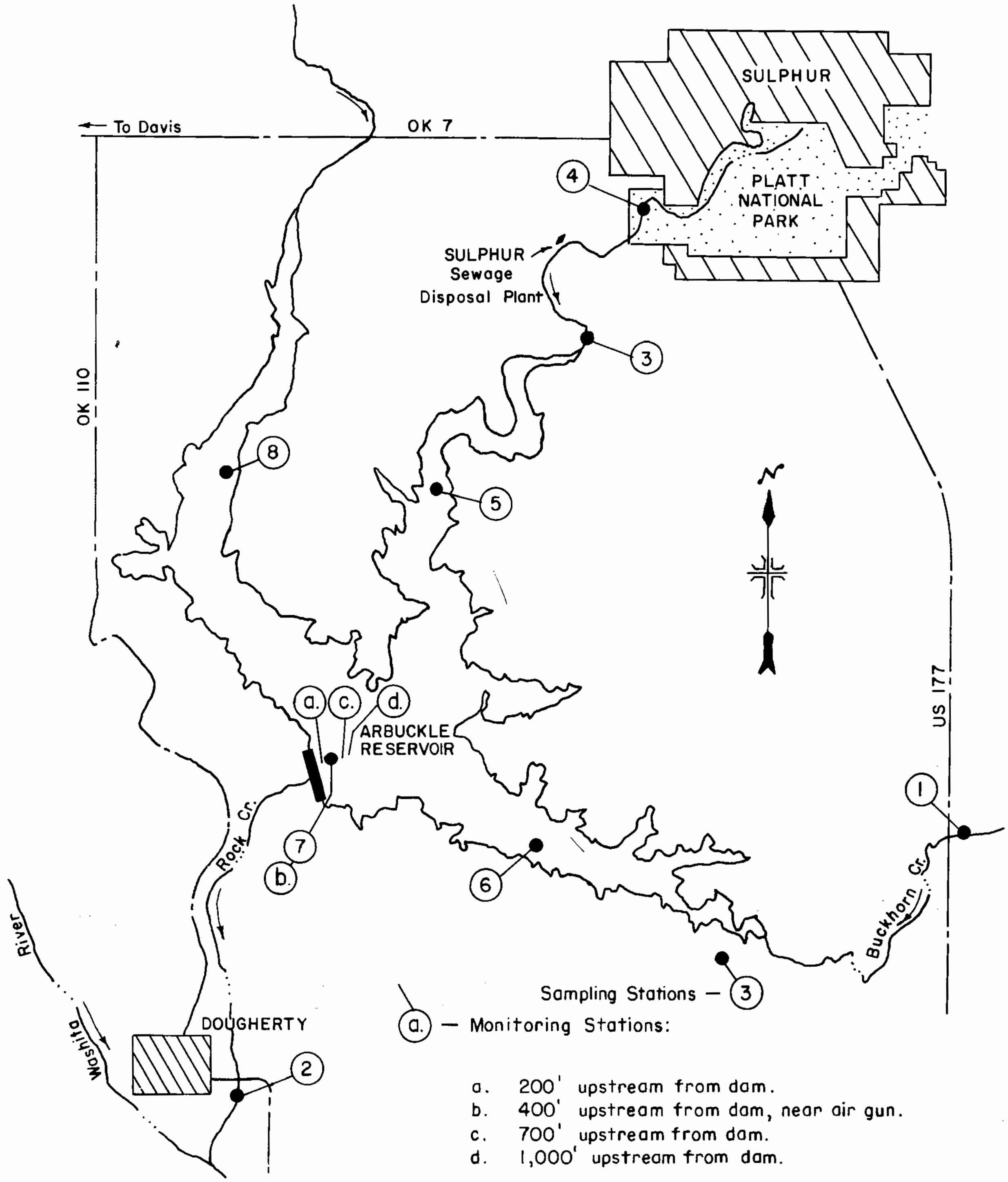


Figure 5. Map of Arbuckle Reservoir. (Courtesy of Southwest Region, USBR)

to the Arbuckle Master Conservancy District for operation and maintenance beginning on January 1, 1968.

Stream water quality data from the 1926-1961 period indicated that the reservoir would yield high quality water for M&I use. This has been borne out by operating experience since 1968. However, some form of chemical, algae, or micro-organism in the reservoir water causes a rapid depletion of chlorine when introduced at the pumping plant and the point of release from the pipeline at the regulating reservoir. Chlorination is therefore required at the points of water treatment. Also, copper sulfate has been used in the regulating reservoir to control aquatic weed growth.

The annual development of thermal stratification during the warm part of the season, with accompanying depletion of DO in the hypolimnion (fig. 6) suggested that steps should be taken to prevent any future serious deterioration of water quality in the M&I deliveries.

It was decided that destratification should be applied to eliminate the DO depletion in the hypolimnion, provide cooler waters at and near the surface to reduce evaporation losses and control algae growth, reduce the organic content of the water, reduce objectionable tastes and odors, reduce the chlorine requirement, and reduce the costs of water treatment. An improved lake fishery would also be expected, as well as improvement in the quality of downstream releases.

To accomplish the destratification, the Bureau's Southwest Region designed and constructed a type of "air gun" for testing. The more usual diffused-air system also was to be tested during a later season for comparison purposes. The air gun consists of a vertical tube with a chamber at the bottom which intermittently releases large air bubbles. The rising bubbles fit snugly in the tube and act as a piston which forces water out above the bubble and draws water from the lower part of the reservoir into the tube. Thus, the reservoir water is continuously circulated and the oxygen-depleted bottom waters are brought to the surface for reaeration from the atmosphere.

The air gun (fig. 7) is constructed of a 2-foot diameter, polyvinyl chloride (PVC) pipe and is supported from a floating, anchored barge. Air is supplied from a compressor on shore to the diffuser which produces small bubbles that rise 4 to 5 feet into a bubble trap. The small bubbles accumulate in the bubble trap which periodically dumps a single large bubble into the vertical tube. Some oxygenation takes place by transfer of oxygen from the bubbles to the water, but the major effect is circulation and reaeration from the atmosphere. The device, tested at Lake of the Arbuckles during the summer of 1973, showed an estimated pumping capacity of 30 ft^3/s or 60 acre-feet per day (74×10^3 m^3/day), withdrawing water from a depth of about 57 feet (17.4 m), which was about 10 feet (3 m) from the bottom of the lake. Temperature, dissolved oxygen, conductivity, iron, phosphorus, ammonia nitrogen, phytoplankton, zooplankton, and the effects on fish growth are being studied by the Oklahoma Cooperative Fishery Unit at Oklahoma State University.

The results of testing during 1973 indicated an overall destratification efficiency of 0.3 percent, using a gasoline engine-driven compressor part of the time and an electric motor-driven compressor part of the time. The electric compressor was considerably more efficient than the gasoline compressor, and calculations suggested that an overall destratification efficiency of about 1.1 percent could have been obtained if the electric compressor had been used exclusively. This latter value compares closely with efficiencies obtained with this type of device at other locations, including many very small impoundments.

Data were not available for computation of the reoxygenating efficiency of the air gun, primarily because the amount of oxygen utilized during the test period was unknown. Other air-gun devices have given an efficiency of about 1 to 2 pounds of oxygen per kilowatt-hour, and there is no reason to believe that the Arbuckle device would not perform similarly. There was a very apparent effect in the immediate vicinity of the device, as evidenced by increased oxygen concentrations at all depths above the device. There was also some indication of a very slight (less than 0.1 mg/1) increase in DO within the hypolimnion throughout the areal extent of the reservoir.

Garton [19], Oklahoma State University, has developed a low-energy destratification device (fig. 8), which is being tested at Lake of the Arbuckles. A 1/2-horsepower device has been applied successfully at two small impoundments in Oklahoma. A maximum flow of 10,703 gal/min (23.8 ft^3/s) (0.67 m^3/s) has been obtained with the device while using 0.498 horsepower. The device is an axial flow pump with a propeller (7-blade cast aluminum, 41-3/4 inch (106.0 cm) outside diameter, 40 to 80 r/min), a bellmouth entrance, a pump body consisting of a 29-inch-long (73.7 cm) cylinder with a 42-inch (106.7 cm) inside diameter, straightening vanes to suppress vortices at the entrance, and a 24-foot-long (7.3 m) plastic diffuser

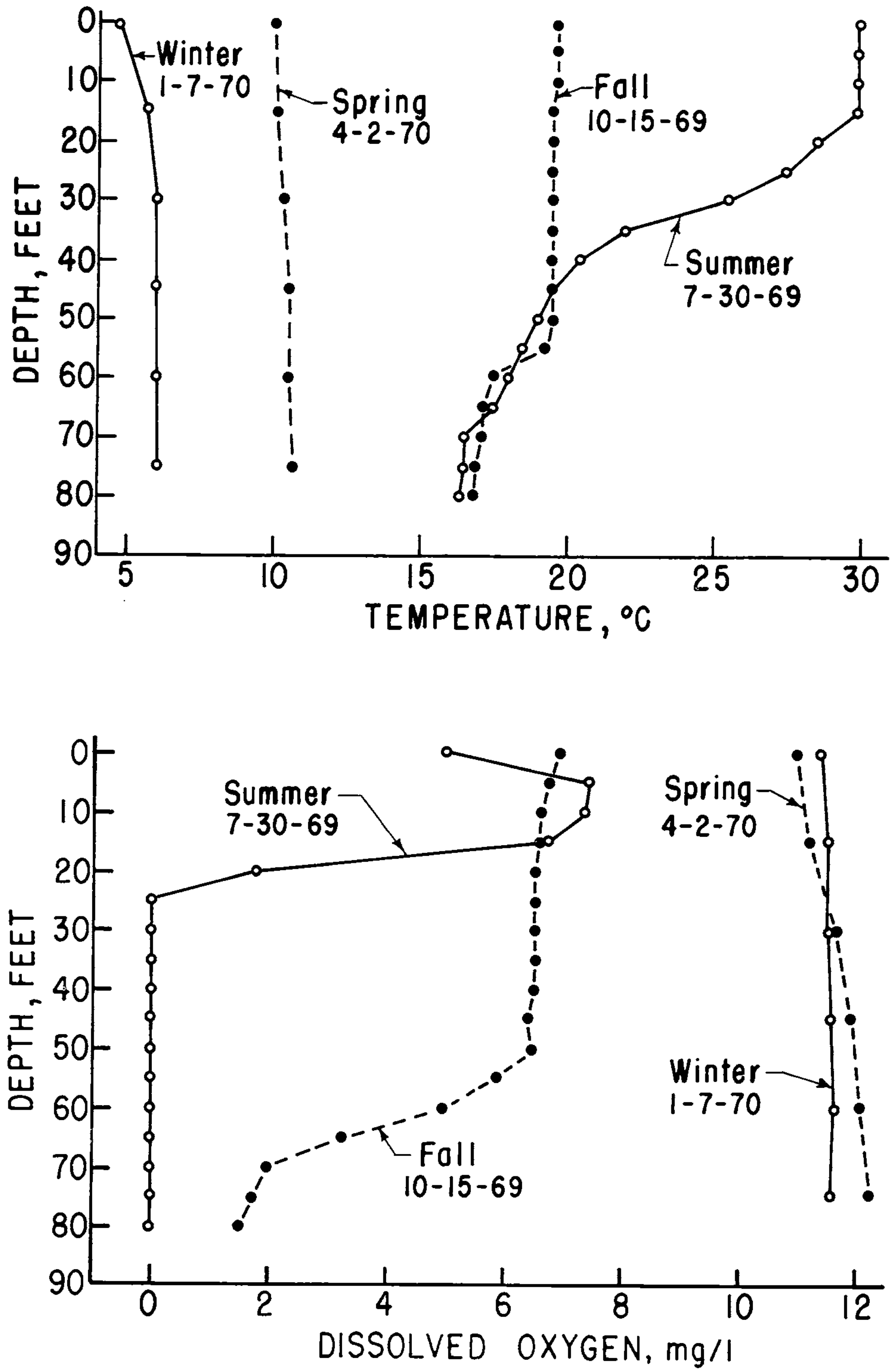


Figure 6. Temperature and dissolved oxygen profiles for selected dates at Lake of the Arbuckles in Oklahoma.

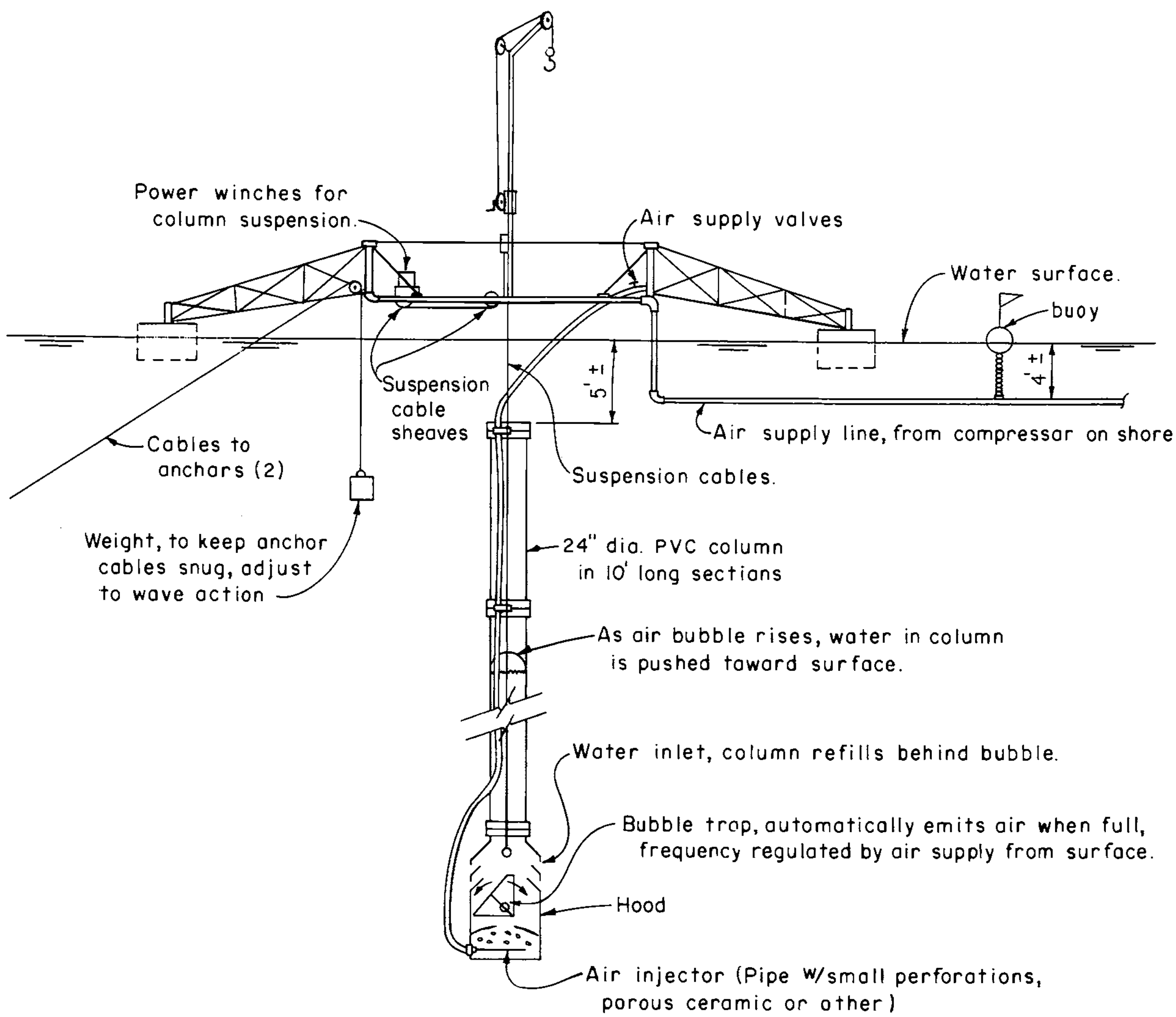


Figure 7. Air-gun device.

under the pump varying from 3.5 feet (1.1 m) to 8.0 feet (2.4 m) in diameter. Water is pumped downward from the reservoir surface.

A 10-horsepower destratifier with a 16-foot (4.9-m) diameter propeller was constructed for the 1974 and 1975 tests at Lake of the Arbuckles. Operation was intended to begin at the onset of stratification with the goal of preventing stratification and maintaining the reservoir in a condition of constant circulation. The same parameters are being monitored as those during the 1973 testing of the air gun. The device is being tested without the diffuser, which will require more power input, but will greatly reduce construction and installation costs.

If the Garton pump shows a marked increase in destratification efficiency over other devices, it probably would not be fruitful to test a diffused air system, since this method has historically shown a destratification efficiency of only about 1 percent.

The Garton pump operated only a short time during the 1974 season because of mechanical difficulties. Pitot tube measurements below the propeller showed a calculated pump flow of about 350,000 gal/min (22.1 m^3/s) at the design propeller speed of 12 r/min. Testing will continue in 1975.

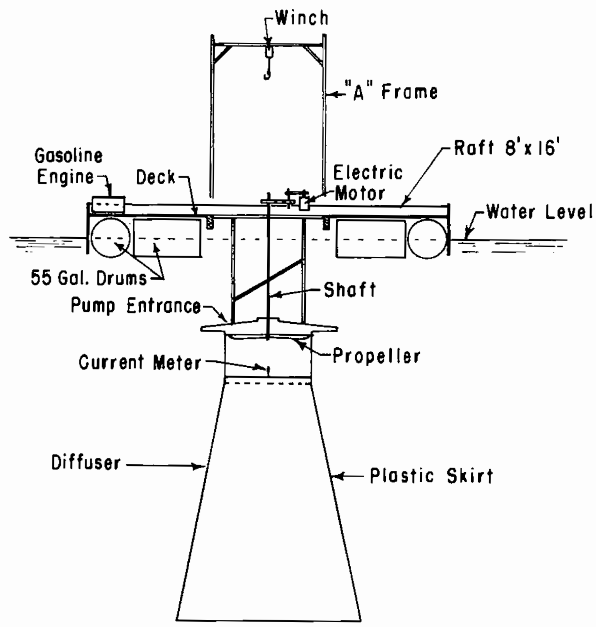


Figure 8. Assembly of Garton pump. (From reference [19])

Lake Casitas

As mentioned previously, a successful diffused-air destratification system has been operating at Lake Casitas in California (fig. 9) since 1968. Since Lake Casitas presents an opportunity for reaeration research, the Mid-Pacific Region of the Bureau of Reclamation has initiated discussions with the Casitas Metropolitan Water District (formerly the Ventura River Municipal Water District) which may lead to a cooperative program. A tentative plan is to: (1) analyze existing data from past operations at Lake Casitas; (2) review alternative methods for reaeration testing; (3) design and construct the most appropriate reaeration or destratification device; and (4) test the device, with appropriate monitoring of physical, chemical, and biological parameters.

Biological Effects

In 1972, under contract with the Bureau of Reclamation, Oklahoma State University and the Oklahoma Cooperative Fishery Unit issued a comprehensive state-of-the-art review of the biological effects of artificial destratification and aeration in lakes and reservoirs [25]. The report includes a summary of available devices for reaeration and destratification of lakes and reservoirs, a review of past investigations concerning biological effects, a statement of research needs, and an annotated bibliography.

Research Needs

The "statement of research needs" is quoted from the foregoing report [25] in its entirety, as follows:

> Greater emphasis must be placed on design and experimentation in studies involving artificial destratification. A team approach is necessary in assessing the effects of artificial destratification on lake ecology. Studies should include rigorous controls so that specific questions can be answered at least for small lakes. It is also useful to develop models to predict and quantitate the perturbation on the system in order to optimize engineering efforts. Long-term changes on a reservoir ecosystem ensuing from annual artificial destratification as compared with antecedent conditions should be analyzed and compared with previous findings derived from observations made in a single summer. A need exists for comparative analysis of the impact of artificial destratification on reservoir ecosystems in different geographical regions in North America. Efforts should involve a decade of sustained effort on one ecosystem. Artificial destratification or hypolimnetic aeration should be considered to be a scientific research project with data carefully recorded and deposited regularly in a central data bank to be available to all researchers. Greater effort must be made to develop aeration tactics in rivers which take advantage of the natural fall of water. These devices ought to require no input of fossil fuel or nuclear energy. There is a need to combine aeration with other engineering alternatives to optimize water quality within and downstream from reservoirs.
>
> Additional effort is needed to study effects of artificial destratification on rates of mineral cycling. Nitrogen stripping using a downflow bubble contact system as described by Speece (1969) should be given immediate review as a possible means for stripping nitrogen from water to alleviate nitrogen supersaturation which causes salmonid mortality. Information on the impact of artificial destratification on cycling of heavy metals, pesticides, and other pollutants is limited. Some hold that since many pollutants (e.g. copper) are lost to the sediments in alkaline and oxygenated waters, artificial destratification and aeration may be a satisfactory means of improving water quality. However, sediment water exchanges cannot be predicted for many elements and compounds at this time (Lee, 1970). Thus, potential pollutants must be monitored in

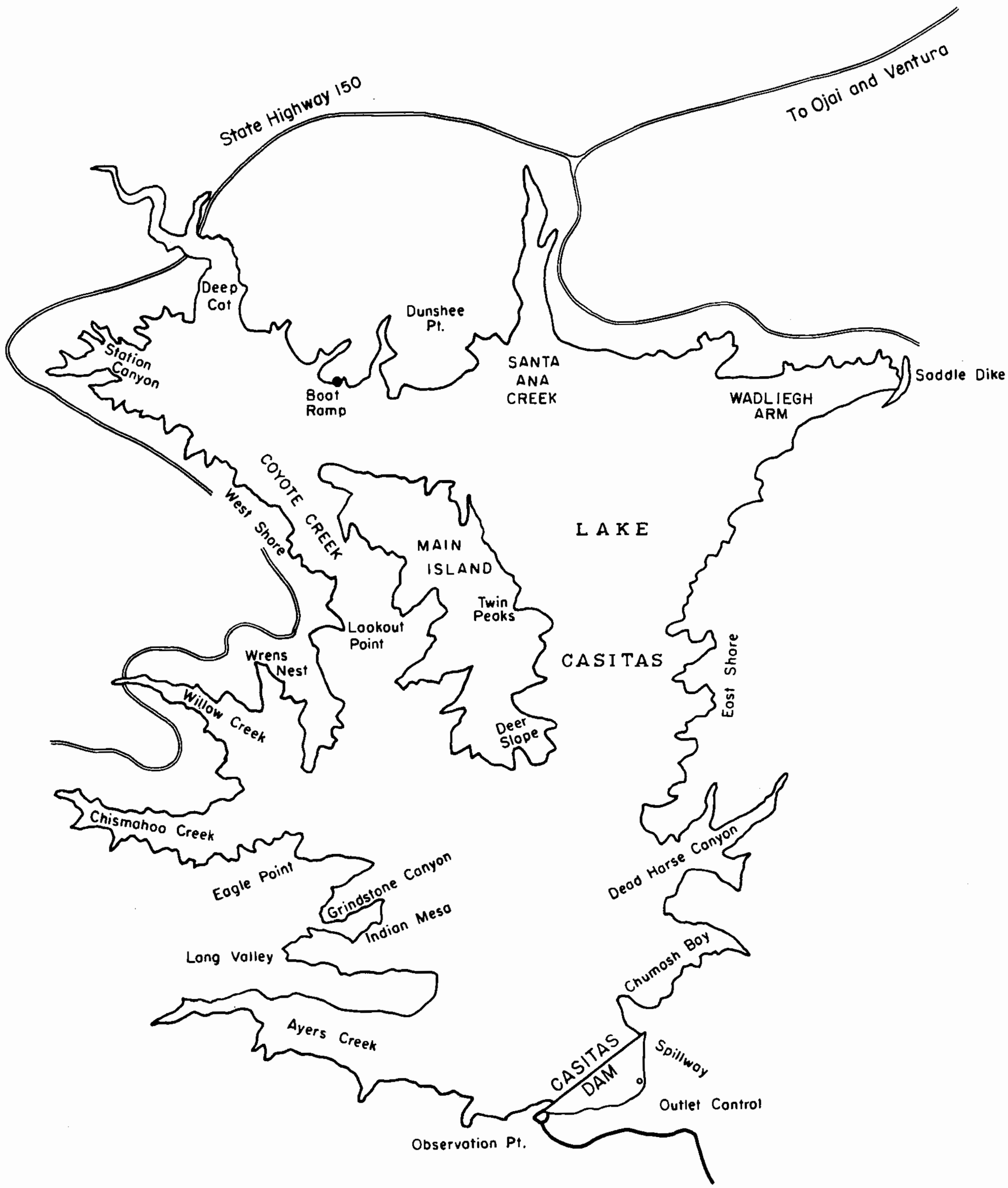


Figure 9. Lake Casitas in California (From Casita Metropolitan Water District information brochure).

the sediments before an artificial destratification attempt is made, especially if it is not known whether mixing will result in suspension of some sediment.

More research is needed on the effect of artificial destratification on structure and function of the biotic community. Information is needed on species diversity of the various groups, population dynamics, microbial ecology, especially human pathogens, and secondary productivity. Further testing of the hypothesis that continuous aeration will retard the process of eutrophication and development of blue-green algal blooms is needed. A need exists to test promising hypotheses of the impact of annual cycles of destratification on dynamics of reservoir fish populations, especially important vital statistics on density, growth, mortality, and recruitment. Careful evaluation of the impact of aeration using U-tubes on fish and other aquatic life needs to be accomplished. Continuous destratification of northern winterkill and southern eutrophic lakes with histories of winterkill should be achieved to evaluate the hypothesis that effective oxidation will reduce detrimental effects on distribution, density, and productivity of aquatic fauna. Downstream effects on aquatic life associated with reservoir aeration needs study.

Additional symposia on reservoir ecosystems are desirable as they produce useful compendia of data, highlight accomplishments, and research needs. A special symposium on aeration of natural and man-made lakes would be desirable. The authors encourage a greatly expanded program of funding of research by Federal agencies charged with responsibility for hydroelectric, water supply, flood control, and irrigation developments.

Extensive monitoring would be required as part of this suggested research. Such monitoring will require a substantial number of people both for recording and analyzing the data. Therefore, monitoring would be expected to consume a large portion of the budget for any reservoir reaeration research activity.

A monitoring program is underway at Lake of the Arbuckles to determine the physical, chemical, and biological effects of artificial mixing at that location.

REAERATION OF RESERVOIR RELEASES

Introduction

Application of reaeration or destratification techniques to reservoirs, with the object of improving reservoir water quality, would be expected also to improve the quality of waters released from the reservoir. When operations within the reservoir are infeasible or otherwise undesirable, application of reaeration techniques after the water leaves the reservoir may be appropriate. Reaeration methods can be applied within conduits, hydraulic equipment, hydraulic structures, and the downstream channel. In some cases, air entrainment, which occurs through operation of gates, valves, conveyance structures, and energy dissipators, provides adequate reaeration or even supersaturation. However, the latter condition sometimes results in gas embolism in fish.

Hydraulic Structures

Background

In 1969, Elder and Wunderlich [11] of the Tennessee Valley Authority (TVA) reported on the use of the Howell-Bunger valve as a reaeration device. A special containment structure was developed. Results showed that this technique provided a high reaeration efficiency, which increased as the discharge velocity increased.

In 1970, Holler [13] described work by the Corps of Engineers in modifying the operation of dams on the Ohio River to increase the capabilities for reaeration. Both of the above techniques provide essentially cost-free oxygenation, since the reaeration devices are intended primarily for other purposes, such as energy dissipation.

The problem of gas embolism in fish emerged prominently in 1970 when large numbers of salmon and steelhead were killed on the Columbia River, apparently as a result of gas supersaturation caused by spillway flows.

Reaeration Capability

Since May 1972, the Bureau of Reclamation has been engaged in a program to measure the effects of typical hydraulic structures on the uptake of dissolved gases

[4]. First priority was given to outlet works and powerplants, with spillways reserved for later study because of their comparatively infrequent use. Measurements were made for 28 structures at separate locations. In 11 cases, reservoir dissolved gas levels near the intakes were below saturation, ranging from nearly zero to 97 percent. Releases passed through various types of energy dissipators and, in two cases, through vented hydraulic turbines. With the exception of one turbine, which had negligible oxygen uptake, all other structures and facilities caused increases in DO to levels ranging from 90 percent of saturation to varying degrees of supersaturation. A basic conclusion is that in nearly all cases, the combined effects of control devices, conveyance structures, and energy dissipators will eliminate DO deficiencies. An analysis is being made of the data to correlate DO uptake with physical characteristics of the structures.

Supersaturation

Grand Coulee Dam is an apparent contributor to the problem of dissolved gas supersaturation and gas embolism on the Columbia River. Extensive data have been gathered at that location under the direction of the Bureau's Pacific-Northwest (PN) Region [2]. The correlation between supersaturation level and spillway discharge is direct. These data, plus other data collected at various types of structures at other locations in the PN Region [3], are included in an analysis to correlate levels of supersaturation with physical characteristics of the structures. Tentative conclusions are extracted from the 1973 report [4] on measurements made by the E&R Center as follows:

1. The dominant factor influencing the level of supersaturation is the pressure to which the entrained air is exposed. Pressure is directly related to the depth of penetration which is determined by the jet's momentum, organization (degree of compactness), and orientation, along with the physical characteristics of the stilling basin, particularly depth.

2. The degree of turbulence in the energy dissipator is a significant factor. Highly turbulent flows (described as frothy, choppy, etc.) tend to show lower supersaturation levels than less turbulent flows (described as rolling, etc.) for similar depths of penetration.

3. The amount of air entrained in the flow appears to be of only secondary importance. Apparently, in essentially all cases, an adequate supply of air is available. The highest supersaturation levels included situations where relatively small quantities of air were entrained in the flow.

Predictive Analysis

A predictive capability has recently been developed. The analysis yields the dissolved gas levels that would result from the operation of a wide variety of spillway or outlet works structures. Both the reaeration capability and the supersaturation potential of these structures may be evaluated. Factors considered include water temperature, barometric pressure, reservoir dissolved gas level, release structure size and shape, release flow velocity, discharge, and stilling basin depth and shape. Comparison of the results from this analysis with measured prototype data has shown excellent agreement. A detailed report on this analysis, which includes several example applications, is being prepared. Figure 10 shows an operating stilling basin with predicted and observed levels of nitrogen supersaturation noted.

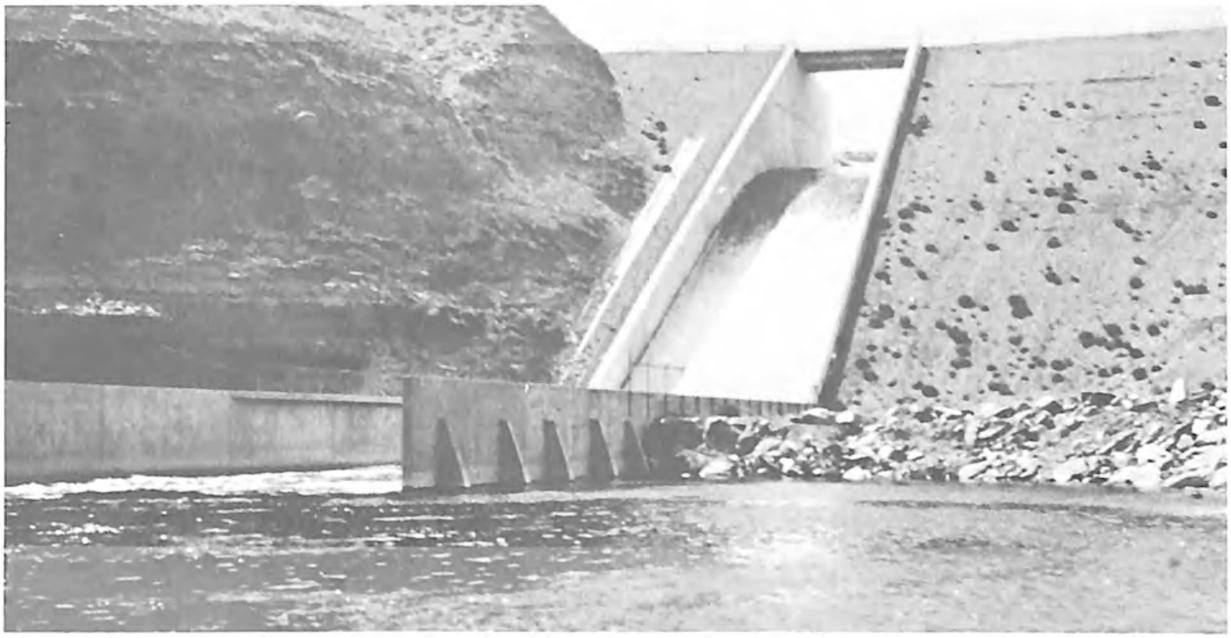
Hydraulic Turbines

Background

The earliest significant experience in reaeration by the venting of hydraulic turbines was in Wisconsin for low-head units [28]. Raney and Arnold reported on the aspiration of air into the draft tube of an Alabama Power Company unit with a power head of about 65 feet (19.8 m) for the propeller turbine [20]. In this case, deflecting plates were installed in the draft tubes to produce regions of negative pressure for aspiration of the air. The Corps of Engineers is conducting tests at Lake Table Rock in Missouri which include investigation of injecting compressed air or molecular oxygen or a combination of the two into the turbine or penstock. This is a high-head installation of about 200 feet (61 m). A cost analysis resulted in the choice of molecular oxygen injection through the Gibson piezometer taps in the penstock. Approximately 20 tons of oxygen per day will be required to maintain a downstream DO level of 6 mg/l.

Reaeration Capability and Supersaturation

The monitoring program conducted by the E&R Center has included hydraulic turbines. One vented hydraulic turbine installation caused very high supersaturation levels while others did not. One reason for this difference may be the quantity of air entering the turbine. The depth of the draft tube, and thus the pressure to which the entrained air is exposed, is certainly a major factor, although this alone did not



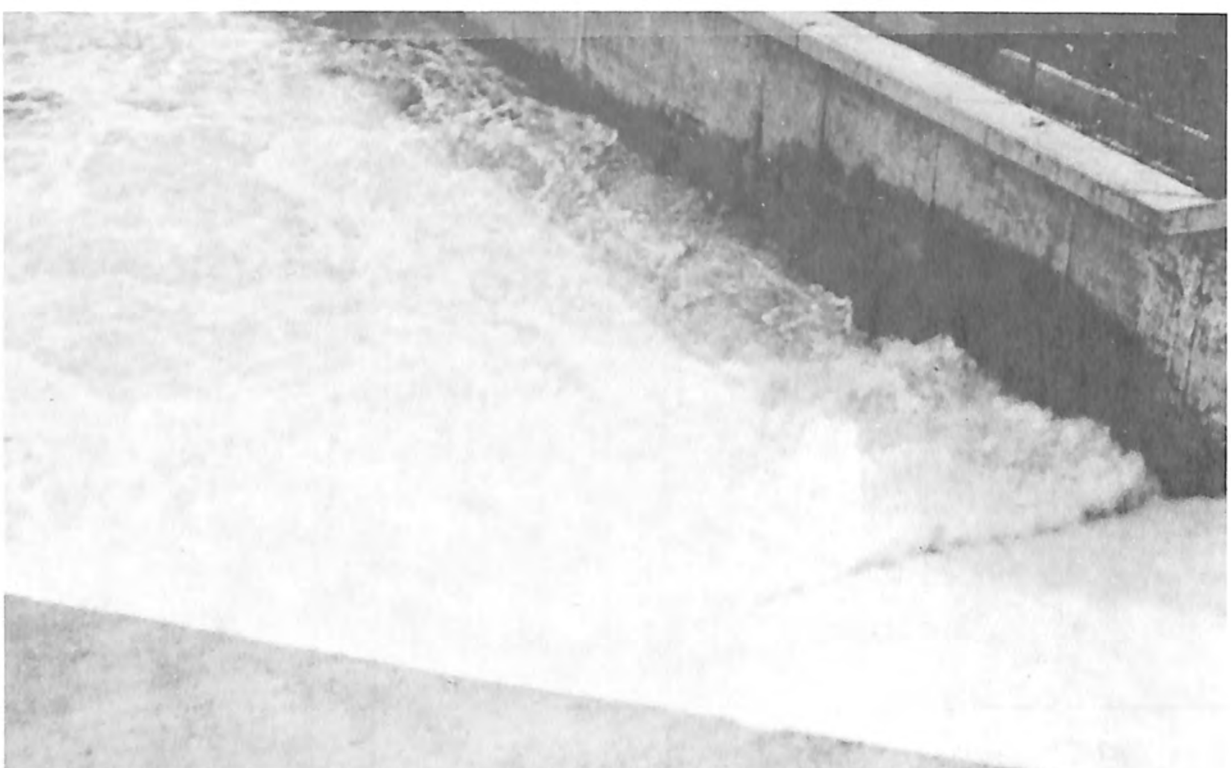


Figure 10. Operating stilling basin with predicted (117 percent) and observed (116 percent) levels of nitrogen supersaturation. Top photo PX-D-75770, bottom photo PX-D-75771

explain the differences observed. The complex swirling flow conditions and boundary geometrics of a draft tube must also influence the time of exposure and possibly the pressure.

Obviously, more research is needed on this aspect of the supersaturation phenomenon. The quantity of air should be monitored at prototype installations. Tests on hydraulic models of turbines might also provide some insight.

Other Methods

TVA is conducting full-scale operational tests on a system for diffusion of molecular oxygen in the reservoir immediately upstream from the penstock intakes. The oxygenated water is thus swept directly into the intakes and only the downstream release is affected. The diffusers for the system were chosen on the basis of laboratory and field tests.

TVA has also investigated the technique of supersaturating a bypassed flow with oxygen, then releasing the supersaturated flow into the main stream for mixing. Thus, only relatively small flows need to be handled.

In any event, the tonnage requirement for oxygen or air will be determined by the deficiency, regardless of the method used. An example calculation of oxygen and air requirements is given in table 3.

Miscellaneous devices which show promise for reaerating reservoir releases include the U-tube and the downflow-bubble-contact aerator, both developed by Speece [21, 22].

HYPOLIMNION REAERATION

Situations occur in which it is desirable to reaerate the reservoir without destroying the stratification. For example, cold bottom waters may be desirable for a downstream fishery or municipal water supply. If the hypolimnion is deficient in DO, methods are available for injection of molecular oxygen into this layer. The basis of this concept is that oxygen will dissolve completely within the hypolimnion and bubbles will not be available to rise through the higher layers and cause destratification. This assumption is not entirely correct, since bubbles of pure oxygen will strip nitrogen and other available gases from the water. Therefore, a reconstructed bubble may continue to rise through the higher layers.

TABLE 3.—*Example calculation for oxygen or air injection*

Equivalent terms for O_2 concentration:

$$
\begin{aligned}
1 \text{ mg/l} &= 28.317 \text{ mg/ft}^3 \\
&= 6.243 \times 10^{-5} \text{ lb/ft}^3 \\
&= 3.121 \times 10^{-8} \text{ ton/ft}^3 \\
&= 1.360 \times 10^{-3} \text{ ton/acre-feet} \\
&= 1{,}360 \text{ tons/million acre-feet}
\end{aligned}
$$

Oxygen requirements in releases:

Month	Avg. O_2 deficiency, mg/l	Release, acre-feet	O_2 required, tons
June	1	800,000	1,088
July	1.5	700,000	1,428
Aug.	2	500,000	1,360
Sept.	2	400,000	1,088
			4,964 tons total

Assuming a cost for molecular oxygen of $50 per ton:

Oxygen cost = 50 (4,964) = $248,200

Assuming maximum discharge of 13,000 ft^3/s

$$
\begin{aligned}
&\text{max. rate of } O_2 \text{ injection} \\
&\quad = (6.243 \times 10^{-5})\,(1.3 \times 10^{4})\,(2) \\
&\quad = 1.62 \text{ lbs } O_2/\text{s}
\end{aligned}
$$

Assuming injection of bubbles under a pressure of 2 atmospheres (1 ft^3 O_2 = 0.18 lb):

$$\text{Volume rate} = 1.62/0.18 = 9 \text{ ft}^3/\text{s } O_2 = 540 \text{ ft}^3/\text{min } O_2$$

If atmospheric air (21 percent O_2 by volume) is used instead of pure oxygen, the corresponding required maximum volume rate is:

$$\frac{540}{0.21} = 2{,}570 \text{ ft}^3/\text{min air}$$

However, this assumes 100-percent transfer efficiency of the oxygen in the air. Assuming an actual transfer efficiency of 10 percent (which is probably somewhat too high, based on experience), the required rate would be 25,700 ft^3/min or 428 ft^3/s of air. This would occupy about 3 percent of the total flow area.

Speece's downflow-bubble-contact aerator can be used for the method mentioned above. Fast [12] and Bernhardt [7] have developed hypolimnion reaeration devices which use compressed air. A bypass technique, in which the water is pumped from the hypolimnion to the shore, aerated, and then returned to the hypolimnion, has also been used [18].

Hypolimnion reaeration has a potential for application at Flaming Gorge Reservoir, where a portion of the hypolimnion never mixes with the remainder of the reservoir and remains at 39° F and zero DO the year around. This layer, technically called the monimoliminion, is about 200 feet (61 m) thick at the dam and tapers to zero approximately 12 miles (19.3 km) upstream. The top of the monimoliminion, the chemocline, is immediately below the penstock intakes. Therefore, mixing with higher levels might allow passage of toxic waters through the penstock, though the monimoliminion has remained stable for several years. The possibility of applying hypoliminion reaeration is being investigated.

INSTREAM REAERATION

Instream reaeration is defined for purposes of this report as a problem separate from that of reaeration of reservoir releases. An example would be a stream which is unaffected by or distant from a storage impoundment, or a stream entering a storage impoundment. Many devices are available for instream reaeration including diffusers, mechanical aerators, cascades, and U-tubes, and are more completely discussed in [14] and [25]. No serious problems have been identified on Bureau of Reclamation projects which could not be corrected by reservoir reaeration or reaeration of reservoir releases; therefore, little attention has been directed to this aspect of reaeration research. However, reaeration of reservoir inflows in some cases may be the most economical alternative.

CORROSION BY MOLECULAR OXYGEN

Injection of oxygen bubbles immediately upstream from the dam or directly into the penstock or turbine will cause structural components to be exposed to free bubbles of pure oxygen or water supersaturated with DO. Through the Federal Interagency Steering Committee on Reaeration Research, the Bureau was encouraged to investigate potential corrosion of materials, particularly metals, when molecular oxygen is injected into reservoirs, conduits, or machinery. This investigation began in 1973 with a literature survey to determine the state of the art, and a test facility is under construction. Early indications from this investigation show that little or no work has been done in this field and that little is apparently known about the potential magnitude of the problem. Laboratory research will be supplemented by examination of turbine components following operation of the TVA and Corps of Engineers projects which involve injection of molecular oxygen. The following is an excerpt from the results of a literature search on materials corrosion associated with reaeration using molecular oxygen:*

> Corrosion in aqueous environments is basically an electrochemical reaction wherein electrons are released at the anode with metallic ions formed by oxidation going into solution. At the cathode, electrons are accepted and negative ions are formed. Action at the anode and cathode are interdependent, i.e., neither can proceed without the other.
>
> In the case of iron (steel) in water, iron goes into solution as ions and electrons are left behind in the metal at anodic areas. These electrons travel through the steel to the cathode, where they combine with hydrogen ions to form hydrogen gas.
>
> In neutral, slow-moving, deaerated waters, the evolution of hydrogen gas at the cathode proceeds slowly and accumulates as a layer of hydrogen on the metal. This layer decreases the cathodic reaction and thus the reaction is referred to as cathodic polarization. Therefore iron corrodes very slowly in quiescent, deaerated waters.
>
> Dissolved oxygen in the water upsets the equilibrium condition established by cathodic polarization. The oxygen reacts with the accumulated hydrogen to form water. As the hydrogen is removed in this manner, corrosion is allowed to proceed. Oxygen is therefore often referred to as a cathodic depolarizer.
>
> From the above discussion, one can see that addition of oxygen can accelerate the corrosion rate of steel in water. Conversely the corrosion rate of some metals and alloys can be reduced by

*Memorandum from Chief, Applied Science Branch, to Manager, Reaeration Research Program Management Team, through Chief, Division of General Research, Denver, Colorado, March 8, 1974.

addition of oxygen. Examples of such alloys are the stainless steels and aluminum. These materials develop stable protective surface films in the presence of oxygen and are thus rendered passive. These phenomena would hold true in practice were it not for dissolved oxygen concentration gradients which develop within the water. Local differences in oxygen content can result in concentration cells whereby cathodes develop at areas of high O_2 concentration and anodes occur in areas of lower O_2 content, such as at crevices and under surface films or encrustations. A prime example is the susceptibility to crevice corrosion of the stainless steels.

In addition to its deleterious effect on metals and alloys, oxygen is also regarded as one of the most damaging influences on organic and synthetic coatings. Oxidation of complex organic coatings may result in simpler, more soluble products which are readily washed away so that the process can continue. Oxidation of natural and synthetic rubber materials can result in cracking, particularly when stress is introduced. [S]ome evidence of deterioration of coal-tar enamel in the form of cracking [has also been observed] at two test sites in [a] test in oxygen-enriched wastewaters. This is highly significant, as coal-tar enamel is currently the standard Bureau penstock lining material. Coal-tar enamel together with cement mortar are also the standard lining materials for ferrous pipelines.

With this abbreviated background of the corrosion theory as well as experiences in mind, a literature search was conducted to determine the effect of pure oxygen additions to fresh waters on the corrosion rate of traditional materials of construction.

Although inquiries were sent to both the Smithsonian Science Information Exchange and the U.S. Department of Commerce, National Technical Information Service, no information was retrieved on this subject.

However, a search of the local libraries revealed substantial information which is summarized as follows:

1. All sources agreed that dissolved oxygen is the major corrosive component in waters.

2. Uhlig [26] reports results of tests in slowly moving water containing 165-ppm $CaCl_2$ at 25° C in which the corrosion rate of mild steel varied linearly from nearly 0 at 0-ppm O_2 to 18 mils per year (mpy) at 8-1/4-ppm O_2.

3. Uhlig also reports that although increases in O_2 initially accelerate corrosion of iron, the rate decreases to a low value at O_2 contents beyond a critical concentration due to passivation of the iron by O_2. The critical concentration would vary with pressure, temperature, and TDS of the water, but for distilled water was found to be 18 ppm as opposed to 9 ppm for waters at pH of 10. However, due to its unreliability, Uhlig discourages the use of oxygen additions beyond the critical concentration for controlling corrosion.

4. Aluminum-base alloys are relatively insensitive to oxygen content [17].

5. Corrosion rate of copper increases with increases in DO concentration [27].

6. The corrosion rate of steel in solutions between pH 4 and 10 is largely independent of pH and is controlled by the diffusion of oxygen at the cathodes [1]. Most fresh waters fall within this pH range.

7. Very little oxygen is utilized in corroding metal. At 5 fps (1.5 m/s) water velocity in a 24-inch main, Larson [16] doubts that more than 0.1-ppm change in DO occurs.

8. Aeration effects are often most pronounced at the water-air interface in a vessel [8].

Much information, as indicated by the sampling above, regarding general behavior of metals and alloys in the presence of oxygen is available. However, it was found that due to lack of specificity, little of the information would be useful in designing to cope with highly oxygenated fresh waters. Rather, the information would be useful in designing tests to obtain the desired information.

REFERENCES

[1] *"A Background to the Corrosion of Steel and Its Prevention,"* Corrosion Advice Bureau Booklet No. 3, British Iron and Steel Research Association, London, Great Britain, 1966

[2] *"Dissolved Gas Monitoring at Grand Coulee Dam and Lake Roosevelt,"* Seattle Marine Laboratories, 1972

[3] *"Dissolved Gas Survey, Pacific Northwest Region,"* U.S. Bureau of Reclamation, Boise, Idaho, December 1973

[4] *"Dissolved Gas Monitoring Report – FY 1973,"* U.S. Bureau of Reclamation December 1973

[5] *"Flaming Gorge Dam Destratification Testing – 1972,"* U.S. Bureau of Reclamation April 1973

[6] Barnett, R. H., *"Reservoir Destratification Improves Water Quality,"* Public Works, Vol. 102, June 1971

[7] Bernhardt, H., *"Aeration of Wahnback Reservoir Without Changing the Temperature Profile,"* Journal of the American Water Works Association, Vol. No. 59 8, 1967

[8] Bosich, J. F., *Corrosion Prevention for Practicing Engineers,* New York, Barnes and Noble, 1970, p. 144

[9] Busby, M. W., *"Elimination of Stratification of Lake Cachuma,"* U.S. Geological Survey, 1970

[10] Carlson, E. J., *"Survey of Reaeration Needs in Bureau of Reclamation Projects,"* U.S. Bureau of Reclamation, February 1972

[11] Elder, R. A., M. N. Smith, and W. O. Wunderlich, *"Aeration Efficiency of Howell-Bunger Valves,"* Journal of the Water Pollution Control Federation, Vol. 41, No. 4, April 1969

[12] Fast, A. W., *"The Effects of Artificial Aeration on Lake Ecology,"* Ph.D. Thesis, Michigan State University, 1971

[13] Holler, A. G., Jr., *"Reaeration of Discharge Through Hydraulic Structures,"* Ph.D. Thesis, University of Cincinnati, 1970

[14] King, D. L., *"Reaeration of Streams and Reservoirs – Analysis and Bibliography,"* U.S. Bureau of Reclamation Report REC-OCE-70-55, December 1970

[15] Koberg, G. E. and M. E. Ford, Jr., *"Elimination of Thermal Stratification in Reservoirs and the Resulting Benefits,"* U.S. Geological Survey Water-Supply Paper 1809-M, 1965

[16] Larson, *"Chemical Control of Corrosion,"* Journal American Water Works Association, Vol. 58, No. 3, March 1966

[17] Mears, R. B., *"Aluminum & Aluminum Alloys"* of *Corrosion Handbook,* compiled by H. H. Uhlig, New York, Wiley, 1948, p. 39-55

[18] Mercier, P. and J. Perret, *"Aeration Station of Lake Bret,"* Monatsbull Schrveiz Ver Gas – u Wasserfachm, 29:25, 1949

[19] Quintero, J. E. and J. E. Garton, *"A Low Energy Lake Destratifier,"* Paper No. 72-599, presented at the 1972 Winter Meeting of the American Society of Agricultural Engineers, Chicago, Illinois, December 1972

[20] Raney, H. C. and T. G. Arnold, *"Dissolved Oxygen Improvement by Hydroelectric Turbine Aspiration,"* Journal of the Power Division, Proceedings, Vol. 99, No. P1 ASCE, May 1973

[21] Speece, R. E., *"The Use of Pure Oxygen in River and Impoundment Aeration,"* 24th Purdue Industrial Waste Conference, May 1969

[22] Speece, R. E. and R. Orosco, *"Design of U-tube Aeration Systems,"* Journal of the Sanitary Engineering Division, Proceedings Vol. 96, No SA 3 ASCE, June 1970

[23] Symons, J. M. and G. G. Robeck, *"Calculation Technique for Destratification Efficiency,"* unpublished report, November 1966

[24] Symons, J. M., *"Quality Control in Reservoirs for Municipal Water Supplies,"* a report of the Quality Control in Reservoirs Committee, Water Quality Division, American Water Works Association, May 1971

[25] Toetz, H., J. Wilhm, and R. Summerfelt, *"Biological Effects of Artificial Destratification and Aeration in Lakes and Reservoirs – Analysis and Bibliography,"* U.S. Bureau of Reclamation Report REC-ERC-72-33, October 1972

[26] Uhlig, H. H. *Corrosion and Corrosion Control,* New York, Wiley, 1963 p 81

[27] Wilkins R. A. and R. H. Jenks, Chapter on Copper from *Corrosion Handbook,* compiled by H. H. Uhlig, New York, Wiley, p. 61-68.

[28] Wisniewski, T. F., *"Improvement of the Quality of Reservoir Discharges through Turbine or Tailrace Aeration,"* U.S. Department of Health, Education, and Welfare Symposium on Streamflow Regulation for Quality Control, Public Health Service Publ. No. 999-WP-30, June 1965

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Bureau of Reclamation

CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	$*0.965873 \times 10^{-6}$	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	$*4.4482 \times 10^5$	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 858-894

ABSTRACT

The research program, Reaeration and Control of Dissolved Gases, has emphasized destratification of reservoirs, biological effects of reaeration and destratification, dissolved gas levels at energy dissipator structures, conception of new methods and devices for reaeration, and corrosion by molecular oxygen. Destratification testing has occurred at Flaming Gorge Reservoir and Lake of the Arbuckles and is being planned for Lake Casitas. Research on biological effects at Lake of the Arbuckles is receiving support and a comprehensive state-of-the-art report has been issued. A dissolved gas level prediction method has been developed from data collected from a wide variety of types of energy dissipators. Laboratory testing on the corrosive effects of the use of molecular oxygen is underway. (28 ref)

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Bur Reclam Rep REC-ERC-75-1, Div Gen Res, Mar 1975. Bureau of Reclamation, Denver, 22 p, 10 fig, 3 tab, 28 ref

DESCRIPTORS—/ aeration/ dissolved oxygen/ *reaeration/ *dissolved gases/ energy dissipators/ supersaturation/ corrosion tests/ reservoirs/ streams/ *progress reports/ *applied research/ bibliographies
IDENTIFIERS—/ destratification (thermal)/ Flaming Gorge Reservoir, UT/ Lake of the Arbuckles, OK/ Lake Casitas, CA

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