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TECHNIQUES FOR REAERATION OF HYDROPOWER RELEASES

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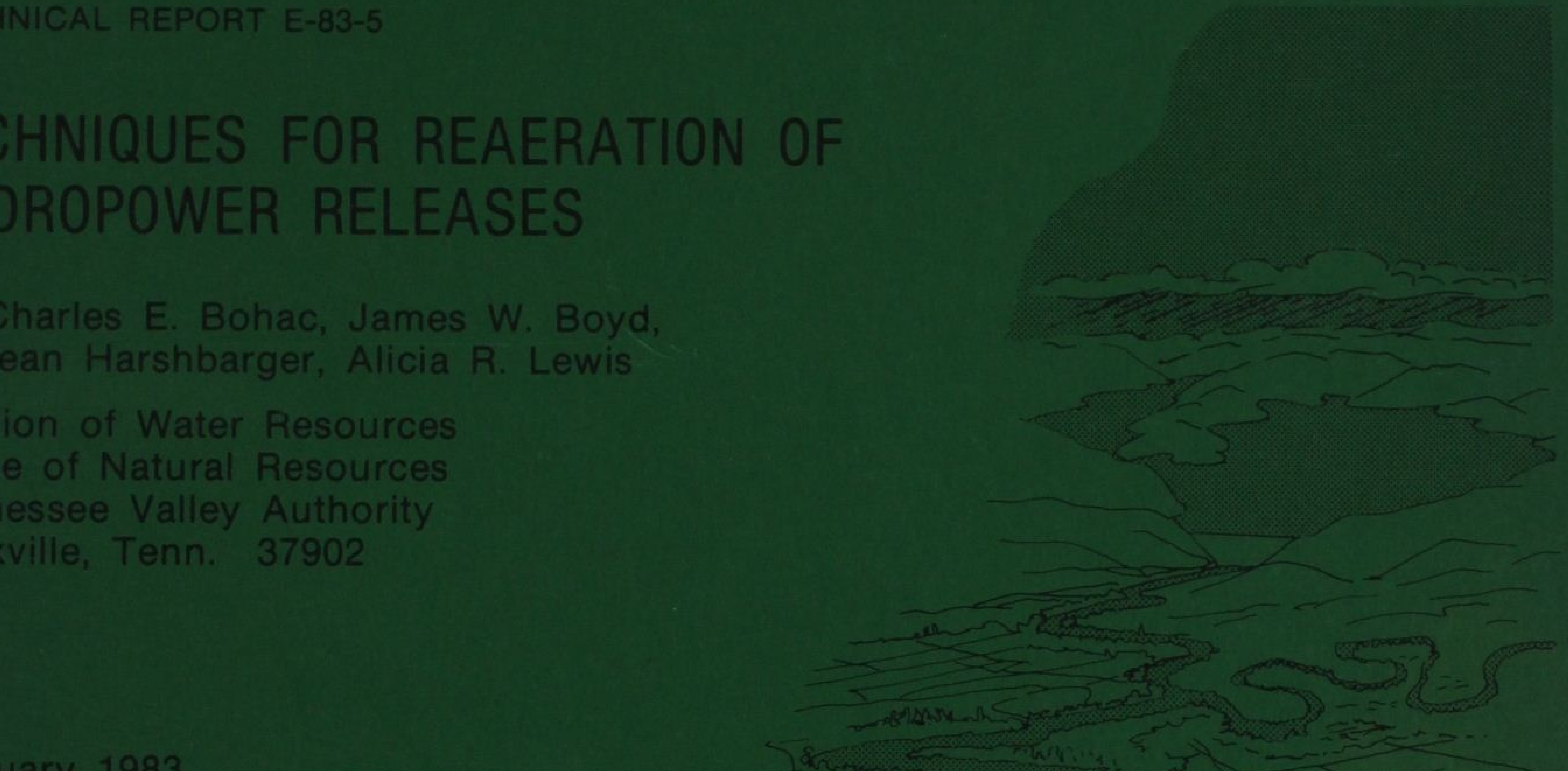

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Methods of aerating hydropower releases were reviewed based upon information from both published and unpublished sources. Techniques which aerated water as it passed through turbines and aeration techniques which were used in the reservoir itself to improve dissolved oxygen concentrations in the releases were the focal points of this review. Both American and European installations were investigated.

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PREFACE

The literature review contained herein was sponsored by the Office, Chief of Engineers, U.S. Army, as part of the Environmental and Water Quality Operational Studies (EWQOS) Program, under Work Unit IIIA.3 entitled Alternatives for Aeration/Oxygenation of Hydropower Releases. The survey was conducted and the report prepared during the period from October 1980 to April 1982 by Messrs. Charles E. Bohac, James W. Boyd, and E. Dean Harshbarger and Ms. Alicia R. Lewis, Division of Water Resources, Tennessee Valley Authority (TVA). Technical data and literature references were provided by the following contributors:

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Included as Appendix A within this report is a survey of European literature and power companies conducted independently by Dr. Peter Volkart for Escher-Wyss AG Machine Works, Zurich, Switzerland. Permission to publish this survey was granted by the Laboratory of Hydraulics, Hydrology, and Glaciology, Federal Institute of Technology, Zurich, through the assistance of Dr. D. Vischer. Translation from the German was provided by Language Services, Knoxville, Tenn.; technical review was provided by Prof. Arnold Hoerler and Dr. Erwin Maerki and by Dr. Svein Vigander and Mr. Richard Ruane, TVA. The translation was incorporated with only minor editorial changes.

General guidance for this report was provided by Dr. Dennis Smith, U.S. Army Engineer Waterways Experiment Station (WES); Mr. Randall Miller, U.S. Army Engineer District, Savannah; Mr. Tasso Schmidgall, U.S. Army Engineer Division, Southwestern; and Dr. Jerome L. Mahloch, Program Manager, EWQOS, WES.

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1.0 INTRODUCTION

Background

Changing institutional and legal considerations, the increase in demands upon the Nation's waterways for all beneficial uses, and the present sense of national urgency to seek the most cost-effective measures to meet water quality goals have all refocused attention on reaeration of hydropower releases. Because of the potential contribution which hydropower release aeration can make to enhance and preserve water quality, the U. S. Army Corps of Engineers Waterways Experiment Station contracted with the Tennessee Valley Authority to conduct a literature search of techniques to reaerate hydropower releases. The specific objective was to compile a summary and a comprehensive list of literature references of state-of-the-art aeration methods to improve the dissolved oxygen (DO) concentration of hydropower releases.

Low DO in hydropower releases is most often caused when, during summer months, reservoirs become stratified with the formation of two distinct layers of water in the impoundments. During the spring in a reservoir which stratifies, the top layer (epilimnion) is exposed to sunlight and becomes warmer and less dense than the cooler bottom layer (hypolimnion). The difference in temperature which develops between the epilimnion and hypolimnion results in very little mixing of the two layers. The natural processes which use oxygen in reservoirs, several of which are respiration of living organisms, decomposition of organic materials, and chemical reaction of materials in the water and sediments, are at work in both the epilimnion and hypolimnion. However, only the epilimnion, through its exposure to air and sunlight, is able to replenish its DO, while DO is gradually reduced in the isolated hypolimnion. Water drawn from the lower levels of a stratified reservoir during turbine operation can, therefore, have a low DO concentration during summer and fall months. Releases from the reservoir during this period may reduce DO downstream to such an extent that there is no longer enough oxygen to assimilate wastes discharged into the river or to support fish and other aquatic life.

Previous Reviews

King (1970) discussed extensively the theory of reaeration and evaluated twelve artificial aeration methods including the use of high-purity oxygen. In addition, over 400 references were abstracted on subjects ranging from the DO aspects of streams, reservoirs, and estuaries to the equipment used for reaeration. The King review is an excellent reference document; a summation has not been attempted here, rather it is recommended that anyone seriously involved with reaeration should obtain a copy of it.

Knapp (1973) presented over 350 abstracts relating to the aeration of natural waters; he did not evaluate or compare any of the reaeration systems and equipment, as did King. A third review by Volkart (1979) covered a broad range of techniques for reaeration, including a very complete description of turbine aeration. Diffused air, weirs, surface aerators, and high-purity oxygen were also discussed in detail. Because this review has not yet been published in English, it was translated and appears as Appendix A of this report.

JBF Scientific Corporation (1971) investigated mechanical surface aerators, diffusers, downflow contactors, and sidestream mixing using high-purity oxygen in relation to river and stream reaeration. The intent of this review was to consider aeration systems for "polishing" the stream after waste discharges had received at least secondary treatment. Although the systems discussed were not reviewed in the context of improving hydropower releases, some of them could be applied for that purpose.

Scope

Most of the research and development activities of the last ten years have been directed toward turbine venting or aeration in the reservoir for the improvement of reservoir water quality in hydropower releases. To supplement and update the earlier reviews, the scope of this report was narrowed from that of previous efforts and focused on turbine venting and reservoir aeration. Studies in these two areas which have not previously been evaluated were reviewed, including information obtained on several as yet unpublished tests and developments.

Simply stated, turbine venting is a process in which water is aerated as it passes through a hydroelectric turbine. Turbine installations usually have internal venting systems, such as automatic vacuum breakers for low-flow or sudden flow cutoff situations, which, when open, allow air to be drawn into regions of subatmospheric pressure typical of enclosed, gravity-induced, vertical flow. For the purpose of aeration, these systems have often been used as designed and modified with larger air supply pipes, compressors, or other devices to boost air flow, or with additional air-injection points or distribution devices. Turbine venting has been traditionally employed on some units to smooth machine operation; although this study reviewed only the turbine venting aspects relating to water quality, a number of references are presented which discuss operational benefits derived from turbine venting. It was found that many early turbine venting efforts were no longer in operation due to institutional changes which had improved reservoir releases; therefore, institutional considerations were described when relevant.

The section on aeration in the reservoir was narrowed in scope to focus upon those efforts directed toward aeration for the primary purpose of release improvement. However, selected reservoir aeration studies not conducted primarily for improving hydroturbine releases but which have application for hydroturbine release reaeration were also reviewed.

Because oxygen transfer mechanisms are vitally important to the development of more efficient reaeration methods, selected references on oxygen transfer research were also cited. Additionally selected references are presented on oxygen transfer tests and measurements, stream aeration, and aeration systems in general.

2.0 APPROACH

The literature search included the traditional review of available literature and associated references and the investigation of private files, personal contacts, and communications with turbine manufacturers and utility companies. In addition, three computerized reference systems were used; a fourth computerized system, which became available near the end of the project, was reviewed manually.

The RECON system, developed for use by the Department of Energy, provided access to a number of different data bases. These bases included citations from primary and secondary source publications reporting on such fields as management, technology, planning, law, political science, economics, geology, biology, and chemistry as they related to environmental issues. The literature covered included periodicals, government documents, industry reports, proceedings of meetings, newspaper articles, films, and monographs dating as far back as 1931. The RECON system supplied international coverage.

The DIALOG system provided worldwide coverage of approximately 3500 journals, publications of engineering societies and organizations, papers from the proceedings of conferences, and selected government reports and books.

Key words used in DIALOG and RECON were: baffle, penstock, turbovent, aeration, and oxygenation reaeration. Combinations of key words included: hub baffle, draft tube, vacuum breaker, and turbine vent. This list was further augmented by the plural variations of the key words and combinations.

A search was also made of the publication Water Resources Abstracts, using the key words turbine aeration, turbine vent, turbine aspiration, hydroturbine aeration, tailrace aeration, draft tube vent, and vacuum breaker.

A manual search was made of the monthly publication Hydromechanics and Hydraulic Engineering Abstracts, published by Delft Hydraulic Laboratory, Delft, The Netherlands. Each issue contained a list of key words and associated abstracts. The abstracts were selected from more than 600 periodicals, report series, Congress proceedings, and monographs. For the years 1978 through 1980 and part of 1981, abstracts for the following key words were reviewed: aeration, reaeration, oxygenation, reoxygenation, air entrainment, entrapped air, air injection, oxygen injection, draft tube, and turbine vent. This information was also part of the computerized data base, Delft Hydro. The data base is searchable online at QL Systems, Ottawa, Ontario, Canada, through Datapac.

3.0 SUMMARY

The two major categories of hydropower reaeration systems which have received the most attention in recent years have been turbine venting and aeration in the reservoir. Generally, neither of the two categories was preferred to the other because the specific techniques within each category were evaluated on the site-specific needs of each project.

Turbine venting at hydroelectric projects for the purpose of reaerating reservoir releases was first used in the United States in Wisconsin about thirty years ago. Turbine venting configurations reviewed herein included oxygen diffusers in the turbine flow, air aspiration into the draft tube below the turbine wheel, and mechanical injection with the use of compressors. In general, the amount of oxygen transferred to the water depended mainly on air or oxygen flow, water flow, mixing time, degree of turbulence, and DO deficit (the difference between the saturation DO concentration and the unaerated DO concentration).

Turbine venting by means of aspiration occurs when subatmospheric pressure (vacuum) in the draft tube draws air in to mix with the turbine flow. Many turbines for which data were reported had accommodations for venting, such as automatic vacuum breaker valves for low-flow or sudden flow cutoff situations. Thus, at many installations atmospheric aeration was induced by the turbine flow by simply opening the vent system. The oxygen concentration was increased by about 1 to

4 mg/l with this method, which was most effective at low turbine-flow and low oxygen concentrations.

Of three basic turbine types in general use, only the Francis and propeller types were suitable for venting in response to a vacuum developed within the draft tube. The relationship between the air-flow entry elevation into the draft tube and the turbine tailwater elevation was critical in determining the magnitude of the vacuum.

A vacuum often existed below the turbine at low water-flow rates but decreased with increasing flow rates. In many cases, turbines were throttled to only a fraction of their capacity in order to maintain aspiration capabilities. To induce additional vacuum, deflector plates were used on the draft tube wall and on the hub or runner cone of Francis turbines. These devices were successful in aspirating air flows of as much as 3 percent of water flow, with associated DO increases of over 4 mg/l at maximum turbine discharges. Power reductions due both to the presence of the baffles and the presence of air were observed for these types of venting systems. The losses varied as a function of head, with high heads yielding a smaller percentage of loss compared to facilities with lower heads, other factors being equal. The power losses were also a function of baffle size, number of baffles, and air-flow rate.

Compressed air injection into the draft tube was used when hydraulic conditions did not permit the use of the aspirating type of turbine venting. Compressed air confined power reduction to only the period of aeration, but it was generally more capital-intensive than baffles.

Reservoir aeration with compressed air was not generally cost-effective compared to high-purity oxygen injection, unless the compressed air system was also designed to destratify the reservoir. Oxygen had several advantages over air in that higher DO levels could be achieved without excessive gas supersaturation. Reservoir aeration with oxygen was capital-intensive but did not reduce turbine efficiency as did turbine venting. The decision whether to use oxygen trucked to the site or oxygen generated onsite was made according to case-by-case economic evaluation.

4.0 TURBINE VENTING

Introduction

Turbine venting is a means of aeration of hydropower releases in which air is aspirated or drawn into subatmospheric pressure regions which occur naturally or are created below the turbine in the draft tube. Vacuum is created through the installation of baffles or deflector plates near vent holes which cause a flow separation and localized low pressure areas near the vent openings. Vents are often provided on hydroturbines as part of a vacuum breaker system to protect the turbine during rapid shutdown and to reduce vibration and cavitation during normal operation. Air or oxygen can also be injected through the turbine mechanism or directly into the draft tube through the use of compressors.

Turbine venting has been used to offset both the effects of wastewater discharges and seasonal low DO releases from stratified impoundments.

Wisconsin

Institutional Considerations

Because of turbine venting's potential for use at a number of dams throughout the United States, it is of interest to examine the history of the one instance where it was used for DO control on whole river systems.

Turbine venting was first used in Wisconsin primarily to offset the impact of partially treated pulp and paper industry and municipal sewage discharges but also to improve upon a diffused aeration system installed in 1945. Initially pulp and paper wastewater was generally subjected only to fiber removal prior to discharge. As the pulp and paper industry grew, the DO problems grew most noticeably on the Fox, Flambeau, and Wisconsin Rivers. In 1949 the Wisconsin Committee on Water Pollution developed cooperative stream survey arrangements with many of the pulp and paper companies. In 1958 arrangements were extended to use the dams which were operated by the pulp and paper companies to provide reaeration of the rivers. The Committee on Water Pollution continued to cooperate with industries in performing stream surveys to determine the extent and degree of the DO problems in order to coordinate the turbine venting effort.

Starting in 1966, the Wisconsin State Government began a series of reorganizations and simultaneously began reacting to increasing activity of the Federal Government in pollution control activities. By 1968 the State had moved away from the cooperative arrangements which were initiated some 20 years earlier; in 1969 the State issued its first discharge requirements which mandated secondary treatment for pulp mill discharges. However, because Federal discharge regulations were anticipated to be forthcoming, actual compliance was delayed until 1973-1974.

By 1977 all the mills had secondary treatment in place, and, because the DO no longer approached the low levels of the past, turbine venting no longer was employed. At the present, Pixley Dam on the Flambeau River is the only turbine-venting facility to be operated.

Several of the older dams where turbine venting was performed are being relicensed. At one such facility (Tomahawk Dam) the license was issued with a requirement to turbine-vent should the DO drop below 3 mg/L in the future.

Although wastewater treatment has so far negated the need for turbine venting, water quality modeling has indicated that under extreme conditions some portions of some rivers might be again stressed. To stay within stream standards should these extreme conditions develop, the dischargers were given a stepwise discharge requirement which requires a reduction in pollutant load until conditions improve. Turbine venting could be considered as an alternative to the load reductions, but it would be up to the waste dischargers to make the necessary institutional arrangements to allow this to happen.[1]

Technical Considerations

Wisniewski (1965), Wiley, et al. (1962), and Wiley and Lueck (1960) reviewed the technical aspects of hydroturbine aeration at power dams in Wisconsin. By 1961, turbines at 18 different dams on the Flambeau, Wisconsin, and Lower Fox Rivers were equipped for aeration. Before aeration at Pixley Dam on the Flambeau River, the DO concentrations were found to average from 3.1 to 4.3 mg/L during the year and only 1.1 to 3.3 mg/L in the summer months. Water temperatures were about 20°C or less, during periods of aeration. Thus, the degree of DO

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[1] Personal communication, 1981, J. McKersie, Chief, Water Quality Evaluation Section, Wisconsin Department of Natural Resources, Madison, Wisconsin.

saturation was usually 40 percent or less which allowed a high efficiency of oxygen absorption. Turbine aeration at this dam produced a DO uptake of at least 1 mg/L.

Twelve dams on the Wisconsin River and five dams on the Lower Fox River were also equipped with turbine aeration systems. The simplest method of aeration used was draft tube venting. Vents had already been installed at several of the turbines to control vibration, so little or no changes had to be made at many of the sites. Sites with the propeller-type turbines, however, required special venting for which massive concrete foundations were needed. Blowers had to be installed at Little Rapids Dam on the Lower Fox River because the low-head turbines did not provide enough suction. The turbine vents at most dams were opened and used when the DO concentrations were below 3 mg/L. It was suggested that aeration should begin when the DO saturation was less than 40 percent in order to achieve high efficiencies. DO uptake in most cases was about 1 mg/L. The costs of turbine aeration were based on power losses which were determined to be caused by a reduction in the amount of water going through the turbine. The reduction in water throughput and hence power output was estimated to be 5 percent.

The Wisconsin turbine venting experience was also documented by Lueders (1956), Scott, et al. (1958), and Scott and Wisniewski (1960).

Water Quality Modeling

Falkner, et al. (1970) examined the cost tradeoff between stream aeration using both turbine venting and mechanical aerators and waste treatment on the Wisconsin River. The analysis was based upon the principle that stream DO levels could be maintained either by adding oxygen to the river or reducing the quantity of oxygen-demanding wastes discharged to the river. Two approaches were used. The first assumed an increase in DO due to turbine aeration and then determined the minimum cost waste treatment plan. The second approach assumed a basic waste treatment plan and then determined a turbine venting and mechanical aeration plan which would achieve the DO standard. Analyses showed that, when turbine aeration was assumed to add from 1.0 to 2.8 mg/L of DO at nine dam sites, waste treatment costs decreased significantly and the annual cost to meet the DO standards was lower when compared to waste reduction alone. Other alternatives showed that mechanical aerators at selected river sites and turbine aeration at nine dam sites resulted in a reduction in cost of almost 30 percent when compared to waste treatment alone. When it was assumed that a minimum of primary treatment would be provided by all dischargers, the turbine venting-mechanical aerator alternative resulted in a savings of about 20 percent when compared to the cost of meeting stream DO standards by waste treatment alone. The study concluded that artificial aeration, which would include turbine venting, could be an important component in a minimum-cost system to improve water quality.

Instream aeration was also examined as a water quality management alternative on the Lower Fox River (Ruff, 1979). Due to growth in industrial and municipal discharges on the Lower Fox, there were several potentially low DO areas, especially during low streamflow conditions.

In order to meet standards under the assumed modeling conditions, new waste load allocations were calculated. Dischargers estimated that annual expenditures of $20 million for advanced waste treatment systems would be required to meet the new waste load allocations. As an alternative to advanced waste treatment systems, the DO levels of the river were modeled and the points of maximum DO deficit were identified. The cost of providing enough instream aeration to meet water quality standards along the entire stream segment was estimated. The estimated annual cost for meeting stream standards by providing instream aeration ranged from $300,000 to $400,000/yr. Although turbine venting was used extensively in Wisconsin, it was excluded from the analysis because none of the dams were located at or upstream from the maximum DO sag points.

Duke Power Company

Lee (1965) compared turbine aeration experiments conducted at Wylie Station Dam in South Carolina with similar reaeration work done in Wisconsin. Problems with low DO levels in the Catawba River at Wylie Station were caused by large BOD loads entering Lake Wylie from tributary streams and by wastes from textile plants and pulp and paper mills downstream. Turbine aeration experiments were conducted at Wylie Station on four 20,100-hp (15,000-kW) Francis turbines with a gross head of 70 ft (21.3 m). The units at Wylie were equipped with vacuum breakers which were operated only at low loads. During medium to high loads, a positive pressure existed in the draft tube. Aeration tests with the vacuum breakers open were run at a low turbine load of only 1340 hp

(1000 kW). Several tests at Wylie Station started with DO saturation levels of more than 40 percent and showed DO uptakes of as much as 2.9 mg/L. No power loss measurements due to the air were made. A 65 percent loss of energy due to operation at low loads was suggested in later discussion.

Duke Power continues to provide turbine venting at Wylie Station but no longer in response to heavy waste discharges upstream. Aeration is now provided to prevent a severe taste and odor problem from developing in the municipal water supply of Rock Hill which has its intake below Wylie Station. Aeration is accomplished by dedicating one unit to aeration during the period of June through September and operating that unit at approximately 1340 hp (1000 kW). At the reduced load, the turbine will aspirate air through its vacuum breaker system.[1]

Alabama Power Company

Raney (1973, 1975, 1977, 1979) reported on model and prototype studies to predict and verify operating characteristics of turbine aspiration systems. Based on the model test data, aspiration systems using deflector plates were designed and installed at ten hydroelectric turbines in the Alabama Power Company system. These turbines, located on the Black Warrior and Coosa Rivers, were low-head units of about

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[1] Personal communication, 1981, J. Waldrop, Manager of Operations, Duke Power, Charlotte, North Carolina.

53,700 hp (40,000 kW). In most cases, the existing air pipes of auxiliary systems for depressing the tailwater were used for air supply lines. These pipes were capable of supplying sufficient air to raise DO levels by 0.5 to 1.0 mg/L. For larger increases, additional lines had to be installed. Oxygen absorption efficiencies[1,2] were found to range from about 20 to 45 percent, depending on the initial DO concentration.

Turbine efficiency losses ranged from practically zero to 2 percent, depending on the air flow rate. In other aspects, aspiration flows often appeared to cause smoother machine operation and decreased cavitation damage.

A prototype aspiration system was installed on a Kaplan turbine at Bankhead Dam on the Warrior River (Alabama) to increase the DO level by 2 mg/L when the initial DO level was 2 mg/L. The system's design included eight deflector plates, which measured 6 in (15.2 cm) high and 12 in (30.5 cm) wide with a wedge angle of 30 degrees. A typical Alabama Power installation is shown in Figure 1. These plates were installed at regular intervals around the wall of the 20-ft-(6.1-m-) diameter draft tube just below the turbine wheel. A DO uptake of 1.7 to 1.8 mg/L was observed at an initial DO level of 3.2 mg/L. An oxygen absorption efficiency of approximately 40 percent and a loss of turbine efficiency of about 2 percent were measured at this site.

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[1] Oxygen absorption efficiency = additional mass of oxygen which becomes dissolved in the turbine discharge X 100/total mass of oxygen added to the turbine discharge.

[2] This term was also called "oxygen transfer efficiency" in many of the documents reviewed.

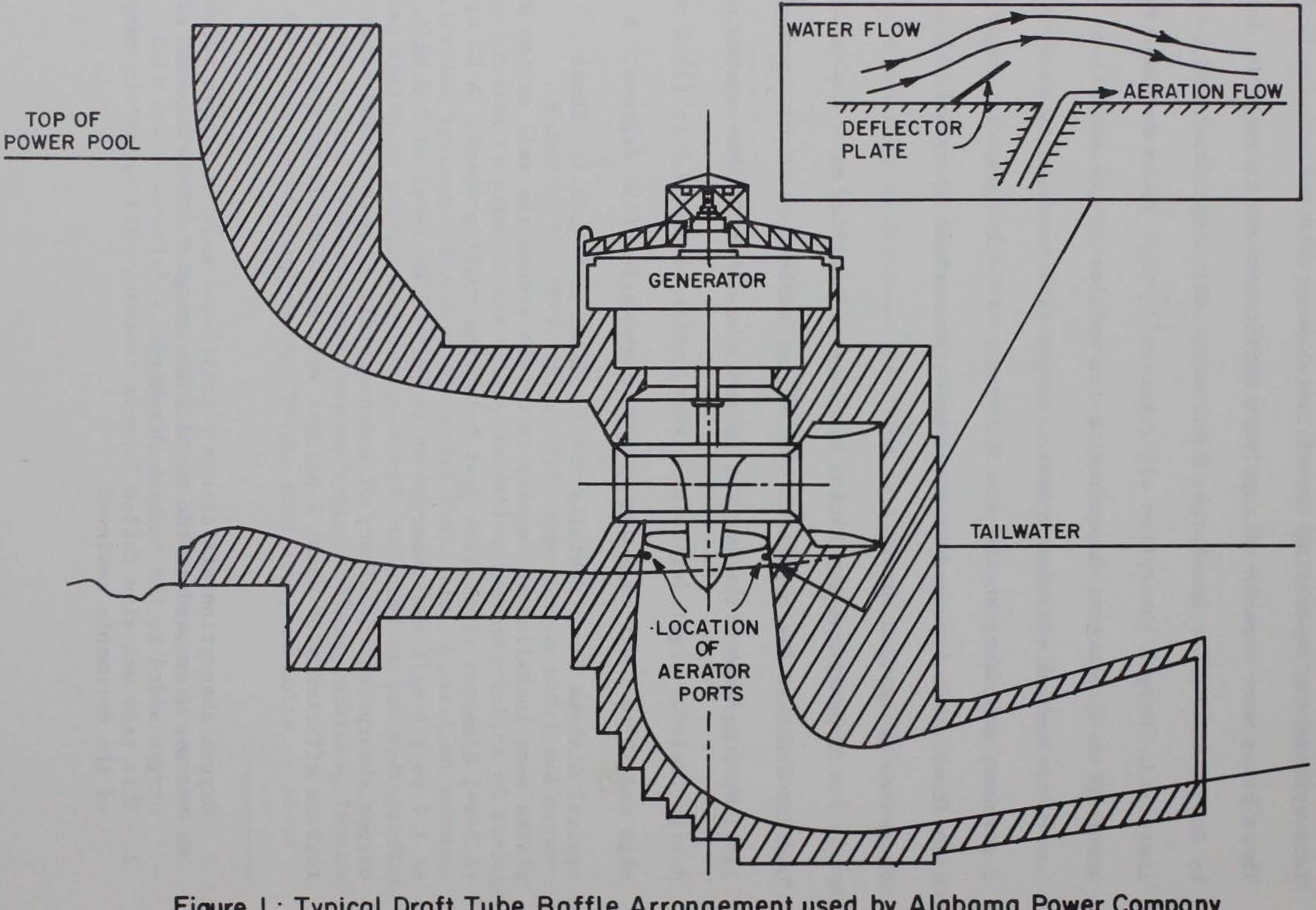

Figure 1 : Typical Draft Tube Baffle Arrangement used by Alabama Power Company

Raney and Arnold (1973) reported on the results of installing deflector plates at Logan Martin Dam (Alabama) which had three 56,000-hp (42,000-kW) Kaplan turbines with operating head at 65 ft (19.8 m). Best gate discharge[1] was about 10,000 cfs (17,000 m^3/min). The results of the two-year evaluation were that (1) the oxygenation efficiency[2] of the aeration system in terms of pounds of oxygen absorbed per kilowatt-hour reduction in generator output due to the presence of the deflectors and air was higher than other aeration processes; (2) a critical parameter was the aeration location elevation relative to tailwater elevation; and (3) to obtain maximum air flow, it was essential to minimize the head loss in the aeration piping system.

Sheppard, et al. (1981) described a model derived from mass transfer theory and field measurements to predict DO and nitrogen concentrations in water discharged from draft tube hydroturbine aeration systems. The model was able to predict oxygen concentrations within $\pm$0.2 mg/L of measured values in 93 percent of the tests performed. The model was intended for use by designers of turbine aspiration systems.

European Experience

Imhoff and Albrecht (1972) discussed turbine aeration processes at Baldeney Dam (Germany) and compared it to Pixley Dam (Wisconsin). At

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[1] Discharge of maximum efficiency.

[2] Mass of oxygen transferred/time/power input for blower, or loss of power due to reduction in turbine generator capability, or a combination of both.

Baldeney, a 20-hp (14.9-kW) blower injected compressed air just above the turbine impeller at 6 psig (0.4 kg/cm^2). With 1940 cfm (54.9 m^3/min) of air, the capacity of the turbine dropped from 530 to 494 cfs (900 to 840 m^3/min). A river discharge of 494 cfs (840 m^3/min) was aerated to transfer 392 lb 0_2/h (178 kg/h) at 20°C and a 50 percent average DO deficit.[1] This required a total power consumption of 169 hp (126 kW) including the turbine losses due to aeration. The resulting oxygenation efficiency was 3.1 lb 0_2/kWh (1.4 kg/kWh). At Pixley Dam two turbine aeration systems supplied oxygen to a total river flow of 406 cfs (690 m^3/min). At 20°C and a 50 percent DO deficit, the oxygen was transferred at a rate of 134 lb 0_2/h (60.8 kg/h) and an oxygenation efficiency of 1 lb 0_2/kWh (0.45 kg/kWh).

The Ruhr River in Germany has presented a major pollution control problem. Although only a relatively small river, a population equivalent waste loading[2] of over 2 million flows through the central area near the city of Essen. In addition to very strict control of effluents by waste treatment plants, the pollution control agency, the Ruhrverband, has applied instream aeration to supplement waste treatment. Three aeration methods were used to try to maintain 4 mg/L in the releases. The methods were: (1) introducing air into hydraulic turbines; (2) diffusers (bubbling from submerged orifices); and

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[1] Percent average deficit = $\frac{[DO_{sat}] - [DO]}{[DO_{sat}]} \times 100$

[2] The number of persons from whom a "normal domestic" or "standard" sewage would produce the same measured characteristic as produced by the waste in question (Babbitt and Baumann, 1952).

(3) mechanical aerators. To remove organic pollution of one population equivalent, at times of low flow, the cost was estimated to be 20 percent less for a mechanical aerator and 5 percent less for the turbine aerator than for expansion of the treatment plant to achieve the same result (Imhoff, 1968).

A field test was made at the Moselle Station to determine the cost and efficiency of pure oxygen as a river oxygenation agent. Planning, performance, and results of the field test were described. A practical example was given to compare cost and efficiency with those of other aeration systems (Hollweg and Thron, 1977).

Full-scale tests were conducted to maintain the oxygen content in the lower parts of the Kalajoki River (Finland) at 7 mg/L. Three methods were investigated: (1) constructing an overflow dam; (2) feeding air into the hydroelectric turbines; and (3) releasing oxygen-rich water from a reservoir with low oxygen demand. At the power plants, air was injected by a fan into the turbine intake screen, into the pressure side of the turbine, and into the suction side of the turbine. Air was also aspirated using only the suction of the turbine. In each of the four cases the water flow was about 636 cfs (1081 m^3/min) and the air flow about 12 cfs (20.4 m^3/min). The fan consumed about 44 hp (33 kW), except on the suction side where it consumed only about 9.4 hp (7 kW). During these tests the generator power output loss was approximately 80.5 hp (60 kW). Oxygenation efficiencies ranged from 3.3 to 8.2 lb of O_2/kWh (1.5 to 3.7 kg/kWh), and oxygen uptakes were between 1 and 2 mg O_2/L at initial DO concentrations of 4 to 6 mg O_2/L (Lakso, 1981).

A bubble-diffuser, turbine aeration using a Rushton-type turbine to aspirate air, and a Rushton turbine acting as a surface aerator were compared by Roustan, *et al*. (1975).

Barkov (1968) described a Russian experience with turbine venting.

Volkart investigated various methods for increasing the oxygen content in rivers, with particular emphasis placed on hydroturbine aeration. Numerical values from the literature served as the basis for relating power consumed for aeration to the weight of oxygen transferred. It was concluded that, of the various physical and chemical parameters governing oxygen uptake, the saturation deficit and the local flow turbulence were dominating. The following aeration methods were studied in more detail: (1) turbine venting, (2) compressed air, (3) weirs, (4) cascades, (5) free surfaces, and (6) pure oxygen. It was concluded that turbine venting stands out as an efficient and relatively economical method. An English translation of the Volkart report appears as Appendix A and contains a very detailed description of much of the European experience.

Portland General Electric Company

At the Portland General Electric Company powerhouse at Willamette Falls on the Willamette River (Oregon), two aeration tests were conducted: (1) venting air into the turbines and (2) molecular oxygen injected into the turbines.

Molecular oxygen was introduced through a multiple diffuser ring encircling the turbine above the runner blade. Oxygen absorption efficiencies as high as 40 percent were obtained, with a power loss less than 2 percent for oxygen flow rates up to 220 cfm (6.2 m^3/min).

Power loss during draft tube venting was 20 percent or about 5020 hp (3740 kW). The oxygenation efficiency was 0.079 lb/kWh (0.036 kg/kWh). No total air-flow measurements through the vents were recorded. The total river flow was about 6600 cfs (10,200 m^3/min), and practically all the flow was passed through the 14 turbines. About six times more oxygen per kWh was exchanged when the air was introduced above the runner blade instead of through the draft tube (Amberg, et al., 1969).

The tests were compared to stream bottom diffuser and side-stream saturation aeration results at the Pearl River near Bogalusa, Louisiana, a Corps of Engineers project (Amberg, et al., 1969).

U.S. Army Corps of Engineers

A synopsis of several techniques to enhance water quality by gas transfer, including turbine venting, was presented by Smith (1980). Although in many applications turbine venting routinely increased DO by 1 to 2 mg/L, there was an upper level of 4 to 5 mg/L that could be achieved. Turbine venting had the disadvantage of increasing dissolved nitrogen in the releases which in combination with oxygen could cause gas bubble disease in fish if total gas concentrations were high. The Corps of Engineers initiated a field study program to determine the magnitude of gas transfer during turbine venting. Smith also reported that the Corps had developed techniques to assist in designing hydraulic structures which help to prevent excess total gas supersaturation.

Weithman et al. (1980) described the history of Table Rock Dam (Missouri) and the subsequent need for DO improvement in the releases, the methods investigated for the improvement, and the efforts to quantify the value of DO in tailwater. Because of the successful introduction of rainbow trout into the Table Rock tailwater after dam construction in 1958, a minimum DO standard of 6 mg/L was imposed on the stream.

The Corps of Engineers tested a number of methods in order to improve the DO in the releases. Release of surface water through the spillway was tried but deemed unworkable because the warm surface water could not be made to mix with the cold water from the turbine releases. Air injection into the turbines was tried, but only enough compressors were available for two of the four turbines. Diffused air in front of the dam was also tested, but again a sufficient quantity of oxygen could not be imparted to the water. In 1973 oxygen instead of air was tried in the diffuser system; but, because the system was less efficient than expected, 13,200 to 17,600 lb of O_2/day (6000 to 8000 kg/day) were needed, and this was considered to be too expensive. In 1978, water was sluiced from the lower levels of the reservoir, but this was abandoned because of fish kills due to excessive gas supersaturation, increased turbidity, and the potential for structural damage at the dam. The selected operating procedure used to maintain DO levels above 4 mg/L was to block open the existing vacuum breaker vent valves and restrict the turbine discharges to the range in which aspiration occurred.

A small supply of liquid oxygen was also maintained and added at night to the approximately 20-cfs (34-m^3/min) discharge of the house-generating units to improve the very low DO levels in the approximately 80 cfs (136 m^3/min) of leakage that occurred through the dam.[1]

The Corps (U.S. Army Engineer Division, Southwestern, 1980) also evaluated a number of additional alternatives for improving the quality of Table Rock releases on the basis of their potential for meeting State of Missouri temperature and DO standards. Alternatives included lake destratification, hypolimnion aeration, selective withdrawal systems, turbine aeration, supplemental reservoir releases, and downstream channel aeration. Four alternatives were identified as having the potential for partially or fully meeting release standards without the costly requirement for injection of oxygen: (1) turbine venting, (2) selective withdrawal, (3) supplemental sluice releases, and (4) a downstream aeration weir. However, contingent upon later analyses of the costs of forced air or oxygen injection, the techniques of lake hypolimnion aeration, oxygen injection into the turbine, oxygen injection into the penstocks, and modified side-channel oxygenation were identified as

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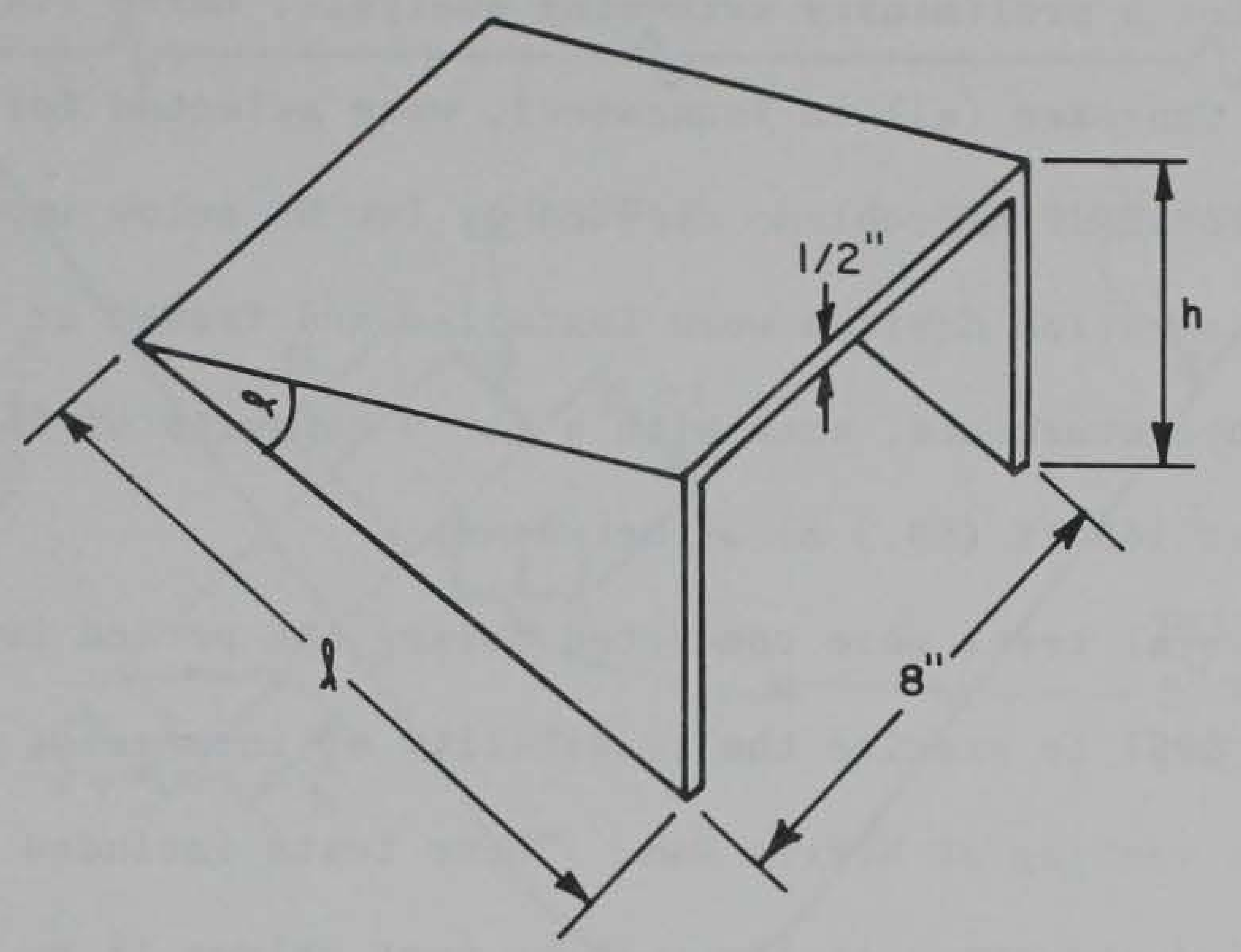
[1] Personal communication, September 1981, T. Schmidgall, Chief, Hydraulic Design Section, U.S. Army Engineer Division, Southwestern, Dallas, Texas.

candidates for continued economic analysis. Evaluation of alternatives at Table Rock is continuing.

An experimental turbine venting program is also underway at Clarks Hill Dam (Georgia and South Carolina) using baffles over the turbine hub vent ports to increase the aspiration capability of the turbines. Testing was conducted in the fall of 1981 and summer of 1982. Data obtained in 1981 indicate DO increases of 1 to 2 mg/L with an initial DO of 3 mg/L in the turbine intake (Mauldin 1982). The baffles used at Clarks Hill are shown in Figure 2.

Stream bottom diffuser and sidestream saturation using molecular oxygen were tested at the Pearl River Project near Bogalusa, Louisiana. Oxygen was added to a stream by means of a multiport diffuser. The multiport diffuser line placed on the stream bottom was found to be much less efficient than the power turbine venting system or the sidestream saturation system. Oxygen absorption efficiency reached only 22 percent for water depth of 19 ft (5.8 m) and velocity of 2.14 fps (0.65 m/sec). Sidestream oxygen absorption efficiency reached 55 percent. Supersaturating 1.64 percent of the river flow increased the river DO by 2 mg/L. The tests were compared to turbine venting results at the Portland General Electric Company powerhouse on the Willamette River (Amberg, et al., 1969).



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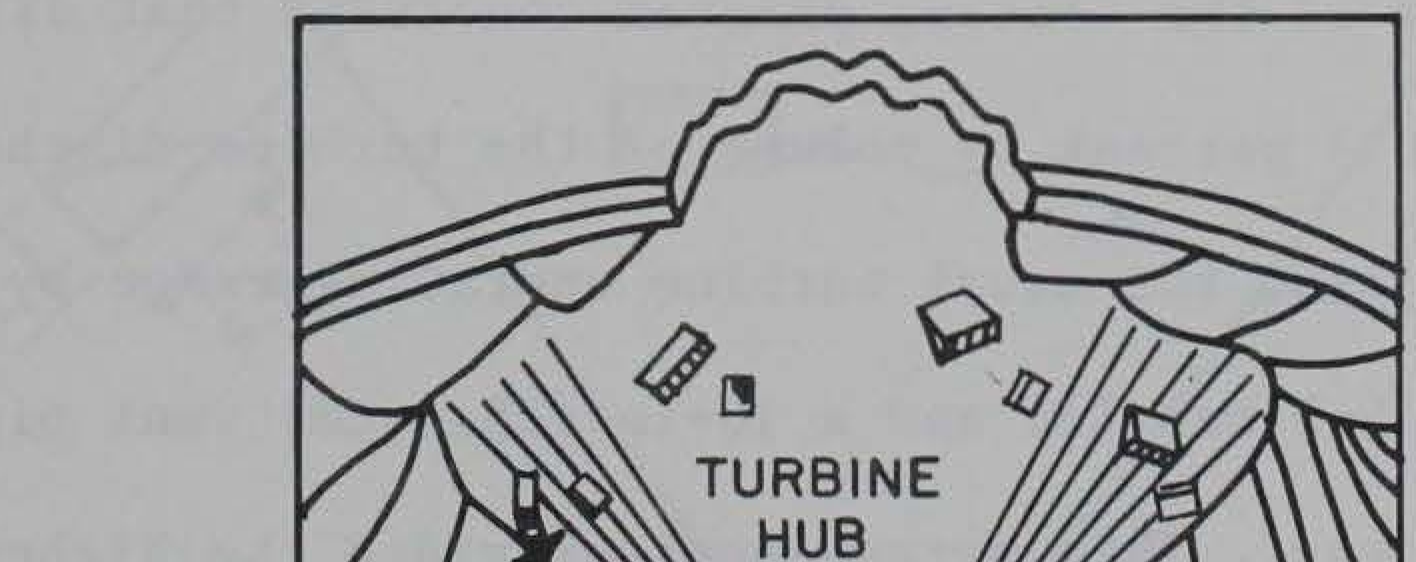


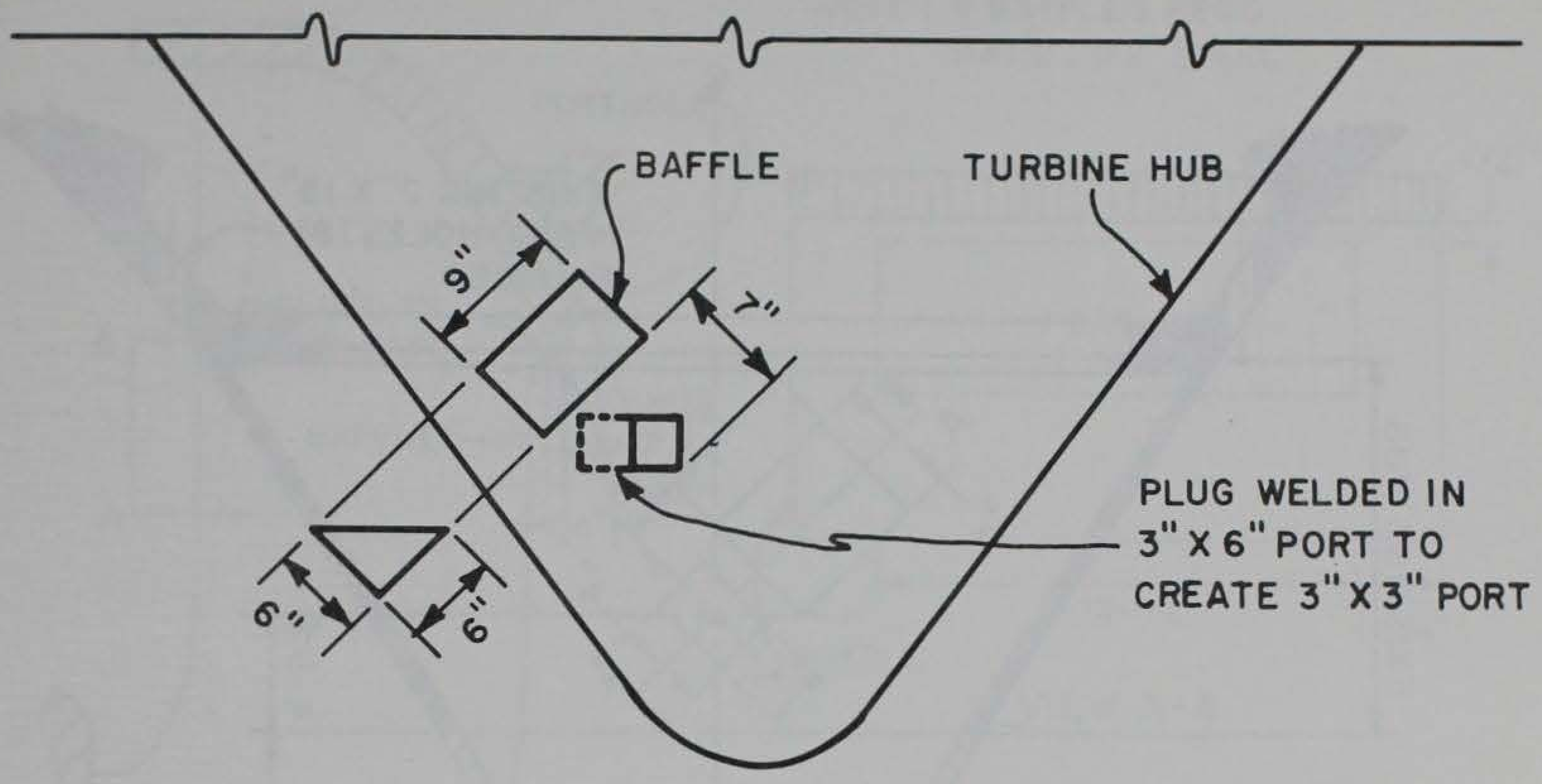
Figure 2 : Hub Baffle Configuration for U.S. Army Corps of Engineers Clarks Hill Project

Tennessee Valley Authority

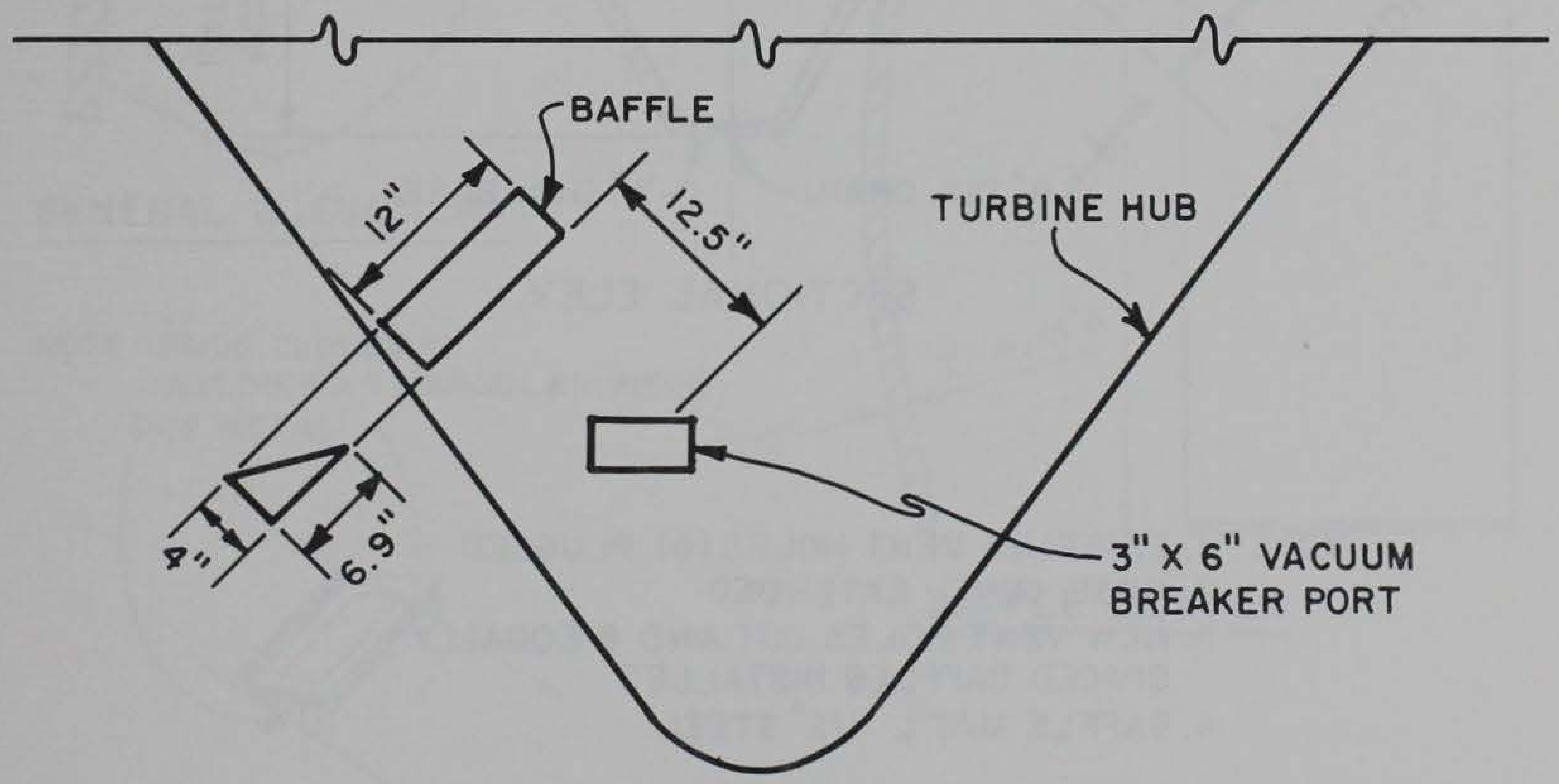
After a preliminary screening analysis, three TVA dams, Norris, Douglas, and Cherokee (all in Tennessee), were selected for initial evaluations to address problems created by low DO below impoundments. Experimental aeration devices were installed and tested at Norris Dam on two Francis hydroturbines, each with a rated capacity of 66,000 hp (49,200 kW) at 165 ft (50.3 m) of net head.

Several tests were conducted during the period September 1979 to September 1981 to examine the feasibility of increasing downstream DO levels by air venting at Norris Dam. These tests included air venting by (1) modified operation of the turbine vent valves (i.e., blocking valves in the open position), (2) installation of a baffle ring near the top of the unit 1 draft tube, (3) installation of two sizes of baffles on the turbine runner cones or "hubs" (hub baffles), and (4) replacement of the existing 8-in (20.3-cm) turbine vent pipe and valve with a 10-in (25.4-cm) vent pipe. Figures 3-7 show these installations and others typical of TVA projects.

A summary of the testing program concluded that air venting flow rates of about 3 percent by volume of the turbine discharge flow rate were obtained over the usual turbine operating range by a combination of the larger hub baffles and a 10-in (25.4-cm) vent pipe through the turbine head cover. This arrangement provided the highest air flow rates--approximately 120 cfs (204 m^3/min)--of any of the modifications tried. Over the range of usual turbine operation, DO increased by 3 to 4 mg/L.

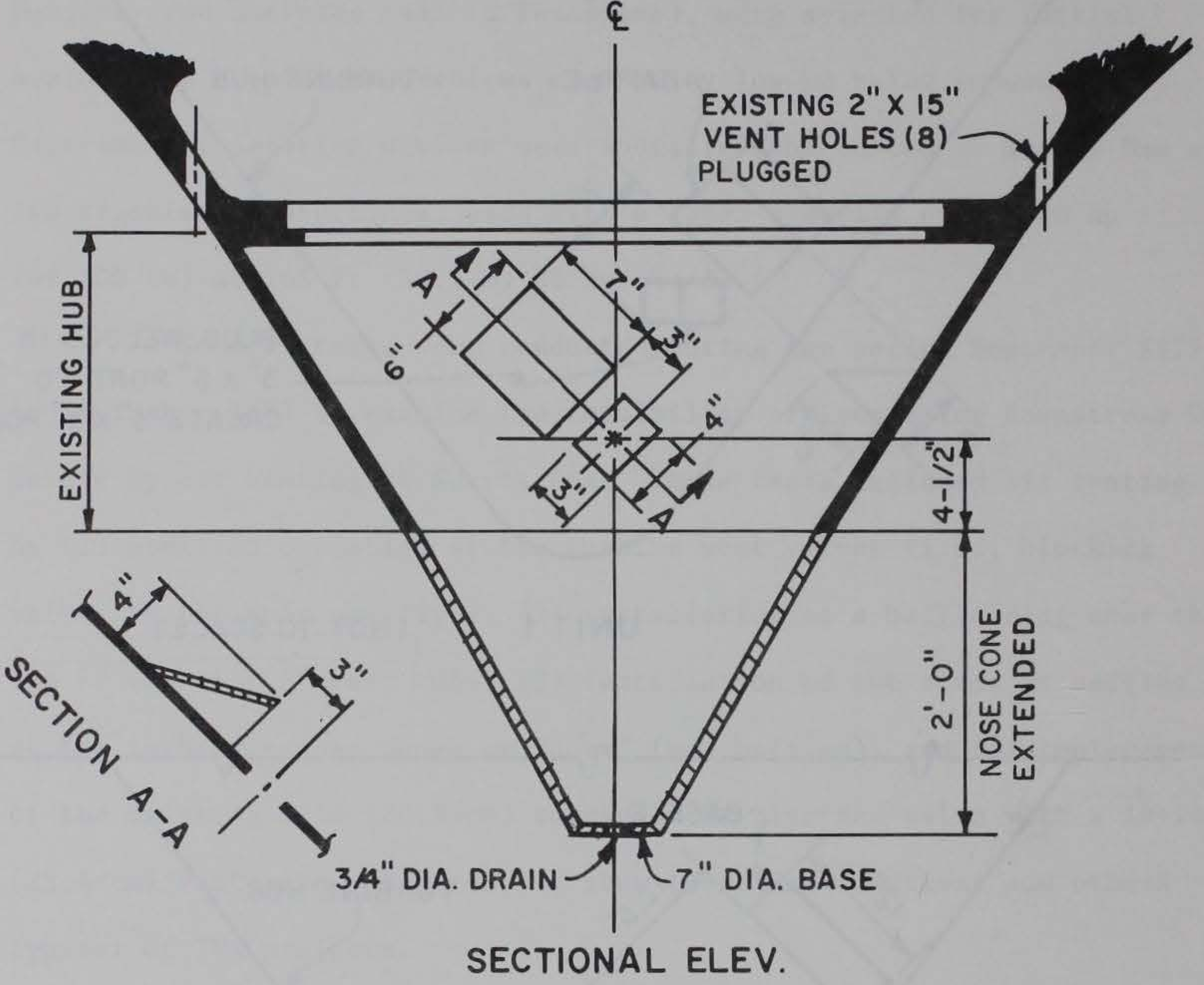


UNIT I (NOT TO SCALE)



UNIT 2

Figure 3 : Hub Baffles Installed on TVA's Norris Units



NOTE: 1. EXISTING VENT HOLES (8) PLUGGED
2. NOSE CONE - EXTENDED
3. NEW VENT HOLES CUT AND 8 EQUALLY SPACED BAFFLES INSTALLED
4. BAFFLE MAT'L 1/2" STEEL

Figure 4 : Hub Baffles for TVA's South Holston Unit

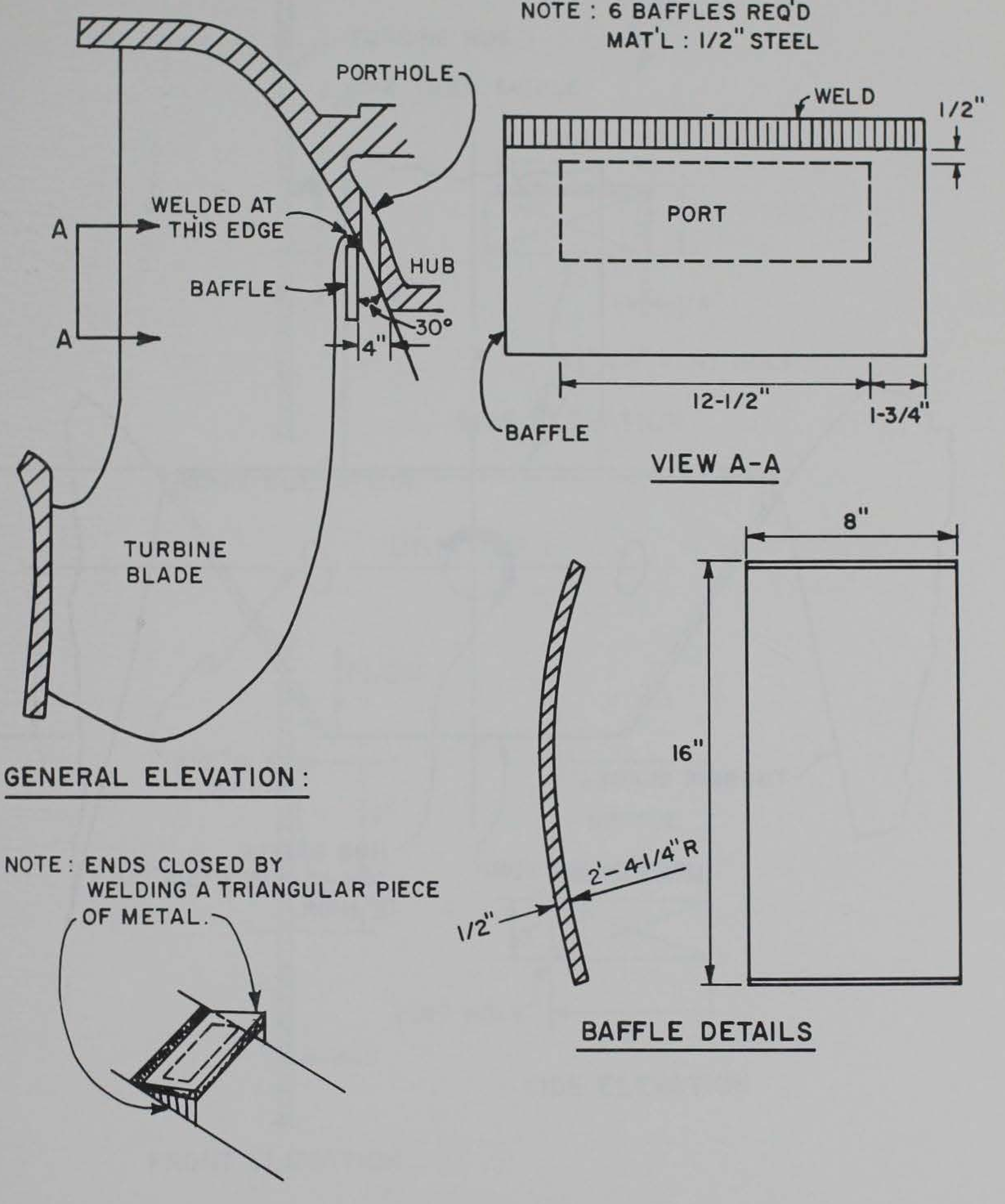


Figure 5 : Hub Baffles for TVA's Douglas Unit 4

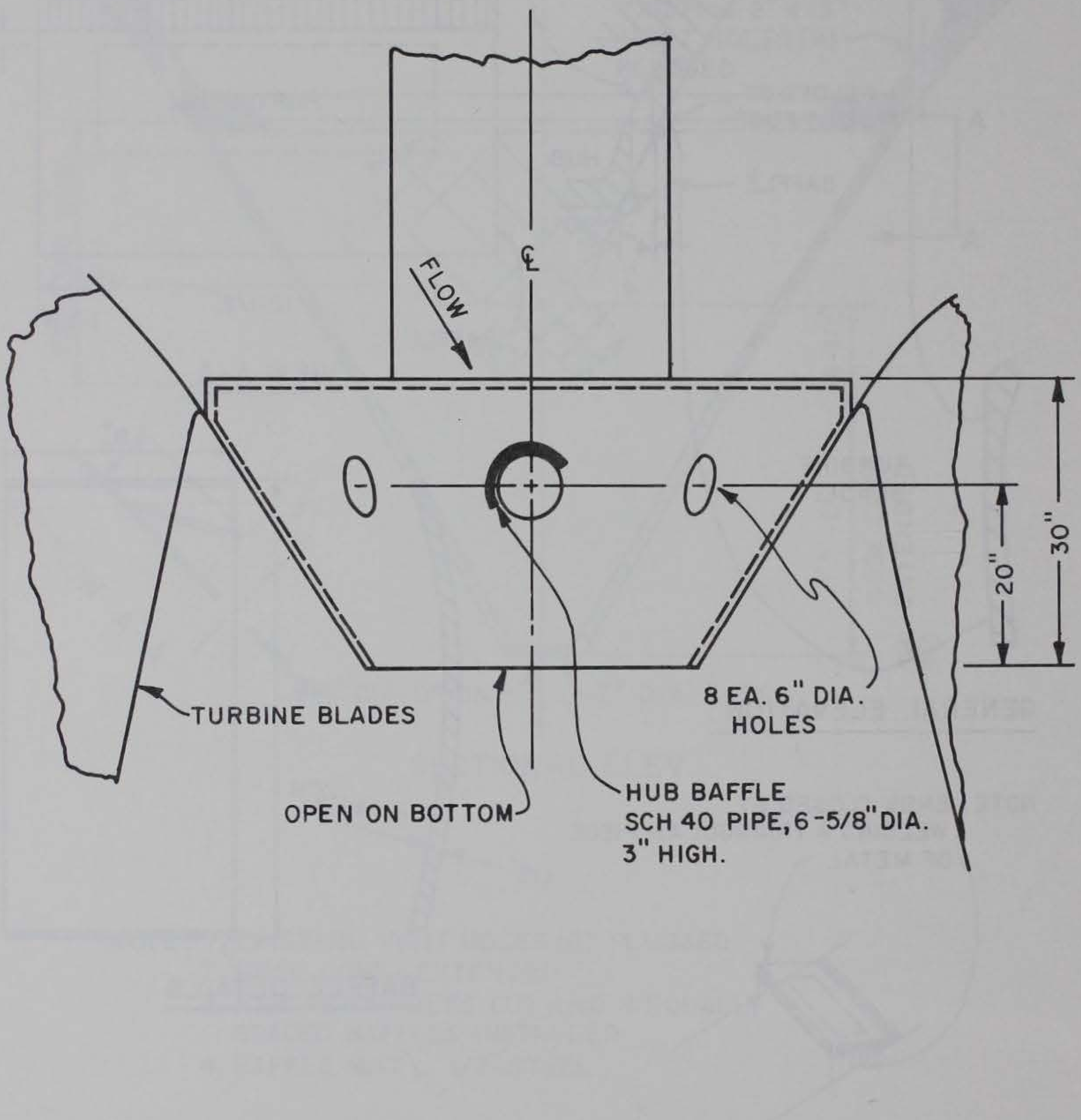
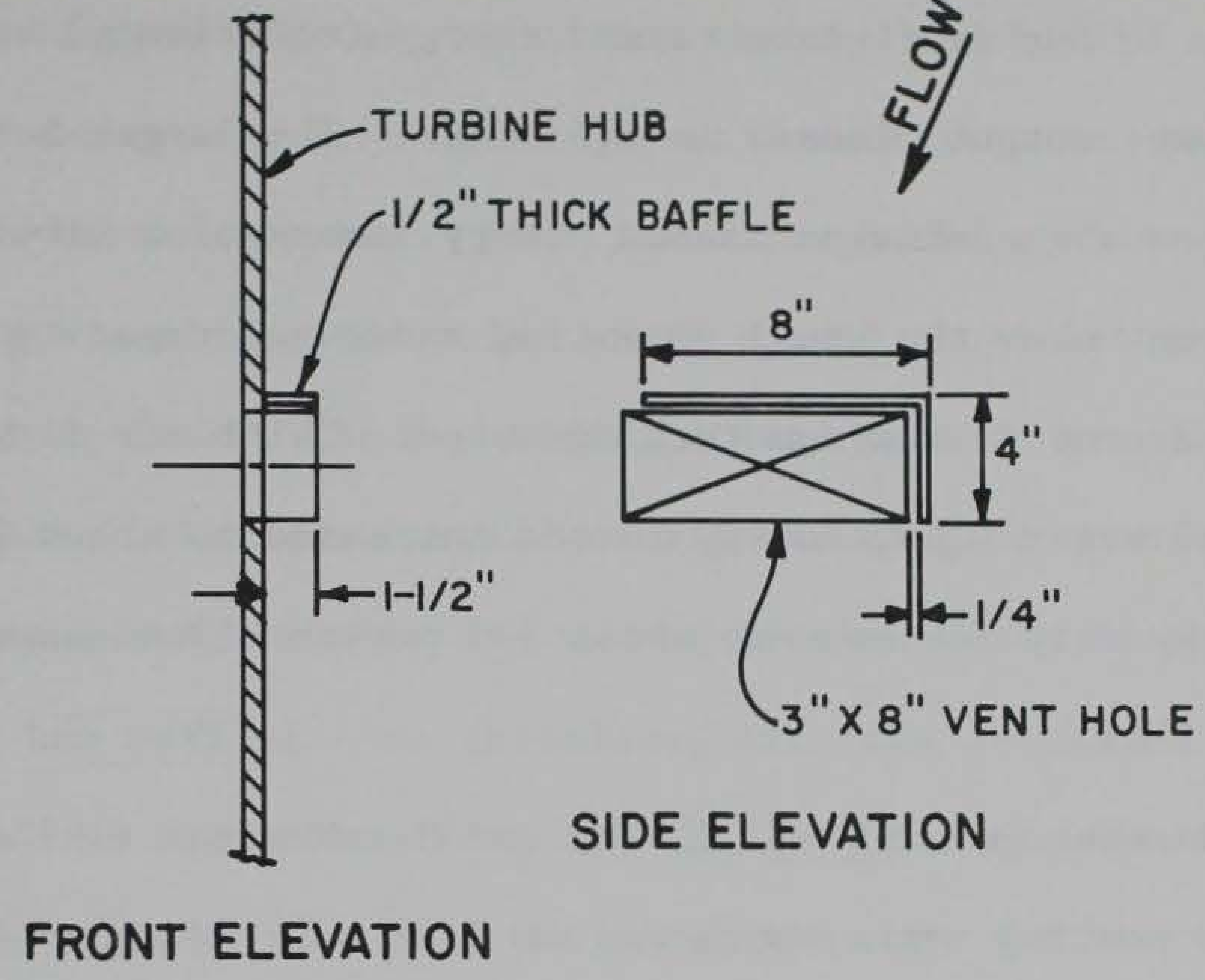
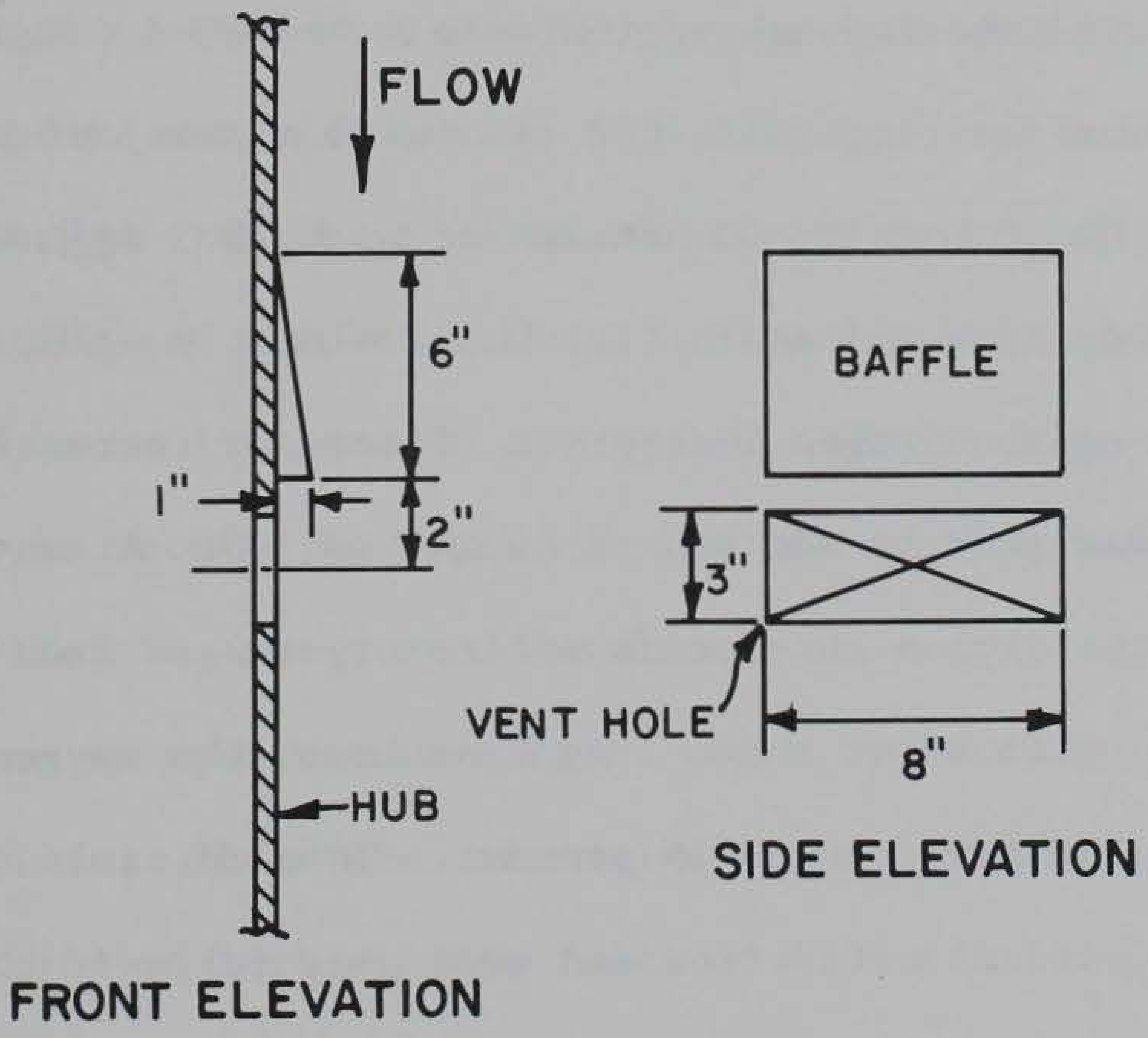


Figure 6 : Hub Baffles for TVA's Wilson Unit 11



UNIT NO. 1



UNIT NO. 4

Figure 7 : Hub Baffles for TVA's Cherokee Hydroplant

The installation of hub baffles on the runner cone or the ring baffle in the draft tube caused energy (efficiency) and capacity (maximum power output) losses in all tests. The larger hub baffles alone with no air admission caused energy losses of a little more than 2 percent over the usual operating range and capacity losses of about 3.5 percent at maximum turbine output. With air flow rates of 3 percent of water flow, energy losses increased to about 3 percent and full-gate capacity losses were about 5.5 percent (Tennessee Valley Authority, 1981).

Harshbarger, et al. (1981) and Harshbarger (1981a) described the turbine venting tests conducted at Norris in detail. The first aeration technique investigated involved use of a continuous baffle ring in the draft tube. Air, which was supplied by a 12-in (30.5-cm) pipe, entered the draft tube through approximately 46 holes cut on 1-ft (0.3-m) centers in the baffle ring. At 4000 cfs (6800 m^3/min) of water flow and an initial DO of 1 mg/L, DO uptakes of up to 3.5 mg/L were measured. At the same water flow and an initial DO of almost 9 mg/L, DO uptake was only about 1.5 mg/L. Oxygen absorption efficiency increased as water flow increased and was greatly influenced by initial DO. At an initial DO of about 9 mg/L, the oxygen absorption efficiency ranged from 20 to 40 percent. At an initial DO of about 1 mg/L or less, the oxygen absorption efficiency ranged up to around 75 percent. Total dissolved gas ranged from 92 to 110 percent saturation and generally followed the same trends as DO. The turbine efficiency loss caused by adding the baffle ring was about 1 to 2 percent. There was also a 1 percent turbine efficiency loss near peak production from air induction through the baffle ring.

The other aeration technique at Norris required modifications to the vacuum-breaker system. Air flow through the system was normally controlled by a cam-operated valve which opened at wicket gate openings of 50 percent or less. The two modifications tested were (1) blocking the valve open so that air entered at all wicket gate openings and (2) adding small baffles over the vacuum-breaker vents on the turbine hub. Before hub baffles were installed, air flow decreased rapidly for water flows above 2500 cfs. With hub baffles, air flow increased as water flow increased. Air flow was about the same for the two different baffle sizes tested (see Figure 3). Test data generally showed that DO uptake decreased slightly as water flow increased and increased greatly as initial DO decreased. During periods of initial DO below 2 mg/L, DO uptake averaged around 2 to 3 mg/L. Oxygen absorption efficiency ranged from about 30 to 70 percent depending on the initial DO concentration and the water flow. The maximum total dissolved gas was measured to be 106 percent saturation. The turbine efficiency loss was found to be about 1 to 2 percent for the smaller baffles and as reported earlier for the larger baffles.

Even an open vacuum-breaker valve appeared to be a major air flow restriction. Therefore, the valve was removed and air flows of 120 cfs (204 m^3/min) at turbine flow rates of 4200 cfs (7140 m^3/min) were observed as discussed earlier. Test results showed that enough air could be added with this configuration to raise discharge DO in excess of 4 mg/L.

Harshbarger (1981b) and Harshbarger and Beard (1981) also presented the results of tests conducted to evaluate hub baffles installed on Cherokee Dam Units 1 and 4. The vacuum-breaker system at Cherokee consisted of a 12-in (30.5-cm) pipe which supplied air under the unit head cover through a 4-in (10.2-cm) cam-operated valve. The spring-loaded valve was usually open up to 60 percent wicket gate opening. The degree of opening was determined by the amount of vacuum present. Air from this system was vented through eight openings on the turbine hub, about 2 in (5.1 cm) below the runner blades. On Unit 1, the hub baffles installed were 1-in- (2.5-cm-) high, 8-in- (20.3-cm-) long, wedge-shaped devices. With the valve blocked open, air flow stayed above approximately 55 cfs (94 m^3/min) to about 3500 cfs (5950 m^3/min) turbine discharge, at which point air flow rapidly dropped off. Adding hub baffles increased the range for the relatively high air flow up to a turbine discharge of 4000 cfs (6800 m^3/min). Blocking the valve open caused a unit efficiency loss of 1.5 percent. Adding baffles lowered the efficiency an additional 1 percent near full load.

The Unit 4 hub baffles were 1.5-in- (3.8-cm-) high vertical plates. The test results again indicated that blocking open the vacuum-breaker valve increased air flow significantly, and adding hub baffles increased the relatively high air flow rate. However, even with baffles, very little air flow was induced above a turbine flow of 4500 cfs (7650 m^3/min).

Fox and Harshbarger (1980) presented the results of tests evaluating the potential for hub baffles at Appalachia Dam Unit 1 (North Carolina). Test data showed a rapid decrease in air flow with an increase in turbine discharge. It was found that negative pressures existed in the draft tube only at turbine discharges of about 1200 cfs (2,040 m^3/min) or more. Since only a small amount of air was induced regardless of vacuum-breaker valve operation, the Appalachia units were not considered to be good candidates for hub baffle aeration. The alternative means of reaeration suggested were inducing air near the draft tube mandoor where negative pressures were sometimes found, or using a forced-air blower. The potential for turbine venting at Boone (Tennessee), Watauga (Tennessee), and Hiwassee (North Carolina) Dams was also investigated (Harshbarger, 1981c).

Bohac, _et_ _al_. (1981) reported on DO trends in the Tennessee River Valley and the impact that increasing DO in hydroturbine releases would have on the Valley's streams. Relative cost comparisons were shown for the Norris project for several turbine-venting alternatives using baffles on the turbine runner cone and on the draft tube wall and for high-purity oxygen injection. It was also estimated that, if the DO in the releases from the Douglas and Cherokee Dams could be increased by 2 mg/L, an additional approximately 78,000 lb/day (35,400 kg/day) of ultimate oxygen demand could be discharged in the Tennessee River below

Cherokee and Douglas while still maintaining present DO levels. For selected stream segments on the Tennessee, Holston, and French Broad Rivers, turbine venting was shown to be potentially several times more cost-effective in improving DO levels than advanced waste treatment for selected industrial discharges.

Higgins and Kim (1981) presented a relatively simple model for characterizing the seasonal DO cycle in reservoir discharges as a function of the basic processes of reaeration, biochemical oxygen demand, and thermal stratification. Numerical techniques for estimating model parameters were presented, and the model and estimating techniques were used to characterize the DO cycle for 17 TVA reservoirs.

Capital and annual costs associated with reoxygenation of turbine releases from Cherokee, Douglas, and Norris Reservoirs using small-bubble diffusers and high-purity oxygen in combination with turbine aspiration were estimated by Fain (1980). Total annual costs were found to range from approximately \$510,000/yr to maintain 6 mg/L of DO at Norris, to \$840,000/yr at Douglas and Cherokee where 5 mg/L was to be maintained.

Union Electric Company

Bagnell Dam on the Osage River at Lake of the Ozarks (Missouri) has employed turbine venting for several years in order to alleviate low DO conditions in the release. The dam was equipped with eight vertical Francis turbines, each rated at 33,500 hp (25,000 kW) at 106 ft (32.3 m) of head with maximum turbine discharge of 4200 cfs (7140 m^3/min). DO concentrations in the releases were observed to be less than 1 mg/L. Aeration is initiated when the DO in the releases drops below 5 mg/L, which occurs about the beginning of June. The low DO period usually lasts until mid-October.

During tests conducted in September of 1979, turbine-venting operation increased the DO concentration about 2 mg/L over the turbine flow range of 120 to 3000 cfs (204 to 5100 m^3/min). The initial DO concentration was about 2 mg/L, and the water temperature was about 72°F (22°C).

The modifications for turbine venting included a 10-in (25.4-cm) pipe which was welded into the turbine head cover. The pipe was valved, and a silencer provided noise reduction. All the piping was restricted to the confines of the turbine pit. Because the aspiration capability of the turbines was significantly decreased at high turbine flow rates, turbine aspiration was limited to below 70 to 75 percent gate opening. Opening the vents at 60 percent gate reduced power output from about 32,200 hp (24,000 kW) to about 29,500 hp (22,000 kW).[1]

Union Electric has experimented with localized mixing immediately in front of the dam to improve the releases from the reservoir. A 17-ft (5.2-m), three-bladed airplane propeller was suspended from a 20-ft- (6.1-m-) square raft. The propellor was powered by a 30-hp (22.4-kW) motor at 30 rpm, and the estimated pumping rate was 500 cfs

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[1] Personal communication, July 1981, R. Miller, Assistant Superintendent, Union Electric Co., Eldon, Missouri.

(850 m^3/min). The device was tested on one of the Bagnell units operating between flow rates of 400 to 4000 cfs (680 to 6800 m^3/min). At 1000 cfs (1700 m^3/min) the pump increased DO in the turbine release about 2 mg/L, while at 3000 cfs (5100 m^3/min) the pump increased DO by about 0.5 mg/L (Garton and Punnett, 1981).

The 1979 results were encouraging enough for Union Electric to undertake a more extensive evaluation of the pump. Presently, plans call for evaluating a cluster of three pumps in front of each turbine. Each unit will be powered by a 30-hp (22.4-kW) motor, rotate at 26 rpm, and be equipped with a 15.5-ft (4.7-m) propeller blade. One of the important variables to be explored is the effect of more strongly stratified conditions than was observed in the 1979 tests. At that time the density difference between water at 10 ft (3.05 m) and water at 75 ft (22.9 m) was 0.04 lb/ft^3 (0.64 kg/m^3) compared to a maximum anticipated density difference of 0.14 lb/ft^3 (2.25 kg/m^3).[1]

Idaho Power Company

The original American Falls Dam (Idado) was constructed in the early 1920's. Deterioration of the concrete, however, required the dam to be rebuilt from 1976 to 1978. Normal operation of the original structure was such that a considerable amount of water was spilled over the dam. This resulted in well-aerated water below the dam and allowed

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[1] Personal communication, July 1981, R. Miller, Assistant Superintendent, Union Electric Co., Eldon, Missouri.

a significant river fishery to develop. Because the new dam was to be constructed with a larger power generation capability, much less water would be spilled as most of the reservoir releases would be discharged through the generators. To mitigate the potential impact of low DO concentrations in the releases, Idaho Power was required to maintain a DO concentration of 6 mg/L in the power plant tailrace, although the standard was subsequently reduced to 5 mg/L.

To provide the necessary aeration capability, the power plant was retrofitted with three 6000-cfm (170-m^3/min) 250-hp (186-kW) blowers, at 7.2 psig (0.5 kg/cm^2). To overcome the 4.5 psig (0.3 kg/cm^2) of backpressure which existed in the draft tube just below the runner, a water-inductor system was provided as a less expensive alternative to increasing the blower horsepower and transformer at the power plant. The mechanical injection aeration system was designed to increase the DO levels from about 4 to 6 mg/L at 20°C. The blowers were run for two summers, but the system performance was not accurately measured.

Capital cost of the retrofitted air injection system was about $700,000, which was considerably more than it would have cost if incorporated into the original plant design and construction.

American Falls has additional features which could be used to increase the DO concentration in the releases. Stainless steel tubing was connected to the penstock to allow the injection of high-purity oxygen. Additionally, the dam was constructed with bulkheads in front of the trashracks that would, with the insertion of concrete stop logs, cause surface water rather than hypolimnetic water to be skimmed for generator intake. These last two methods have thus far not yet been tried.[1]

A new powerhouse will shortly be constructed at Cascade Dam in southwest Idaho. The powerhouse will be equipped with two Kaplan turbines rated at 8590 hp (6400 kW) at 81 ft (24.7 m) of head. Blowers will be used to supply air to the draft tube. The system will be designed with a manifold around the draft tube just below the runner. A small discontinuity, where the outside turbine wall meets the draft tube wall, will also be provided to increase the ability of the blowers to inject air into the draft tube. The system will also have the capability to inject air from the turbine hub.[2]

American Electric Power Service Corporation

American Electric (1969) examined the feasibility of turbine venting at Winfield Reservoir on the Kanawha River (West Virginia). The hydrogeneration facility was equipped with three units, each rated at 6150 kW. The turbines were equipped with vacuum-breaker systems which were used for turbine venting by replacing the spring-loaded vacuum-breaker valves with standpipes. Maximum air aspiration of about 80 to 90 cfs (136 to 153 m^3/min) was achieved at about 30 to 40 percent gate.

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1. Personal communication, July 1981, J. Dumble, Senior Engineer, Idaho Power Co., Boise, Idaho.
2. Personal communication, July 1981, G. W. Brewer, Project Engineer, Idaho Power Co., Boise, Idaho.

Air flow was reduced to 0 at a gate opening of 70 percent and above. The experiment was successful in achieving about a 3-mg/L increase with initial DO conditions of 0.7 to 2.5 mg/L, but approximately 644 hp (480 kW) of generation was lost.

The tests were conducted to determine only the feasibility of using the Winfield project to increase the DO. To provide the proposed aeration flow would require low turbine flow. One method would be to operate two of the three units at high load to meet power demand and the third unit at low load (30 to 40 percent gate) to supply aeration.

California

Several northern California dams which were originally constructed without power-generating capabilities are now being considered for retrofit for generation. Typical projects under consideration include the Putah Creek Power Project at Monticello Dam at Putah Creek, the Lake Mendocino Power Project at Coyote Dam located on the E. F. Russian River, and the Lake Siskiyou Power Project at Box Canyon Dam on the Sacramento River. The generators for these facilities would range from about 5370 to 16,100 hp (4000 to 12,000 kW), and all would use Francis turbines. All dams are on trout streams where State standards require minimum DO of from 7 to 9 mg/L, depending on the time of year. Because it is anticipated that minimum DO in unaerated releases will be about 2 to 4 mg/L, some type of release improvement must be provided when the turbines are installed. Turbine venting is under consideration in relation to these projects.[1]

Laboratory Investigations and Water Quality Modeling

Quigley and Boyle (1976) developed a mathematical model to predict aeration and power performance at hydroturbines vented for aeration. They described the experimental design, test facilities, and test procedures used in the laboratory study conducted to develop the model. Induced air flows in their 8-in- (20.3-cm-) diameter Kaplan turbine model produced DO increases of up to 4.1 mg/L. A change in turbine efficiency of 1 to 2 percent resulted for air-water ratios of 3 and 9 percent by volume, respectively. The most significant effect of vented draft tube operation was the reduction in peak power attainable.

Quigley, et al. (1979) also addressed the issue of whether reduced generation capacity due to less water flowing through the turbine when air was present reflected an actual loss of power. Vented draft tube operation was considered to be merely throttling the unit, with the water still saved behind the dam at the same elevation and energy potential. Thus, power foregone in turbine venting was not considered to be power lost, but rather power deferred for future use.

Quirk and Elder (1970) examined approximately 170 miles (273 km) of streams in order to develop a mathematical model that would

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[1] Personal communication, 1981, D. S. Graham, Project Engineer, Tudor Engineering Co., San Francisco, California.

predict BOD and DO profiles under any condition of flow, temperature, or waste discharge. The model was used to investigate (1) BOD assimilation capacity under critical weather and flow conditions and (2) the effects of sludge deposits, hydroturbine venting, low-flow augmentation; and to develop comparative economics for alternative solutions to achieve proposed water quality standards. It was determined that hydroturbine venting transferred oxygen to the river equivalent to about 15 miles (24.1 km) of atmospheric reaeration.

5.0 AERATION IN THE RESERVOIR AND DESTRATIFICATION

Introduction

Reservoirs are aerated to increase DO concentrations in the hypolimnion of the reservoir, to increase the DO concentration in the reservoir release, or both. Destratification efforts which result in the mixing of the oxygen-rich epilimnion with the hypolimnion are similarly directed. This section concerns reservoir aeration and destratification techniques which are applicable for DO improvement in hydropower releases.

Comparative Methods

Ruane (1972) investigated a number of methods for increasing the DO concentrations downstream from reservoirs, both generically and for the specific case of Fort Patrick Henry Reservoir (Tennessee). Methods reviewed included reservoir destratification, aeration of the hypolimnion with either air or oxygen, selective withdrawal of water using a submerged weir or multilevel intakes, turbine venting, diffused air aeration of the turbine releases, mechanical surface aeration in the tailrace, U-tube aeration, weir aeration in the tailrace, and several methods of injecting oxygen into the turbine releases. On the basis of the literature, preliminary design, and cost evaluation, it was concluded that no method was universally preferred, but that a site-specific evaluation was required. This evaluation should be based on the level of

DO desired, consideration of other water quality requirements, the physical characteristics of the dam and the turbine system, and the severity of the DO depletion.

For the specific case of Fort Patrick Henry, it was concluded that only oxygen injected into the release, using diffusers placed in the reservoir in front of the dam, would be feasible (Ruane et al., 1977).

Fast and Lorenzen (1976a) compared hypolimnetic aeration which maintained stratification and aeration by destratification. Seventeen hypolimnetic aeration/oxygenation systems were reviewed in three major categories: (1) mechanical aeration, (2) pure oxygen injection, and (3) air injection.

Capital and operating costs for several oxygen and air injection systems for the San Vicente Reservoir (California) were compared (Fast and Lorenzen, 1976b). A "partial-air lift" design in which aeration took place within an aeration chamber submerged in the hypolimnion was found to have the greatest capital cost, while the oxygen systems had the greatest operating cost. The "full-air lift" design, in which water was upwelled by air injection from the hypolimnion to the reservoir surface before return to the hypolimnion, was the least costly to install and operate and was also almost twice as efficient as the other systems in terms of oxygen absorbed per unit of power input.

Aeration in the Reservoir

Fort Patrick Henry Reservoir

Nicholas and Ruane (1979) and Vigander and Ruane (1975) reported on the investigation of oxygen injection using small-bubble diffusers at Fort Patrick Henry. In particular, the selection of the aeration method from eleven candidate methods was described.

Because of the complexities of the flow fields of rising bubble plumes from diffused oxygen systems in deep impoundments, it was necessary to study the oxygenation system's efficiency and its dependence on basic parameters such as diffuser pore size, oxygen supply flux, diffuser size and spacing, bubble rise height, water currents, and water quality. Vigander (1979) reported on laboratory tests to determine oxygen transfer efficiency and laboratory and field tests to determine potential operation and maintenance costs of small-bubble diffusers. Results showed that for each oxygen flux tested, the rate of DO increase was constant between the initial DO concentrations of 0.5 to 6 mg/L. However, the higher fluxes resulted in more rapid DO uptake. The oxygen absorption efficiency was 95 percent or better as long as 80 percent or more of the bubbles released were smaller than 1 mm in diameter. Other tests indicated that increased depth did not materially affect efficiency; however, the deeper the diffuser or the larger the bubble rise height, the better the oxygen absorption efficiency. To achieve better than 90 percent absorption, it was determined that the off-gas must contain less than about 45 percent oxygen for most diffusers tested.

Field tests were then conducted using 136 diffusers mounted in four rows on each of ten frames, with the frames positioned in front of the turbine intakes. Field testing showed that the diffuser selected on the basis of the laboratory results yielded considerably lower transfer efficiencies, dropping more than 30 percent from that measured in the laboratory. A small diffuser with pore size of 1.5 to 2 µm yielded more promising results, with decreases in efficiency of only slightly less than the laboratory data. Spacing between the diffusers was found to significantly affect the transfer efficiency of the diffusers (Vigander and Ruane, 1975).

Schohl *et al*. (1978) used data from the Fort Patrick Henry tests to investigate the effect of various parameters on the costs of a small-pore diffusion oxygenation system.

Fain (1978) summarized approximately 29 preliminary reports on the Fort Patrick Henry project in a final project report. The report presented data from the laboratory and pilot installation at Fort Patrick Henry and estimated the costs of a prototype system for the reservoir based on the construction, operation, and efficiency data of the pilot installations. The cost estimates were based on a Marox aluminum alloy in fiberglass diffuser with a pore size of 1.5 to 2 µm, an oxygenation efficiency of 98 percent, and a submergence of 70 ft (21.3 m). It was estimated that 1000 diffusers with an average distance from the dam of 150 ft (45.7 m) would be required to maintain a minimum DO concentration of 4 mg/L. The estimated total annual cost in 1976 dollars was $350,000.

Clarks Hill Reservoir

The oxygen injection research at Clarks Hill Reservoir (Georgia and South Carolina) was summarized by Miller and Gallagher (1980) who described the relationship between Hartwell Dam, Clarks Hill Dam, and the new Richard B. Russell Project on the Savannah River between Georgia and South Carolina. Water quality objectives for the releases from Hartwell and Richard B. Russell were for temperatures not to exceed 70°F (21°C) and for the minimum DO to never fall below 5 mg/L and the daily average below 6 mg/L. The extensive research which was conducted at Clarks Hill in an effort to develop methods to meet those requirements was also discussed.

Speece (1975, 1979) prepared the original feasibility study to investigate various aeration methods at Clarks Hill. Methods investigated included surface aeration, air injection, spillway aeration, penstock air injection, high-purity oxygen using sidestream aeration and penstock injection, and high-purity oxygen injection directly into the reservoir. In the latter case, confined-column and trajectory hypolimnion oxygenation were also investigated. An additional high-purity oxygen method consisting of aeration of the unconfined oxygen plume, using both pulsed injection in proportion to turbine discharge at the dam and continuous oxygen injection upstream from the dam, was also examined. One of the key elements in the feasibility study included an examination of using either trucked-in oxygen or oxygen produced onsite.

The results of the Clarks Hill research leading up to a 1980 full-scale demonstration were presented by Speece *et al*. (1978). It was determined that pulsed oxygen injection to match turbine discharge could raise the DO from 2 to 6 mg/L, with an associated oxygen absorption efficiency of about 85 percent. The highest absorption resulted when using diffusers with fluxes ranging from 0.5 to 2.0 ft/min (0.15 to 0.61 m/min). Ninety percent oxygen absorption efficiency was observed for a bubble rise of 100 ft (30.5 m) at a diffuser loading of 500 lb/ft^2/day (2440 kg/m^2/day) with a submergence depth of 140 ft (42.7 m). Experiments also showed that hypolimnion injection of oxygen 300 ft (91.4 m) in front of the dam resulted in approximately 100 percent of oxygen reaching the turbine discharge. A continuous injection of 100 tons/day (98,800 kg/day) of oxygen for eight days into diffuser racks located about one mile upstream from the dam, using a flux of 10 ft/min (0.3 m/min) at an oxygen loading of 2000 lb/ft^2/day (9760 kg/m^2/day), resulted in 35 percent of the oxygen reaching the turbine discharge. Use of a flux of 2 ft/min (0.61 m/min) and loadings of 500 lb/ft^2/day (2440 kg/m^2/day) resulted in a 50 percent recovery of the oxygen in the turbine discharges. In an effort to cause the oxygen-enriched water to come to equilibrium in the penstock withdrawal zone, a 10- by 10-ft (3.05- x 3.05-m) deflector was positioned 40 ft (12.2 m) over the diffuser racks. It was concluded that, for efficient discharge of oxygen-rich water, the plume from the diffusers must be deposited within the penstock withdrawal zone. Performance of various configurations was evaluated using a baffle placed in the path of the rising bubbler. The optimum baffle position was found to be 25 ft (7.6 m) above the diffusers, with an oxygen loading rate of 250 lb/ft^2/day (1220 kg/m^2/day). This system performed better than not having a baffle, but the improved performance did not offset the additional cost. It was also found that a linear configuration of diffusers was superior to the 20- by 20-ft (6.1- x 6.1-m) diffuser rack configuration. By operating the linear diffuser system at a loading rate of 575 $lb/ft^2/day$ (2807 $kg/m^2/day$), it was possible to optimally position the highest concentration of oxygen-enriched water within the withdrawal zone without the use of a baffle.

On the basis of the above research, it was recommended that the full-scale system should be designed with a diffuser loading of 500 $lb/ft^2/day$ (2440 $kg/m^2/day$) with diffusers spaced on 1-ft (0.3-m) centers. The total injection rate would be 100 tons/day (90,800 kg/day) through 2000 diffusers positioned linearly across the reservoir, 10 ft (3.05 m) from the bottom and approximately one mile upstream from the dam. More details of the Clarks Hill project were presented by Speece *et al*. (1976, 1977).

Based on the six years of studies and field tests at Clarks Hill, a continuous oxygen system will be located approximately 1 mile upstream from the Richard B. Russell Dam (Georgia and South Carolina) now under construction. A supplemental injection system will also be located immediately upstream from the dam. The systems were designed to provide 6 mg/L of DO in the releases that are expected 90 percent of the time. The continuous injection system design included provisions for 2000 diffusers and 150 tons O_2/day (136,000 kg/day) at 125 psig (8.8 kg/cm^2) to be supplied by a cryogenic oxygen plant (Urbine, 1981).

Smith et al. (1981) conducted a modeling study to evaluate the effects of four geometries of cofferdam on the oxygen injection system in the proposed Richard B. Russell Reservoir. Additionally, the respective injection rates required to maintain a DO in the release of 6 mg/L were estimated.

Destratification

A number of studies were devoted to artificial destratification methods to improve the DO in reservoir releases. In particular, diffused air- and water-pumping methods were experimentally investigated in a laboratory tank by Dortch (1979a, 1979b) and Dortch and Holland (1981). The results were used to relate mixing time to pumping condition, reservoir size, and stratification parameters (i.e., density gradients). The reports were intended to be used for planning and preliminary design of hydraulic destratification systems.

Smith (1980) reviewed several methods for enhancing DO that the Corps of Engineers investigated. Pneumatic destratification efforts at ten California reservoirs were described, with particular emphasis on Casitas Reservoir where DO, temperature increase, and nitrogen supersaturation were monitored.

Most of the California reservoirs investigated were on the order of about 10,000 acre-ft (1.2 x $10^7 m^3$) of storage, except Casitas Reservoir, which had a storage volume of about 254,000 acre-ft (3.1 x $10^8 m^3$). It was determined that nitrogen supersaturation up to about 135 percent could be expected with compressed air injection, with the magnitude depending on the lake size, design, degree of stratification, and magnitude of heat transfer to the reservoir (Johnson, 1981).

Barnett (1979) described the reaeration destratification efforts at Casitas and developed procedures using Lake Casitas data to allow systematic diffuser sizing, selection, and design for compressed air systems used to destratify and/or aerate impoundments.

King (1979) also discussed the destratification of Casitas as well as Lake of the Arbuckles (Oklahoma), while Brim and Beard (1981) reported on the pneumatic-induced circulation of Lakes Perris and Skinner (California).

Garton and Jarrell (1979) and Garton and Punnett (1981) presented results from the destratification of two small lakes, Hams Lake and Lake of the Arbuckles, with large-diameter axial flow pumps. The pumps were large-diameter airplane propellers hung from platforms and powered by small motors through gear reducers, which mixed large volumes of water to prevent or break up stratification.

Merritt and Fast (1981) discussed the implications of dissolved nitrogen increases in pneumatically destratified reservoirs. Graham (1981) described the characteristics and energy efficiency of air-plume mixing of stratified reservoirs, and Summerfelt _et al_. (1981) discussed aeration by mechanical pumping to prevent fish kills. The use of helical aerators to destratify Parvin Lake (Colorado) was discussed by Lackey (1973).

Allatoona Reservoir (Georgia) was the site of extensive investigations by the U.S. Army Engineer District, Savannah (1973) to determine the effects of the operation of diffused air systems to destratify the reservoir.

During the study, Allatoona Reservoir contained a storage volume of 367,000 acre-ft ($4.5 \times 10^8 m^3$), and the powerhouse was equipped with two hydroturbines with a rated output of 48,300 hp (36,000 kW) at 90 ft (27.4 m) of head. Maximum turbine discharge was about 4000 cfs ($6800 m^3/min$).

In particular, the water qualities of the lake and of the releases were monitored as response variables. The initial investigation used compressors for the diffuser system located about 2000 ft (610 m) upstream from the dam. Five 65-hp (48.5-kW) air compressors each rated at 250 cfm ($7 m^3/min$) at 100 psig ($7 kg/cm^2$) were manifolded together. The air distribution system consisted of 2-in (5.1-cm) plastic hose which led from the manifold to the diffuser units. The 45 diffuser units were suspended 10 ft (3.05 m) above the lake bottom, and each consisted of two 66-ft (20.1-m) crossed pipes each containing 24-in- (61-cm-) by 3-in- (7.6-cm-) diameter diffusers. It was determined that the compressors possibly affected DO in a zone extending about four miles upstream from the dam. The compressors were able to increase DO at depths from 30 to 80 ft (9.1 to 24.4 m) with some increase at depths below 80 ft (24.4 m). Fall turnover, which usually occurred in mid-October, was observed in late August and early September. Historically, the hypolimnion was devoid of oxygen in early September.

With the compressor system in operation, DO concentrations of 4 to 6 mg/l were observed uniformly to depths of about 100 ft (30.5 m).

DO in the releases generally exceeded 4 mg/L. However, the release temperature was also warmed about 2 to 4°C.

Aeration Devices and Theory

Bryan (1965) reported on the use of an aerohydraulic gun consisting of a vertical pipe between 0.5 and 3.5 ft (0.15 and 1.1 m) in diameter, into which bubbles having approximately the same cross-sectional area as the pipe were introduced intermittently from an air distributor. The gun acted to aerate the water and also as a pump to mix the reservoir. Applications at Blelham Jarn (Great Britain), Inniscerra Reservoir (Ireland), and Loch Turret Reservoir (Scotland) were discussed.

Hise (1979) mathematically reviewed the effects of bubble size on bubble rise velocity, dissolution of gas bubbles, and bubble plumes for bubble sizes up to 0.12 in (0.3 cm) in diameter. It was determined that there was considerable advantage to the use of diffusers producing bubbles less than 0.04 in (0.1 cm) in diameter.

Whipple et al. (1979) described the use of the Rutgers Hypolimnetic Oxygenation System to improve lake coldwater fishery and improve potable water supply by reducing release of phosphorus from lake sediments. The system tested consisted of a liquid oxygen tank and gasifier on shore. The distribution system consisted of polyethylene tubing counterweighted with reinforcing rod. The oxygenator was submerged in 45 to 50 ft (13.7 to 15.2 m) of water and made up of 20 Norton

Model 2240 diffusers with pore sizes of 8 to 15 μm. The oxygenator was 12 by 6 by 18 ft (3.6 x 1.8 x 5.5 m) and was suspended from a wooden raft with styrofoam flotation. A hood was provided over the oxygenator to impede the rise of the bubble plume. The oxygenator was operated at 40 lb/hr (18.2 kg/hr), and the oxygen absorption efficiency was determined to be about 20 to 30 percent.

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APPENDIX A: STREAM AERATION METHODS OF OXYGENATION: APPLICATION OF WATER TURBINES

Appendix A comprises the following report, originally sponsored by the Escher-Wyss Corporation of Zurich, Switzerland, and included through the courtesy of the original publisher, the Laboratory of Hydraulics, Hydrology, and Glaciology annexed to the Federal Institute of Technology, Zurich, and Dr. D. Vischer of the Laboratory. Translation from the German was provided by Language Services of Knoxville, Tennessee. References cited herein are listed in the alphabetical list at the end of Appendix A.

PREFACE

In many rivers, the wastewater load brings about an oxygen deficiency which is excessive from an ecological standpoint and must therefore be eliminated or at least reduced. In this regard, we must think of reducing the pollution load primarily by constructing effective treatment plants and only secondarily by artificial oxygen transfer, since the latter does not attack the root of the problem but only combats the symptoms. Nonetheless, oxygenation is being considered at the present time in many areas, and several noteworthy applications already exist. These include not only direct oxygen transfer but also all measures which fall in the category of stream aeration: cascade aeration, surface aeration, diffused air aeration, etc. These systems correspond in part to the aeration tank facilities in treatment plants and can be understood with reference to such facilities. The use of turbines in existing hydroelectric power plants, however, represents a special solution which requires more detailed explanation.

Dr. Peter Volkart has written the present report in response to a suggestion and on behalf of the Escher-Wyss AG Machine Works in Zurich. It presents the results of a study of the literature and a survey of European power companies and presents the possibilities for using water turbines for stream aeration. It gives an overview of the large-scale tests which have been carried out to date and relates them to experiments with other aeration measures. Among other things, the specific energy expenditure is used as a comparative value; i.e., the number of kilowatt hours which must be produced in order to transfer one kilogram of oxygen into a river or stream.

In conclusion we thank the agencies and power companies mentioned in the text which made available to us their valuable data, and also Prof. Arnold Hoerler (Dr. h.c.) and Dr. Erwin Maerki for a critical reading of the manuscript.

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SUMMARY

Various methods for increasing the oxygen content of rivers are examined. Special attention is given to water turbines as aeration devices. Individual numerical values which relate the power to be expended for aeration (kWh) to the absorbed amount of oxygen (kg 0_2) are obtained from the literature. In addition, other evaluation criteria and suggestions for further development are compiled.

Of the various physical and chemical parameters for oxygen uptake, the saturation deficit and the local flow turbulence (boundary surface renewal of air bubbles) proved to be the dominant parameters. The following methods are explained in detail: turbine venting, diffused air, cascade, surface, and pure oxygen aerators.

Overall, turbine aeration proves to be effective and relatively economical based on the data available at the present time. Limitations are placed on it by the fact that it is locally fixed and dependent on the inflow of water.

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SYMBOLS USED

Symbol	Unit of Measure	Definition
B	m	width of overfall
BOD_5	mg/L	five days biochemical oxygen demand
C	mg/L;ppm	concentration
C_0	mg O_2/L H_2O	oxygen concentration in headwater
C_S	mg O_2/L H_2O	saturation concentration (Fig. A1)
C_t	mg O_2/L H_2O	inlet concentration at time t
C_U	mg O_2/L H_2O	oxygen concentration in tailwater
D	mg O_2/L H_2O	saturation deficit = $C_S - C_t$
D,Ø	m	inside diameter
D_B	m	mean air bubble diameter
H	m	total fall head (turbine, overfall, cascade)
H_A	m	fall head to "breaking point" in overfalls
K	%/s	absorption coefficient of single bubble in water
K_L	s^{-1} m^{-1}	coefficient for turbulence and temperature
K_2	s^{-1}	reaeration constant
L	m	general length. Specific cascade length in flow direction
N	-	number of steps in cascades
Ow	-	headwater
P	kW	power
Q_L	m^3/s	quantity of air
Q_W	m^3/s	quantity of water, discharge

S	-	degree of saturation = C_t/C_S
T	°C	temperature
Uw	-	tailwater
W	-	efficiency
a	-	coefficient for the degree of water contamination
b	-	coefficient for the type of weir
g	m/s^2	acceleration due to gravity
h	m	thickness of the overflowing nappe on the weir
h_W	m	water depth
k_h	m^{-1}	fall head constant for polluted water
k_{h15}	m^{-1}	fall head constant for pure water at 15°C
pH		pH value (chem. hydronium ion concentration)
q	$m^3/s/m$	specific discharge
r	-	$C_S/(C_S - C_U)$
t	s	time
α	-	coefficient for the detergent content
ρ_w	kg/m^3	density of water
τ	$°C^{-1}$	turbulence coefficient

1. INTRODUCTION

The present report is the result of a thorough study of the literature on the topic of stream aeration. The technical aspects of artificial transfer of oxygen into flowing water was posed as the central problem. The primary subjects of investigation are installations in rivers and streams which are used for the generation of electrical energy, for shipping, or as receiving bodies for wastewater or cooling water. Special attention is given water turbines (Kaplan turbines, tubular turbines, Francis turbines) as possible aeration units. Systems which are used in wastewater purification, on the one hand, and in deep, stagnant water such as natural lakes or impounding basins, on the other hand, are mentioned in passing for the purpose of comparison. An important goal is the compilation of basic data which make it possible to compare different methods with regard to their economic efficiency. Best suited for this purpose is a comparison between energy demand (kWh) and actual oxygen transfer (kg O_2). The capital investment and operating costs are only included in the analysis for some examples, due to the fluctuation in prices depending on place and time.

The literature which was available in 1978 focuses primarily on the areas of aquatic biology and process engineering and the description of particular plants which were already constructed and generally had very specific boundary conditions. Publications which deal with turbines as possible aeration units usually refer only to a small number of basic articles. For this reason we also surveyed almost a hundred public agencies and power companies in the course of collecting information for this report and inquired about measurement data and practical experience.

In the report we deal first of all briefly with the different processes in flowing water--some of them simultaneous--which affect the oxygen balance of the water. The functional relationship of individual parameters such as temperature, turbulence, etc., and the oxygen uptake rate is then treated in greater detail, after which the individual aeration structures and machines are described. The latter are basically used in order to optimize the sometimes opposing parameters for aeration. Finally, an extensive tabular compilation of already completed and calculatable systems provides another basis for the evaluation of specific projects.

2. OXYGEN BALANCE

The actual oxygen content at a particular point in a body of running water is determined by the interaction of a variety of physical and biochemical processes. The oxygen can first of all be absorbed from the atmosphere on the more or less level water surface. Its penetration rate can be calculated approximately, as described by Streeter (1935). It is also known that oxygen can diffuse from entrained air bubbles into the flow interior through turbulence of the flowing water at weirs, overflows, sluice gates, etc. Furthermore, algae and underwater plants can produce oxygen through photosynthesis depending on the chlorophyl content of the water and the lighting conditions. The influence of algae is important in this connection, primarily in the so-called alphamesosaprobic and betamesosaprobic flowing waters.*

The oxygen present is consumed first of all by biochemical oxygen depletion, then by algae and underwater plants, then as a result of the sedimentation of the pollutants formed or dissolved in the water, and--last but not least--by the decomposition of bottom mud and by oxidation of the decomposition products stirred up out of the mud. In oxygen depletion (biological self-purification), the carbon compounds are oxidized first in the initial stage of decomposition, and in a later second stage the nitrogen compounds are also oxidized. This nitrification takes place through autotropic bacteria which satisfy their energy requirement by oxidation of ammonium (NH_4^+) and nitrite (NO_2^+) ions. The second stage of decomposition does not begin until the pollutants have been in the river for several days and is only of significance for water temperatures above 10°C.

With regard to the sedimentation of pollutants, we should note that the corresponding solid particles are deposited as mud at flow velocities less than about 20 cm/s, in dammed sections of streams, for example. They are stirred up again at velocities greater than about 30-45 cm/s, for example after a weir has been opened, and deplete

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*alphamesosaprobic = highly contaminated (water quality class III): O_2 depletion generally over 50%, fish kill possible, etc.

betamesosaprobic = moderately contaminated (water class II): O_2 depletion generally below 50%, life zone for many fish, etc.

oxygen from overlying water layers. In slowly flowing and even shallow waters attention should also be paid to respiration of the bacteria living in the bottom mud and to the diffusion of organic and inorganic (e.g., H_2S) constituents from the mud into the water.

Even the preceding abbreviated description of the oxygen exchange processes leads one to suspect that exact mathematical determination of the individual O_2 rates is only possible using simplified assumptions. In practice, the oxygen balance of running water is largely influenced by processes which cannot always be exactly determined or predicted, such as the discharge of clarified or unclarified wastewater or cooling water from thermal power plants, the effects of navigation and its structures, and the regulated impoundage and vigorous turbine operations at river power plants. In these individual cases, which are not sufficiently covered by theory, it is probably imperative that both the O_2 and also the BOD_5 content* of the water be measured over long periods. Note that it is difficult to compensate economically for inadequate wastewater aeration in a sewage treatment plant through subsequent riverwater aeration.

2.1 Necessary Minimum Oxygen Content in Streams

In general we distinguish, with regard to polluted water, between the aerobic and the anaerobic state. In the first case,

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*BOD_5 = Five days biochemical oxygen demand. At 20°C it corresponds to the 0.684-fold oxygen quantity in mg/L which is necessary in order to decompose the organic substances in water by means of bacteria; i.e., to oxidize them. In healthy rivers the BOD_5 will not exceed 4 mg/L.

dissolved oxygen is still present in the water; in the second, the anaerobic state, the once-active organisms have died out. Anaerobic bacteria must take over further biological decomposition. They also need oxygen, but they get it from compounds like sulfates or nitrates contained in the water. An oxygen content of 1.5 mg 0_2/L is assumed as the approximate boundary value between the two regions. Of particular importance in this regard is that the self-purification capacity of a river is considerably higher in the aerobic state than in the anaerobic state. According to Albrecht and Imhoff (1973), for example, a certain quantity of organic contamination will be half decomposed in three days at 20°C in the aerobic state, but in seven days in the anaerobic milieu.

If the goal is also to satisfy requirements for drinking water utilization or for the fishing industry, then a minimum 0_2 value of 1.5 mg/L is no longer adequate. For waters supplying drinking water, a value of 2.0 mg 0_2/L must basically be exceeded, according to Bernhardt, _et_ _al_., (1967, 1969).*

The minimum value for the guaranteed survival of fish is even higher. From the literature we can obtain minimum values of 3.5 to 4.0 mg 0_2/L for whitefish and eel and 6.0 to 7.0 mg 0_2/L for salmonids such as trout, salmon, grayling, etc. The last value is close to the saturation value C_S for oxygen in water. Fish are very sensitive to a rapid reduction in the oxygen content; they are better

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*Cited in original text but not in original list of references.

able to survive very low values if a sufficiently long adaptation period is available. Accordingly, dead fish can be an indicator of the sudden decrease in the oxygen content, for example due to wastewater accumulation, cooling water surges, or shutdown of an aeration unit.

Other consequences of under-aeration can be:

- an excessive change in the taste of drinking water caused by anaerobic decomposition processes.
- irritating water odor caused by hydrogen sulfide.

2.2 Parameters of Oxygen Uptake

The oxygen balance in flowing water is controlled by a great number of generally mutually dependent parameters. The various parameters will be examined in detail below, since they are ultimately used as criteria in the evaluation of different aeration methods and systems.

2.2.1 Physical Parameters

Oxygen Deficit D, Oxygen Saturation S

The driving force for the exchange of materials is the concentration gradient between the saturation concentration of oxygen in water C_S (mg O_2/L H_2O = ppm) and the inlet concentration C_t at time t.

The physical oxygen transfer, assumed to be a kinetic reaction of the first order, follows the equation

$$\frac{dC}{dt} = K_2 \cdot (C_S - C_t)$$

or

$$\frac{dD}{dt} = - K_2 \cdot D$$

c (mg/L) oxygen concentration in water

C_S (mg/L) saturation concentration of oxygen in water (Figure A1)

C_t (mg/L) oxygen concentration at time t

t (s) time

D (mg/L) oxygen deficit (C_S - C_t)

K_2 (s^{-1}) reaeration constant. It can be assumed in the river = $K_L \cdot h_W$. K_L is a temperature-dependent and turbulence-dependent quantity between the value 0.1 and 0.8 (Reisig *et al.*, [1976]), h_W the water depth.

Simple integration leads to the relation

$$D_{(t)} = D_{(t = 0)} \cdot e^{-K_2 \cdot t}$$

The equations written state essentially that the oxygen uptake increases superproportionally with increasing oxygen deficit D. Accordingly, the aeration efficiency drops sharply when the saturation concentration C_S is approached. Frequently the following expression is encountered in this connection:

S --- degree of saturation = C_t / C_S = (1 - D/C_S)

Figure A1 shows the range of saturation concentration C_S of river water as a function of temperature T and pressure p. Apparently, water can absorb more oxygen at low temperatures and higher pressures. At 10°C and atmospheric pressure the value for C_S is 11.0 to 12.0 mg

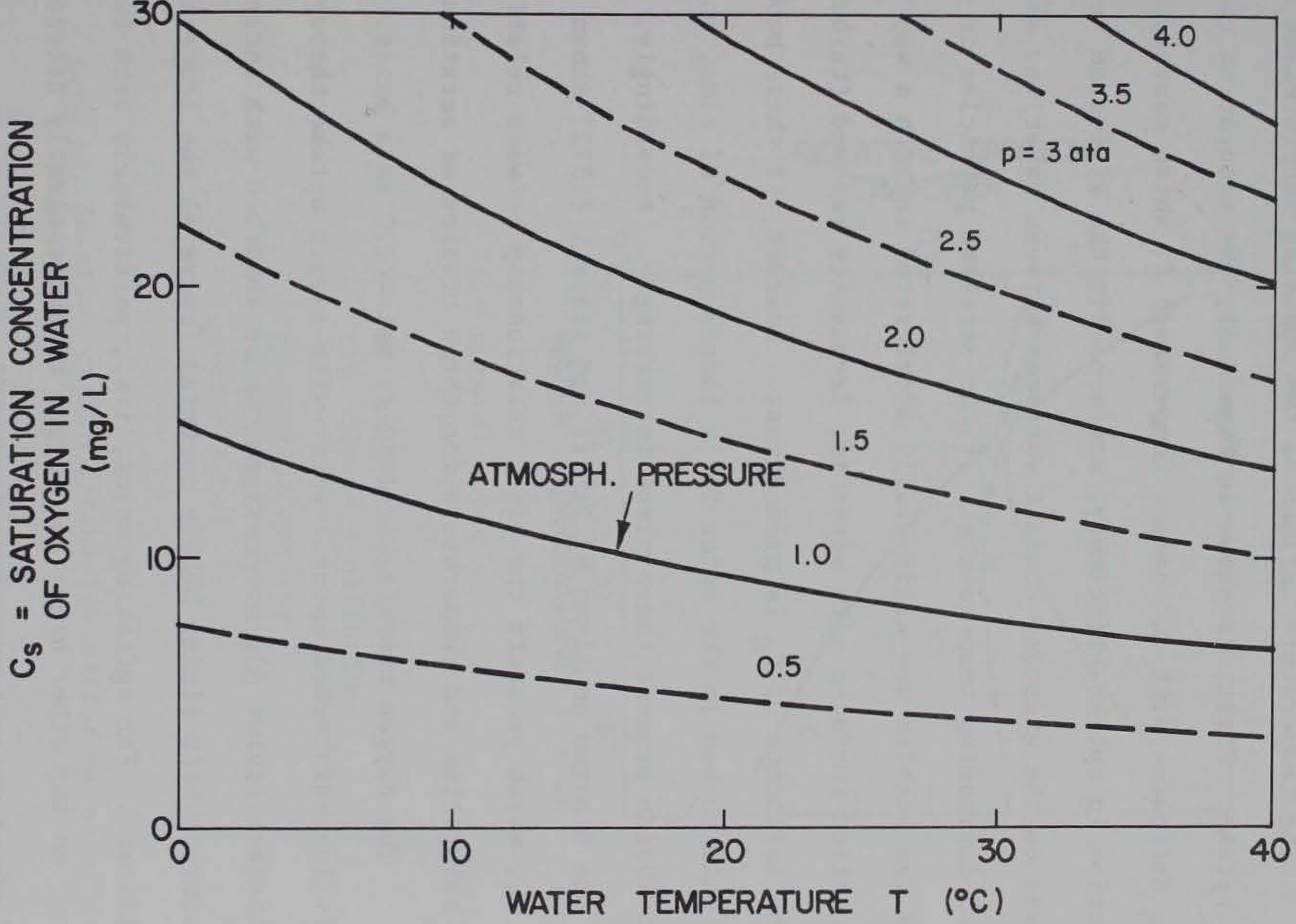


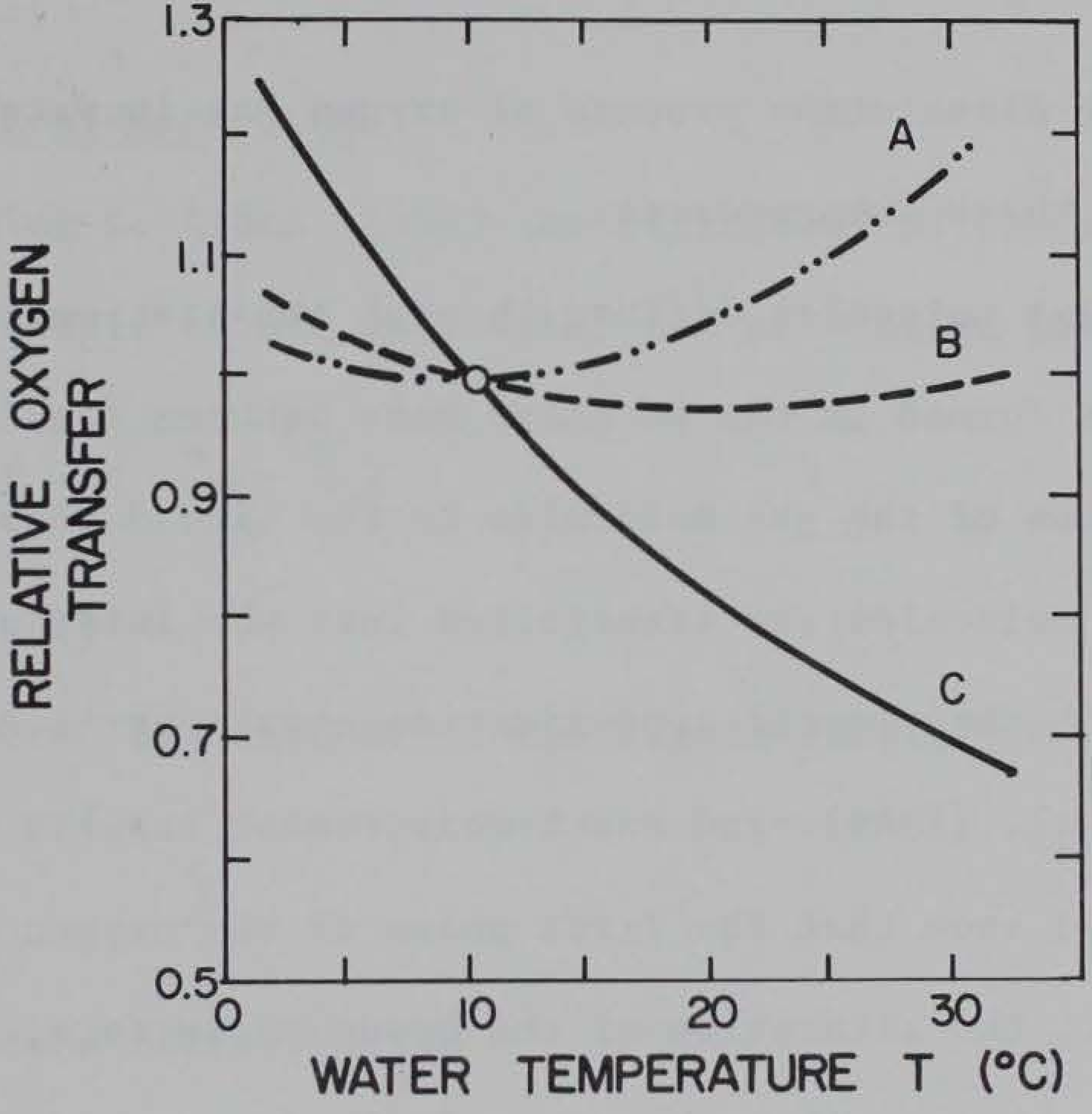
Figure A1. Solubility of oxygen in water.

O_2/L H_2O. This value is reduced, with a 20 percent salt content in the water, for example, to 8.5 to 9.5 mg/L (linear dependence).

Temperature T

The temperature influences two opposing subprocesses of oxygen uptake. First, as shown in Figure A1, the saturation concentration C_S decreases with increasing temperature T, which corresponds to a reduction in uptake efficiency, and secondly the diffusion velocity increases on the existing contact surfaces between water and aeration gas with increasing temperature. If the aeration particles in the form of gas bubbles are artificially accelerated in such a way that their contact surfaces with water are frequently renewed (turbulence), then the influence of C_S is predominant. However, if these bubbles remain undisturbed in the water for a longer period of time, then the pure diffusion process takes place increasingly. Accordingly, we obtain the diagram as given by Imhoff and Albrect (1972) shown in Figure A2, which presents the basic relationship between relative oxygen saturation and temperature for three classes of aeration methods.

The oxygen transfer at 10°C is set = 1.0 as a basis. In practically undisturbed natural water with oxygen uptake through the water surface (curve A), more oxygen can be absorbed with increasing temperature. With rising bubble curtains (curve B) the temperature is insignificant. For agitating units, i.e., particularly with turbine aeration, on the other hand, the oxygen transfer clearly decreases with elevated water temperature (curve C).



A = natural water
(diffusion)

B = diffused air aerator
(turbulence + diffusion)

C = mechanical aerator
turbines, spray cones, rollers
(turbulence)

Figure A2. Relative oxygen uptake for different aeration systems.

Pressure p

High pressure increases the reactivity and leads to higher saturation concentrations C_S, as shown in Figure A1.

2.2.2 Hydrodynamic Parameters

Turbulence

The dissolution process of oxygen gas in water is basically divided into three subprocesses:

1. The O_2 gas molecules diffuse through the stationary gas film which is formed in the boundary zone between liquid and gas.
2. Transition of the gas molecules to the liquid phase is completed.
3. The gas molecules are transported into the interior of the liquid.

Both theoretical approximation equations--see, for example, Wilderer *et al*. (1969)--and exact-measurement results as given by Pasveer (1955) show that the first phase of the oxygen dissolution process, i.e., the saturation of the boundary surface, takes place very quickly, whereas the subsequent diffusion stage proceeds more and more slowly. Pasveer has shown that on the contact surface, saturation is possible at 1/1000 sec contact time, while at a depth of $4 \cdot 10^{3}$ mm only a saturation mass of 5 percent is achieved. After 1/100 sec, saturation at $4 \cdot 10^{3}$ mm is only 50 percent and at $10 \cdot 10^{3}$ mm, still only 5 percent. From this it follows that it is more effective to renew the contact surfaces repeatedly than to leave them undisturbed over longer periods. Increased turbulence thus increases the oxygen transfer from bubbles into the water for the reason that it sharply accelerates the subprocesses which transport O_2-saturated boundary surface layers into the water or through which new water molecules reach the phase boundary surface. Ultimately the turbulent fluctuations on the phase boundary surfaces are controlling. In this sense, a steeper channel slope, a higher, geometry-related local velocity, and a greater discharge volume contribute to improved O_2 transfer.

Bubbles: Size, Residence Time

According to Kobus (1969) the efficiency of the oxygen transfer from a single bubble into water can be written as

$$W = K \cdot t \cdot \left(\frac{C_S - C_t}{C_S} \right)$$

W efficiency

K (%/s) absorption coefficient of the single bubble (reduced in clouds)

t (s) time

C_S (mg/L) saturation concentration

C_t (mg/L) instantaneous oxygen concentration in water

The absorption coefficient K decreases with increasing bubble diameter D_B and in river water is 6.0 for $D_B = 1$ mm, for example, and 2.0 for $D_B = 5$ mm. In addition, the rising velocity of a bubble in quiescent water increases at greater diameters under the influence of buoyancy, which shortens the residence time and thus the reaction time in water. The final result is that a certain aeration volume is better distributed over many small bubbles than over a few large bubbles, since then a higher efficiency is achieved. Otherwise the oxygen uptake is directly proportional to the surface of the bubbles.

2.2.3 Biology

By means of pure physical aeration from the air, oxygen can only be absorbed until the saturation value C_S is reached. This value can be exceeded by assimilation of algae and underwater plants. In the quiescent state (impoundage) extreme oversaturation can also occur by means of the flora (macrophytes and microphytes). Important preconditions for such a process are a high chlorophyll content and intensive incidence of light, i.e., influences which cannot be primarily affected by human impact. This biogenic aeration is significant, above all, in the critical months--from the standpoint of water economy--of April to October, but not in winter.

The following parameters also increase biogenic oxygenation:

- low temperature (but less activity)
- high flow velocity
- low river depth
- great river depth
- frequent low water flow

2.2.4 Other Influences on the Water Surface

Wind

According to Downing *et al*. (1955) the wind over the water surface does not contribute to increased oxygen transfer (enlarged surface, overtopping) until a velocity of 3 m/s (wind strength 2) is reached. Rising wave height and frequency increase the wave uptake.

Oil Film

Oil films with a thickness of 10^{-6} to 10^{-3} cm are practically without effect. The transfer rate does not decrease until a film width of 0.1 mm is reached. An oil layer of 1.0 mm--still 1 L of oil per m^2--reduces oxygen uptake to about a third.

Air Humidity

The effect of air humidity is important only in natural aeration without artificially increased turbulence. Lower humidity of the air layer causes higher evaporation and thus rising salt concentration on the surface.

Since the heavier salt-containing layers sink down, high air humidity results in a displacement of this natural circulation and a delayed renewal of the boundary surfaces and, therefore, ultimately a lower oxygen uptake.

3. WHEN IS ARTIFICIAL AERATION INDICATED?

From the survey of the limiting parameters we can see that several unfavorable parameter combinations can easily occur in nature. The goal of artificial aeration will then be to combat rapidly and effectively the conditions which critically affect the oxygen balance. This presupposes a precise knowledge of the inflow and operating conditions in the water. Even better, probably, are permanent stations whose measured data create the necessary time reserve before startup of the aeration facilities.

An oxygen deficiency which can be eliminated by aeration can be expected primarily in the following cases:

- With rapid cooling and heavy, light-absorbing cloud cover, assimilation can collapse within 24 hours. The oxygen content can then fall very abruptly below the minimum oxygen content for guaranteed survival of fish or for maintaining the aerobic state.
- In the winter, biogenic oxygen production decreases considerably. This condition is substantially worsened if ice prevents uptake from the atmosphere. Impounded sections of rivers are affected by this phenomenon.
- Intermittent loading with pollutants discharged in batches endangers chiefly those organisms and water plants which generally cannot adapt rapidly enough.
- The addition of large quantities of deaerated warm water considerably disturbs the oxygen equilibrium. Depending on the discharge, it is appropriate to aerate the cooling water streams before they are discharged into the river.
- With extreme low-water flow, the existing oxygen content decreases because natural turbulence is eliminated, the surface is sharply reduced, and sediments are stirred up, without at the same time reducing the flow of pollutants accordingly.

- -- Intense heating from solar radiation and rapid biochemical decomposition of pollutants.
- -- Discharge from lakes with low-O_2 deep-level water which is carried to the surface during circulation periods.

In the following chapters we will deal with the different aeration methods. Aeration media include:

- -- air on contact surfaces or in bubble form,
- -- gaseous or liquid oxygen,
- -- ozone,
- -- cold or enriched water.

Accordingly, we enumerate the following aeration methods:

1. turbine aeration,
2. diffused air aeration,
3. weir and cascade aeration,
4. surface aeration,
5. addition of pure oxygen,
6. other methods such as Venturi tubes, shaft aerators, atomization systems, deep water aerators, etc.

4. METHODS OF RIVERWATER AERATION

4.1 Turbine Aeration

4.1.1 Principle

The air required for increasing the oxygen content can be added to the turbine of a river power plant either upstream from the runner in the above atmospheric (overpressure) region or directly downstream from the runner in the below atmospheric (underpressure) region. The flow turbulence created by the turbine contributes to the mixing and renewal of the bubbles which also give off oxygen to the water by diffusion when they rise again in the tailwater. With an increasing volume of air, the oxygen transfer probably increases, whereas the efficiency of the oxygen transfer and of the turbine shows a decreasing tendency. The general advantage of this type of aeration lies first of all in the fact that the river can be treated at a single point through which the entire quantity of water must flow. At dam locations there are also installations and personnel available. A disadvantage, particularly in the case of long reaches, lies in the fact that the point of aeration is fixed in a longitudinal profile and the apparatus is not mobile.

4.1.2 Aeration Effect of Turbines Without Air Feed

Since the installation of channel steps for energy recovery has a negative effect on the oxygen balance of running water, we must ask whether the condition causing this new situation does not contribute again to an increase in the oxygen content by circulating and stirring up the water during the turbine process. Positive contributions to aeration can be assumed to be the circulation of the water layers and the bubble uptake in the tailwater eddies. However, it should also be kept in mind that it is even possible for oxygen to be removed from the water in the negative pressure area of the draft tube and that the stirring up of bottom mud could increase biogenic depletion.

This problem has not been examined in detail to date. However, we have been able to find some of the rather rare series of measurements; these make it possible to compare oxygen in the headwater and the tailwater.

Tables A1 and A2 list values from the Bremgarten-Zufikon Power Plant which is located on the Reuss River in Switzerland. In spite of different water flows and a wide temperature range, the oxygen contents are near the saturation limit. We find, first of all, that the C_t values do not change substantially after the turbines are passed. Only a weak trend indicates a slight oxygenation during turbine operation. Measurements taken on the Moselle River (Germany) correspond to the above. Sixty percent of the data from the four plants Mueden, Frankel, Neet, and Enkirch yield slightly higher oxygen values in the tailwater. The values are near the transition to the anaerobic state (C_t = 1 to 4 mg/L; end of August with temperatures from 19.5 to 23°C).

Some further data from Austrian power plants on the Danube River are presented in Table A3. The oxygen measurements were taken 100 m upstream and 1000 to 2500 m downstream from passage through the turbines.

Finally, Table A4 lists some data from the Rhine Dam of the Laufenburg power plant (river center). The power plant is equipped with 10 horizontal two-pair Francis-type turbines. The measurements

Table A1. Bremgarten-Zufikon Power Plant on the Reuss (Switzerland)

1976

Water Quantity m^3/s	Water Temperature ^oC	Oxygen Content mg O_2/L	Oxygen Saturation %	BOD_5 mg O_2/L
50	3.7	11.0 = OW	87	1.7
	3.9	11.6 = UW	92	2.5
45	3.8	11.4	91	2.3
	3.8	11.3	105	3.4
45	7.4	13.0	113	4.2
	7.0	12.3	106	3.3
85	12.6	9.8	97	3.8
	12.7	10.1	100	3.7
200	12.8	9.9	99	2.5
	13.0	10.1	100	3.0
145	20.6	8.8	102	2.0
	20.4	9.0	104	1.9
175	14.8	9.3	96	2.6
	14.8	9.5	98	3.7
90	19.7	7.8	90	2.8
	19.3	7.7	88	2.2
115	14.6	8.7	91	2.1
	14.4	8.7	90	2.3
53	6.4	10.7	91	1.1
	6.4	10.8	92	1.3
80	4.6	10.9	89	2.4
	4.7	10.9	88	2.2

OW = Zufikon Power Plant (headwater)
UW = Bremgarten, Steg (tailwater)

Table A2. Bremgarten-Zufikon Power Plant on the Reuss (Switzerland)

1977

Water Quantity m^3/s	Water Temperature °C	Oxygen Content mg O_2/L	Oxygen Saturation %	BOD_5 mg O_2/L
47	2.7	11.9	92	2.8
	2.8	12.6	98	3.4
90	5.6	10.4	86	1.9
	5.6	10.6	95	2.3
95	8.5	10.7	96	2.3
	8.3	10.6	95	3.1
205	6.5	11.4	97	1.9
	6.5	11.6	99	1.9
220	12.6	11.5	114	3.3
	12.5	11.4	113	2.9
245	15.2	9.4	99	2.1
	15.2	9.5	100	1.9
260	16.8	8.6	93	2.9
	16.8	8.5	92	2.0
205	17.6	9.0	99	2.8
	17.4	8.7	96	2.8
65	13.4	9.0	90	1.7
	12.9	8.8	88	1.6
63	12.6	9.3	92	2.2
	12.4	9.4	93	2.2
105	7.1	10.3	88	1.4
	7.2	10.9	92	1.3
70	5.8	10.7 = OW	90	2.2
	5.8	10.9 = UW	92	2.3

OW = Zufikon Power Plant (headwater)
UW = Bremgarten, steg (tailwater)

Table A3. Austrian Power Plants

Name of Power Plant	Turbines	Water Vol. Rated/Maximum m^3/s	Fall Head m	Oxygen Content Before mg/L	 After mg/L	Period
KW Aschach	4 Kaplan Vertical	510/625	15.0	9.4	9.2	Spring '64
				10.9	12.0	Fall '64
				9.2	9.1	Fall '65
				9.9	9.9	Fall '66
KW Ybbs- Persenbeug	4 Kaplan Vertical	350 and 388 372 and 394	10.6	10.2	10.0	Spring '61
				8.4	8.4	Fall '62
				9.7	9.6	Fall '63
				9.2	9.2	Fall '65
				9.6	9.6	Fall '66

Table A4. Laufenburg Power Plant - Rhine Dam

Water Quantity	Temperature		Oxygen Content		BOD_5		pH		
	Before	After	Before	After	Before	After			
m^3/s	°C	°C	mg/L	mg/L	mg/L	mg/L	Before	After	Date/Environment
390	12.1	11.9	7.32- 7.23	7.66	1.05	0.97	7.55	7.57	Oct. 1962/heavy fog
450	11.1	11.0	7.59- 7.34	7.77	1.53	2.15	7.58	7.60	Nov. 1961/cloudy, dry for long period
1040	3.2	3.4	7.90	7.90	2.55	2.11	7.90	7.90	Jan. 1962/cloudy, partly sunny
1080	5.1	5.2	12.34-12.78	12.35	2.40	3.10	5.10	5.20	Feb. 1961/nice, warm
1100	19.8	20.4	8.23- 8.29	8.15	1.48	2.03	7.85	7.85	July 1962/ warm, sunny, wind
1185	5.4	5.4	11.84-12.53	12.40	3.18	4.17	7.92	7.95	April 1962/rain, W wind
1195	13.0	13.2	10.24- 9.96	10.40	2.20	2.00	8.00	8.00	May 1961/sunny, N wind
1225	17.4	17.6	8.96- 9.28	10.19	1.33	2.19	7.90	7.90	Aug. 1961/sunny, previously dry

were taken in the headwater at depths of 0.3 to 12.5 m,* but in the tailwater on the surface.**

Although the examples cited take into account differences in machine types, water quantity, temperature, initial oxygen content, BOD_5, or pH value, no systematic relationship with O_2 concentration variation is apparent.

We can draw the conclusion that the water passes the turbines with no significant change in the oxygen content. Thus water turbines without additional aeration equipment are not sufficient to effectively eliminate the oxygen deficiencies in a river.

Turbine Aeration with Air Feed

A survey of the literature gives indications of possible injection points for air:

> Raney *et al*. (1973), Wagner (1955 and 1958), Wolff (1966),***
> Escher-Wyss (1969 and 1972).***

The diagrams in Figures A3 and A4 show vertical sections through a propeller turbine (Kaplan-type turbine) and through a tubular turbine; the technically relevant and possible aeration points are drawn in and numbered in the direction of flow. A comparison in tabular form of constructed turbine aeration plants follows in Table A5.

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*Before (i.e., upstream).

**After (i.e., downstream).

***Cited in original text but not in original list of references.

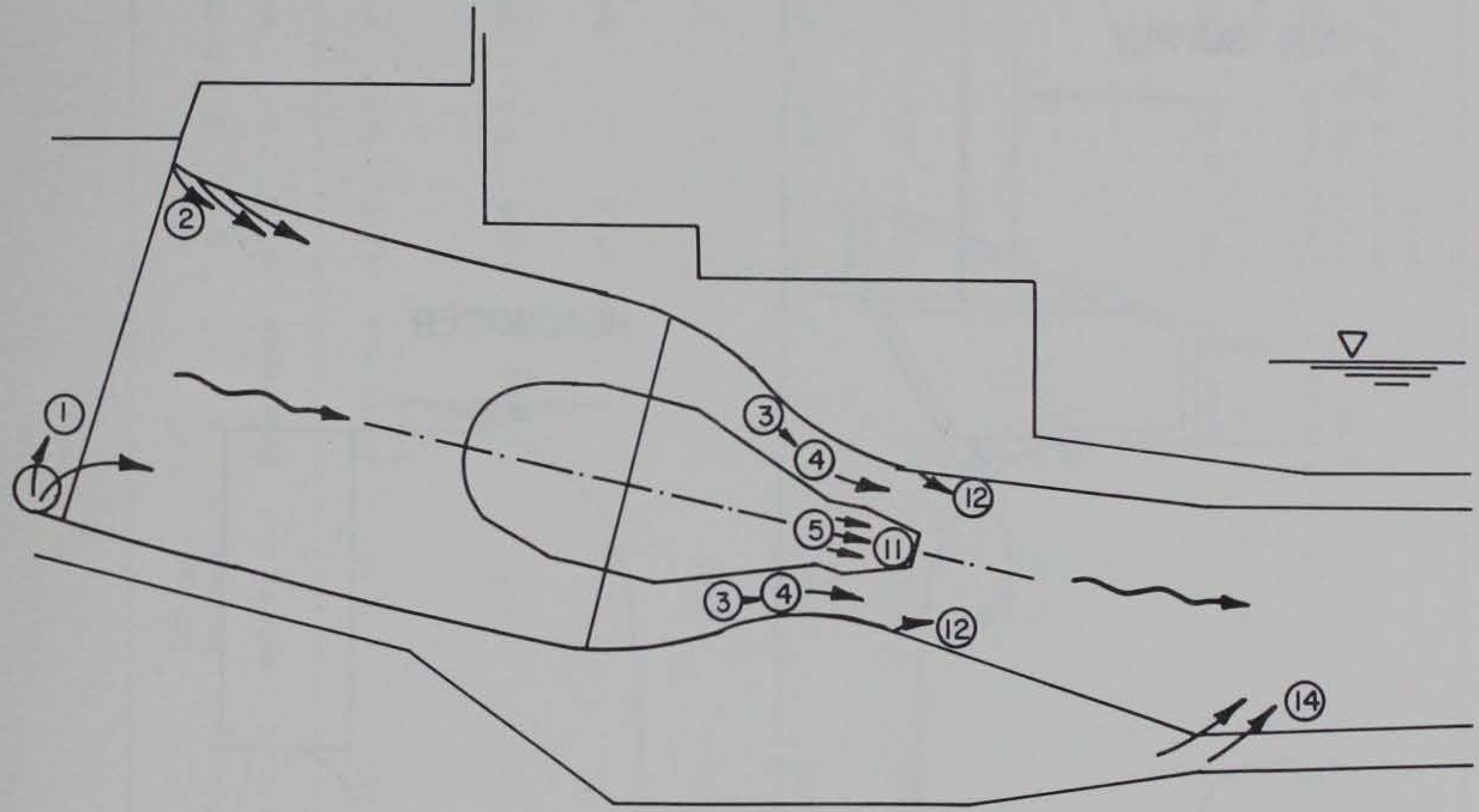


Figure A3. Possible points for air supply (diagram).

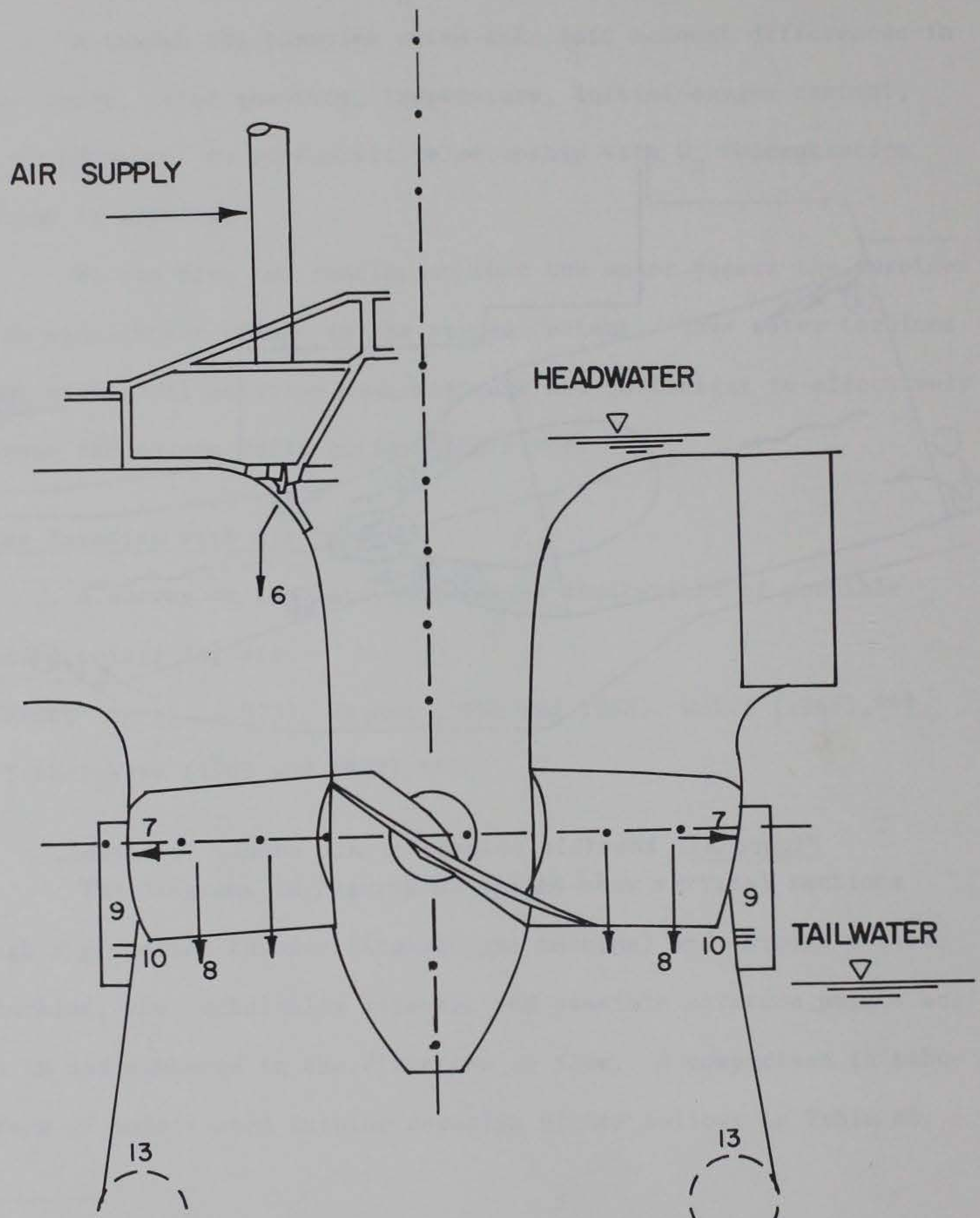


Figure A4. Possible points for air supply (diagram)

Table A5. Turbine Aeration Systems

Power Plant River	Turbines	Aeration System	Power kg O_2/h	Energy Demand kWh/kg O_2	Reference	Q_w m^3/S	H m	P (Turb) kW
Pixley Dam, Flambeau River	2 Francis horizontal	2 input points opposite one another; downstream from runner	257	0.70	Scott e.a. 1960	12.0	6.4	600
Rat Rapids, Wisconsin	4 Francis horizontal	4-inch line	356	1.13		9.6	6.1	320
Rotschild, Wisconsin	Francis		-	0.41		49.9	6.1	800
Port Eduards, Wisconsin	Francis		504	1.65		12.2	5.2	375
Kimberly, Fox River	4 Propeller	4-inch line, runner	191	0.67		34.5	2.7	900
Rapide Croche, Fox River	Propeller	"	538	0.69		29.5	2.4	800
Flambeau River (flows with Mississippi)	Kaplan			0.49	Raney e.a. 1973			
Poppenweiler, Neckar	2 Kaplan				Wagner 1958	30	6.92	1803 ($P_{expansion}$)
Baldney, Lower Ruhr River	Kaplan	Wagner-Voith (annular gap: position 9)	120	0.98	Wagner 1965	Total costs 0.15 DM (1955)/kg O_2 at 30 operating days per year		

Table A5. Turbine Aeration Systems (Continued)

Power Plant River	Turbines	Aeration System	Power kg O_2/h	Energy Demand kWh/kg O_2	Reference	w m^3/S	T °C	Q_L/Q_W
Poppenweiler,	2 Kaplan	Tubular annulus con-	40- 93	0.45-1.0	Wagner	12.3	17	1.5-5.8
Neckar		nected to runner	69-207	0.87-1.37	1958	19.4	17	1.4-8.0
		plane, D(runner):	151-330	1.05-1.70		26.2	17	1.3-9.4
		2410 mm, 400 aeration	131-430	1.87-2.23		33.0	17.1	7.03
		holes each 15 mm, 50	72/102	0.78/1.06		19.4	17.7	7.09
		and 100 m downstream	324	3.03		33.2	17.7	9.22
		from barrage lock	65-209	0.15-0.53		20.0	14.7	0.4-2.3
			207	0.53		20.5	14.8	2.3
			245	0.61		23.5	14.8	2.1
Mettlach,	Kaplan	Wolff: pipe 4 m with		0.39	Wolff	25.5	10.5	0.98
Saar		holes, 9 m below	0.74	1966	17.7	11	1.41	
		normal impoundage,		0.66		21.1	11	1.19
		outlet surface		1.00		25.5	11	0.98
		2.51 m^2 (on stop log		1.67		9.0	24	2.78
		beam) (exit concentra-		0.71		17.7	26	1.41
		tion=2.0 +/- 0.5 mg/L)		1.56		25.5	24.5	0.98
				0.71		25.5	24.5	0.98
	Kaplan D-draft tube	8 Deflectors, 152 mm high, 305 mm wide, turned 30°	150	Approx. 0.60	Raney 1977	Turbine loses 2% power. From 1.7 to 3.2 mg/L, uptake effect 40%		

4.1.3 Positive Pressure Region

Point 1: Upstream from the Turbine

According to this so-called Von Wolff process, air is introduced upstream from the turbine, generally after the screen, through porous tubes on the bottom. The increased pressure at great water depth favors oxygen transfer from the air bubbles, but also requires additional power in the form of a compressor or blower. The clouds of bubbles encounter advantageous turbulence conditions when passing through the turbine and have a long residence time until they appear again in the tailwater. A certain reduction of the dissolution rate is possible in the negative pressure region below the runner, since here air can be separated again in the form of very fine bubbles.

The Von Wolff method requires additional apparatus for which maintenance is necessary, but it has the advantage that no changes must be made in the turbine system itself. This makes it possible to install the process in existing dams. This process can be applied in all turbines commonly used in low-head power plants. With a vertical-axis, the entire water jet is included equally in the aeration process without an increase in the danger of cavitation. With horizontal-axis or diagonal-axis turbines, dynamically balanced aeration cannot be guaranteed. The air has the tendency to collect at more elevated locations with a lower static pressure. This reduces the aeration effect, creates new cavitation nuclei at the point which is already the most endangered, and can lead to pulsating separations on the runner.

Point 2: Upper Edge of Intake

A supply upstream from the turbine, with only low static water pressure, does save compressor power but makes control more difficult. The advantageous effect of pressure on the dissolution process is eliminated. In systems which do not have a vertical axis, the danger of air collecting locally, which was mentioned above under Point 1, is usually so predominant that this method must be ruled out.

Point 3: End of Pear-Shaped Reinforcing Rib

The success of this method depends on rationally locating and maintaining the feed pipes and the air blower. This method is possibly of interest in the case of tubular turbines when the air is inducted only in the deeper lying half-space.

Point 4: Guide Vane Front Edges

The statements under Point 3 apply here, more or less. However, an additional factor is that in the positive pressure region, immediately upstream from the rotating elements, the pressure interactions between aeration flow and turbine rotor are intensified. With high water flow and correspondingly greater air flow, the turbine efficiency will probably decrease further.

Point 5: Annular Gap between Neck and Hub

The statements under Point 4 apply.

Point 6: Cut-Off Gap on Turbine Neck

An appealing idea is to use already existing openings for aeration. The cutoff gap, a circular ring with a width of about 8 cm, has much too great an outlet surface. The desired fine-bubble clouds would not form, but rather large air pockets which could also disturb the smooth operation of the turbine. If it is possible to cover this circular gap sufficiently with a fine-pored material--not a very easy experiment for a location which is not easily accessible--then effective oxygenation seems possible.

4.1.4 Negative Pressure Region

In the negative pressure region downstream from the guide wheel plane, air flows through a bypass, in part automatically. Of course this causes a partial reduction in the negative pressure and thus in the turbine efficiency, which should be viewed in relation to the saving in compressor power. Turbulence and residence time are basically shorter than in the excess pressure systems. Although the basic installation costs are lower, retrofitting is difficult. It should also be mentioned that the eddying effect and thus the aeration efficiency decrease with decreasing water volume.

Point 7: Runner Gap

The guide vanes are hollow on the inside. The air would exit at the point with the greatest circumferential velocity. It is not known whether the air injection can adapt to the unstable pressure conditions in the gap between the vane and the housing. No practical experience has been acquired, probably because retrofitting would be too expensive.

Point 8: From the Runner Wing

If it can be justified from the standpoint of turbine operation, this system will probably yield the highest aeration efficiency of all the different turbine aeration systems. The bubble distribution immediately downstream from the runner plane is at a maximum, the turbulence along the bubble boundary surfaces still effective, and the residence time until reappearance in the tailwater is still adapted to the first, more rapid diffusion phase. A practical test would be profitable.

Point 9: Aeration Ring with Holes Right Beneath the Runner Plane

This Voith Wagner System, described by Wagner (1958), was first installed on the Neckar River near Poppenweiler, downstream from Stuttgart, as shown in Figure A5. It turned out that the amount of air drawn in depends on the operation point of the turbine and the throttle position of the air valve. With constant air feed, the drop in efficiency increases more than linearly with the water flow. Thus one must invest, for 1000 L air taken in for example,

at $Q_w = 20\ m^3/s$, 200 kW
at $Q_w = 33\ m^3/s$, 500 kW.

Similarly, at constant Q_w the aeration expenditure in kWh/kg O_2 also increases with increasing air volume. These basic relationships also apply to the other turbine aeration systems.

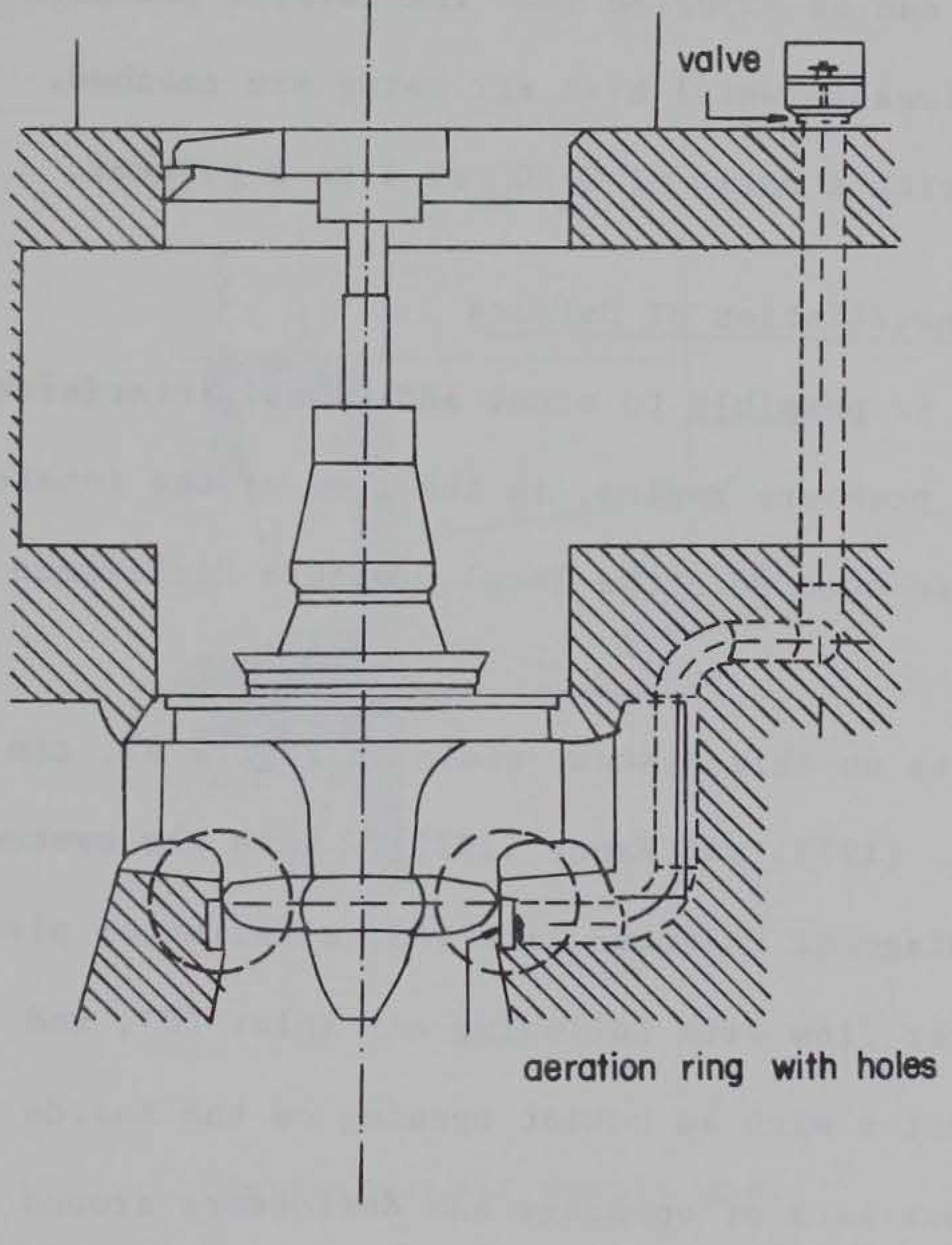


Figure A5. Air supply through aeration ring.

Point 10: Air Supply Gap Below the Runner Plane

As described by Wagner (1955), experiments were carried out with a small Kaplan-type turbine as shown in Figure A6. The best results were obtained using an annular gap of 2 mm divided into individual openings. If uniform air supply is guaranteed, then smooth operation of the turbine is likely.

It can be expected that the turbine efficiency will not decrease noticeably until high air rates are reached. This transition takes place with a ratio of Q_L/Q_W of 1 to 2 percent.

Additional Installation of Baffles

It is possible to mount additional interference elements in the negative pressure region, in the area of the intake point (10), which increase even more the local pressure difference from the atmosphere.

Data on this system, shown in Figure A7, can be found in Raney *et al*. (1973) and Raney (1977). With the systems described there is a diagonal injector line (A), a deflector placed against the vertical water flow with following air inlet (B), and a corresponding hollow deflector with an outlet opening on the inside (C). There are generally four sets of openings and deflectors around the circumference.

Using this method, it was possible to further increase the oxygen transfer rates in the turbines of the Logan Martin Dam in the U.S. Data on the change in efficiency are not available.

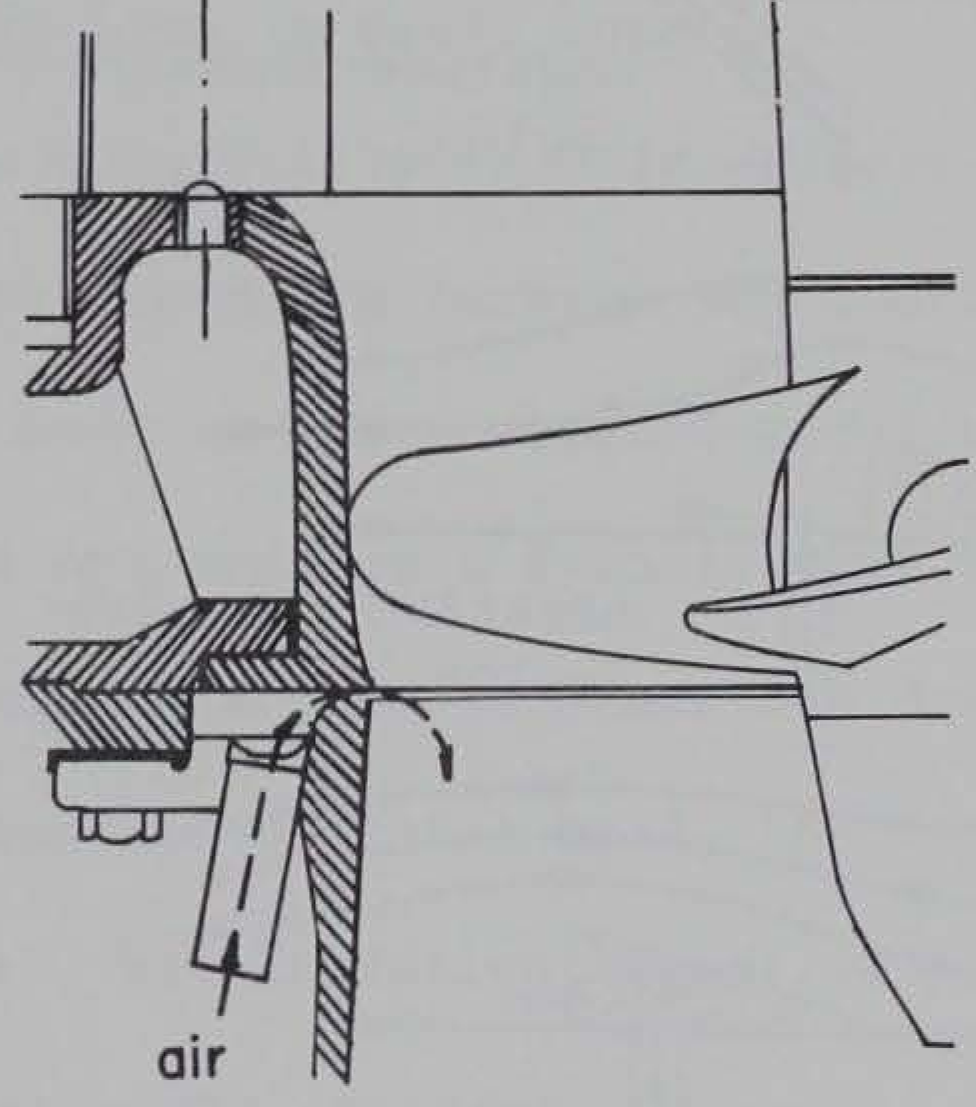


Figure A6. Air supply gap.

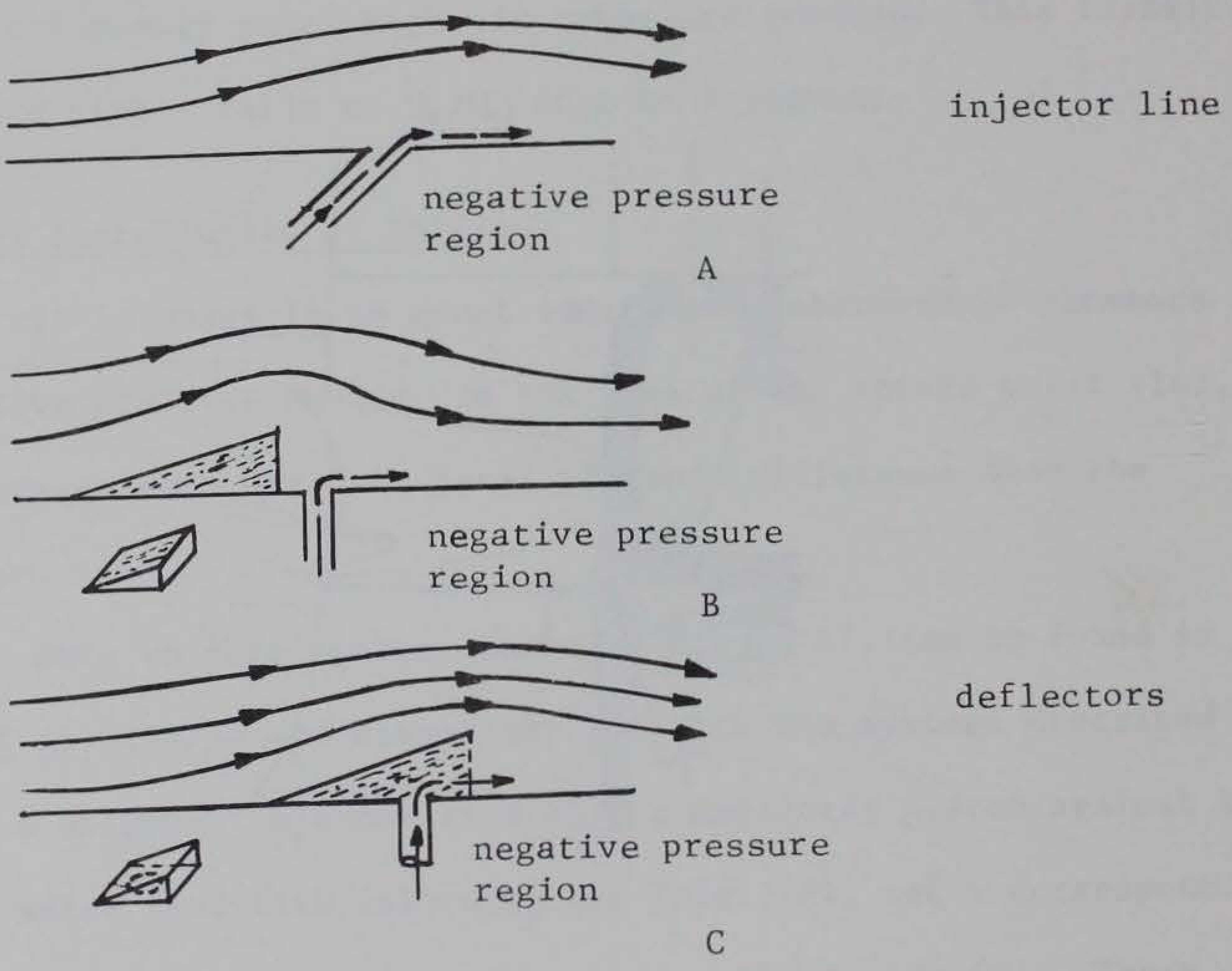

injector line
negative pressure region
A
negative pressure region
B
deflectors
negative pressure region
C

Figure A7

Point 11: At Hooded Outlet

Turbine experts fear a substantial decrease in turbine efficiency. This process has no obvious advantages over other methods.

Point 12: Narrowest Draft Tube Cross Section

Similar fears concerning efficiency exist as mentioned under Point 11. An advantage, on the other hand, is that the air exit can take place directly from the housing. The high flow velocity at the narrowest point holds the bubbles rather tightly to the wall.

Point 13: Closed Circular Line in Draft Tube

In principle, a possibility is offered here of getting air into the draft tube without changing turbine and housing. The resulting interfering elements however--even without aeration--result in an efficiency loss which was measured on a Francis-type turbine as one percent. Since in the case of Kaplan turbines the draft tube recovery is even greater in relation to the total head, the conditions there are even more unfavorable. With aeration, negative pressure is even further decreased.

Point 14: Near Tailwater

Systems located close to the tailwater level actually have nothing to do with turbine aeration. The twist and turbulence effect of the turbines is weakened; the emerging water jet increases the rising velocity of the bubbles and shortens their residence time when compared with a straight diffused air aerator.

4.2 Diffused Air Aeration

4.2.1 Principle

This method involves injecting compressed air into flowing water in such a way that the rising air bubbles give off oxygen to the water in the most efficient way possible. The air must be introduced with fans, blowers, or compressors. Similar systems are also used as oil containment booms in harbors, as salt retention systems in river mouth areas, as pressure dampers in underwater blasting, and as aeration devices in wastewater engineering. In the last instance they are used to aerate the wastewater before it enters the presettling tank, for pretreatment in oil and grease collectors, for defoaming mechanically presettled wastewater, for moving mud, and for oxygen supply in biological systems.

4.2.2 Types

Diffused air aeration in shallow water is divided into the following three categories, analogous to water and sewage engineering:

-- fine-bubble aeration:	produced by means of diffuser plates or filtering candles which have pore diameters on the order of 1/10 mm.
-- medium-bubble aeration:	here nozzle hoses and perforated pipes with hole diameters of up to 5 mm are used.
-- large-bubble aeration:	[the air] exits directly from the distributing pipes.

Based on the analysis of the individual parameters for oxygen uptake, it follows that the outlet location for the air bubbles should lie as deeply as possible below the water surface since there, higher pressure and long residence time during bubble rising are inherent. Since bubble curtains represent a hydraulic resistance for flowing water, they should be used if possible where they will aerate the river over its entire width so that no large sections of the water will be able to escape the bubble stream. The best input points are therefore generally in the tailwater directly downstream from a barrage lock. Usually power connections and good access are also available at such locations. Turbine efficiency is not affected by this method. In locating the aeration units in the form of horizontal pipes, hoses, mats, etc., care should be taken that they do not lie on the river bottom, since they would then stir up more mud, which would deplete the oxygen supply. The diffused air aerators therefore generally are supported by beams or floats. Vertical pipes have not proved successful and require repeated cleaning.

In rough approximation we can say that the specific power requirement of all bubble curtains for a 100 percent deficit can be expected to be 1.5 to 3.5 kWh/kg O_2. The effectiveness of a system depends essentially on how the configuration of the outlet openings and the injection pressure can be selected and adapted to the varying riverwater flows. Given the same amount of air, small bubbles are more effective than large ones. Small bubbles are generated by means of very small outlet openings and under slight excess pressure.

Nozzles with small throughputs and sufficient spacing would theoretically be ideal. Since, however, it is difficult to inject the necessary total amount of air with such a method, a denser configuration of openings and a higher throughput must be accepted in practice. Nonetheless, the formation of bubble chains with fine-bubble aeration or large single air pockets with large-bubble aeration must be avoided. Diffused air aeration is in principle a mobile process and can be used along the entire body of water. Since the system must frequently be turned on and off, the danger of obstructions and plugging must not be ignored, especially in the case of fine bubbles, which are otherwise more effective.

A comparison of constructed diffused air aeration systems follows in Table A6.

4.3 Weirs, Channel Steps

On rivers which are dammed up or regulated, there are fixed or movable overfall weirs, bear-trap gates or steep weirs, or single- or multiple-stage channel steps (cascades) which can contribute substantially to the oxygen content of the water. A specially designed weir achieves a remarkably high efficiency. This category of aeration devices also includes slope changes, which cause a hydraulic jump, and navigation locks. When the upper miter gate of a lock is opened, a strong water jet sprays through the initially very narrow opening and acts like a water-jet pump. Emptying the lock chamber then leads to intensive turbulence in the water.

Table A6. Diffused Air Aeration Systems

Place River	Type	Specifications	kg O_2/h	kWh/kg O_2	Comments
Flambeau River	Diffuser plates, fine bubble	24 m^2 filters, depth 3.60 m	26.0-20.5	1.74-2.20	
	ditto + filter cylinder	Ø 10 mm, L = 1 m each, depth 3.6 m	43.2-36.1	1.05-1.25	
Heil Lippe	Nozzles, large bubble	6240 nozzles Ø 6 mm, units 24 x 1 m, depth 0.95 m	28.4-32.6	1.74-1.52	
	Plastic plates, fine bubble	Porous, depth 1.05 m	41.4-52.0	1.20-0.95	
	Plastic plates	Ø 1 mm, depth 1.05 m	42.4	1.17	
Herringen Lippe	Nozzle hoses, medium bubble	5200 nozzles Ø 1 mm, 10 units 25x6 m, depth 4 m	21.8	3.45	
Baldeneysee	Nozzle hoses medium bubble	1500 nozzles to 150 m, Ø 0.5-0.7 mm, depth 2.50-6.35 m	28(mean)	1.45(mean)	
Passaic R.				0.74	Raney 1973
Delaware R.				0.84	Raney 1973
	Pressure hoses on float	Depth 1.2 m	25.2	2.78	Goldberg 1973*
ARA	Spray cones	D = 45 cm	0.3	0.36	Klapper 1976
		D = 240 cm	110.0	0.41	"
ARA	In circular tanks	D = 3.6 m		0.34-0.42	Boehnke 1969
Intensive Fish System	Tube screen cascade			3.42-3.66 with low saturation deficit	Knoesche 1972*
Floating aeration bridge			30	1.62	(Example)
Wahnbach Reservoir	Circulation hypolimnion		23	1.20	(Example)
	Complete circulation		16	2.40	(Example)

*Cited in original text but not in original list of references.

Oxygen uptake at overfall weirs with free-falling nappe and at steep weirs, where the water is accelerated and passes through a steep ramp to be submerged in the tailwater, can be divided into two separate processes. We distinguish between oxygen transfer to the overflowing nappe as basically a molecular diffusion process and uptake from the air bubbles in the tailwater as a turbulent mass transfer process. Accordingly, we find in the literature data for the efficient design of the crest or the ridge and for the development of the tailwater. The central parameter of both partial processes is the fall head H.

Several authors give formulas or diagrams for the determination of oxygen uptake at overfall weirs or steep weirs. According to Gameson (1957) the following equation is valid for overfall weirs with fall heads of between 0.40 and 2.70 m:

$$\frac{C_S - C_O}{C_S - C_U} = 1.0 + 0.11 \cdot a \cdot b \cdot (1 + 0.046) \cdot T \cdot H$$

C_S (mg/L) saturation concentration of oxygen in water

C_O (mg/L) oxygen concentration in the headwater

C_U (mg/L) oxygen concentration in the tailwater

a - coefficient for the degree of pollution

1.25 = weak

1.00 = medium

0.8 = highly polluted

b - coefficient for the weir type

1.0 = weir with free overflow

1.3 = step weir

T (°C)	water temperature
H (m)	fall head

Londong (1973) proposes the following equation for overflows and cascades with a height of up to 3 m:

$$C_U - C_O = (C_S - C_O) \cdot \left(1 - e^{-k_h \cdot H}\right)$$

where $k_h = k_{h15} \cdot \alpha \cdot (1 + (T - 15)\,\tau)$

k_h (m^{-1})	fall head constant for polluted water
k_{h15} (m^{-1})	fall head constant at 15°C for pure water is between 0.2 and 0.7, depending on fall head and water flow
τ $(°C^{-1})$	turbulence coefficient between 0.01 and 0.02
α -	coefficient for the detergent content, between 0.3 (little turbulent wastewater) and 0.9 (turbulent river water)

Tebbutt et al. (1977) express the oxygen uptake at cascades by three characteristic numbers:

flow number $= \dfrac{q^{2/3}}{g^{1/3} \cdot L}$

gradient $= H/L$

reaeration factor $= (\ln(r)) \cdot (g/H)^{1/2} \cdot (1/N)$

where

q (m^3/ms)	specific discharge = Q_w/B
g (m/s^2)	acceleration due to gravity
L (m)	cascade length (plan)
H (m)	total fall head over all steps
N -	number of steps
r -	$C_S/(C_S - C_U)$

When ρ_w = density of water (kg/m³), we obtain a ratio of oxygen transfer to power loss of

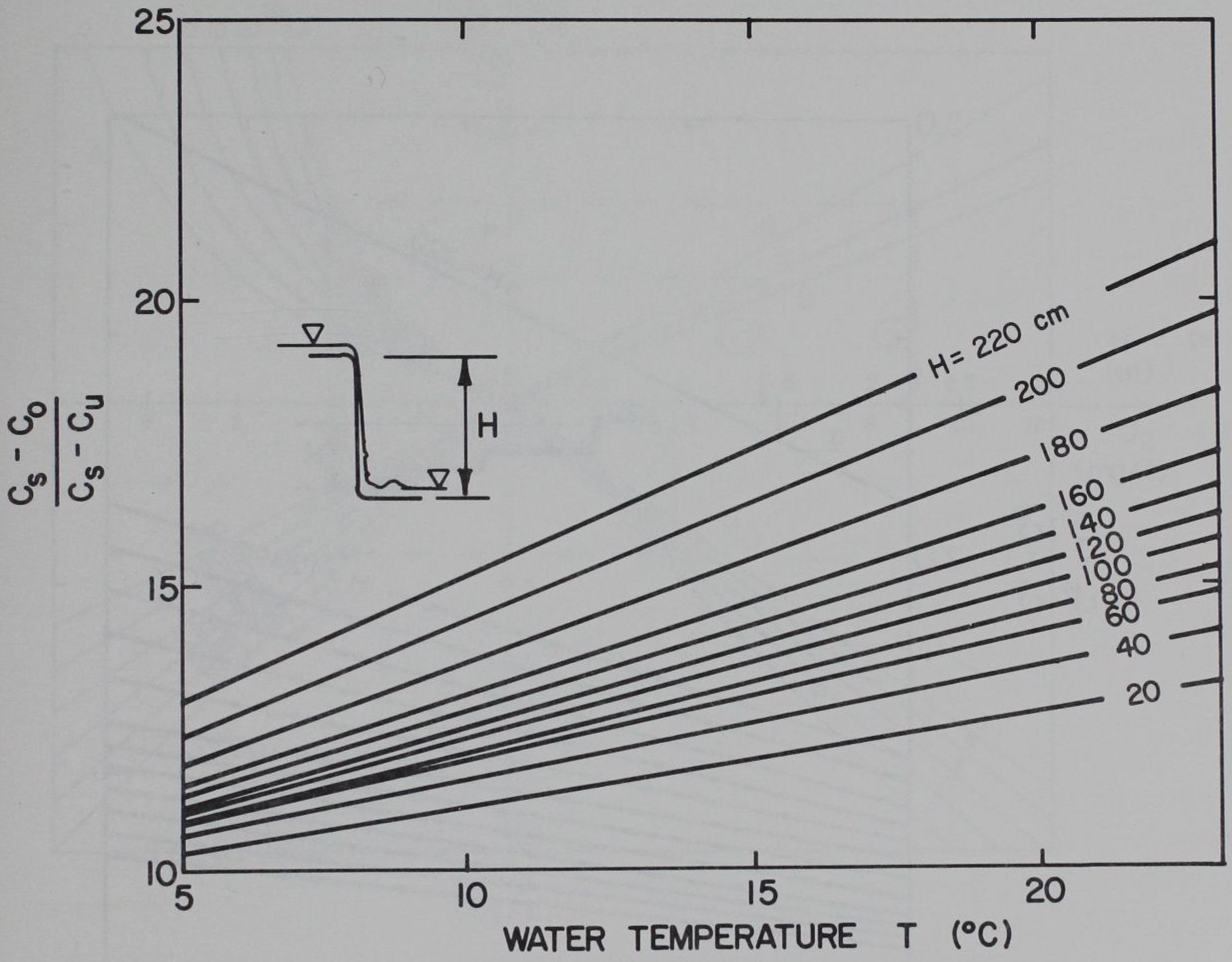
$$\frac{\rho_w \cdot q \cdot C_s \cdot \frac{r-1}{r}}{\rho_w \cdot g \cdot q \cdot N \cdot H} = \frac{3.6\ C_s \cdot \frac{r-1}{r}}{g \cdot N \cdot H} \ (k_g\ O_2/kWh)$$

Dimensioning data in diagram form are found in Manczak (1964) for single-step falls and three-step cascades (Figures A8 and A9) or in Albrecht (1968) for vertical falls and cascades (Figure A10).

These formulas and diagrams apply to specially investigated weir types and are not universally applicable. However, the various studies indicate some rules for achieving the highest possible oxygen transfer.

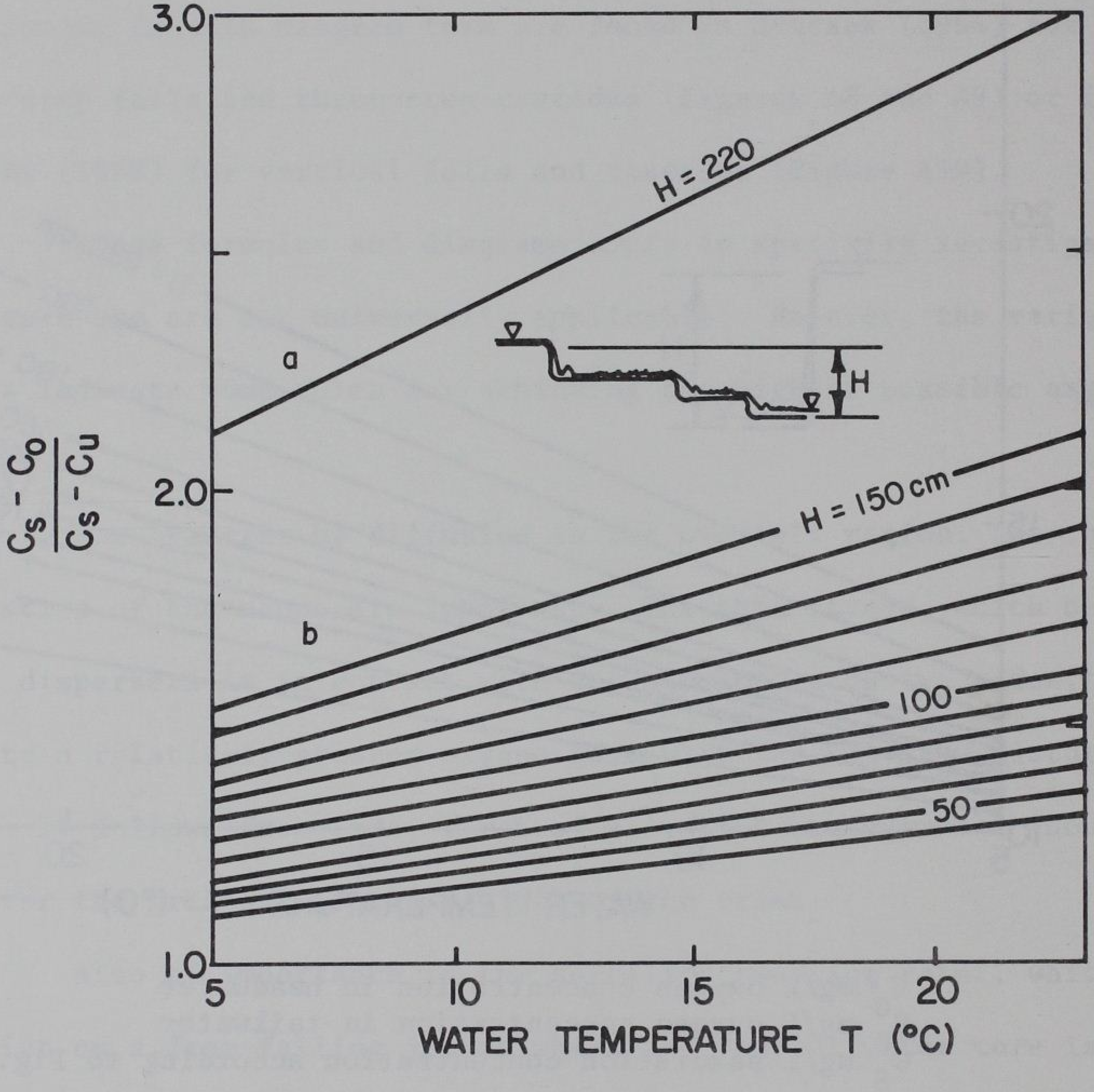
For transfer by diffusion in the overfall region, the characteristics of the nappe are important. The thin stream, which because of jet dispersers is in contact with the atmosphere on two sides, exhibits a relatively greater oxygen gain than the thick, undisturbed nappe. It follows from this, first of all, that the overfall should flow over the greatest possible width of the crest.

Also of importance is the so-called breaking point, which is the point on a free-falling jet at which the compact water core is pulled apart at the surface. It corresponds to that point in spillways and canal rapids where air bubble uptake begins. From this moment on, energy loss predominates due to increased air resistance in the oxygen transfer balance, and the jet dips, in decelerated fashion, into the tailwater. Figure A11 shows that the fall head H_A is about two meters



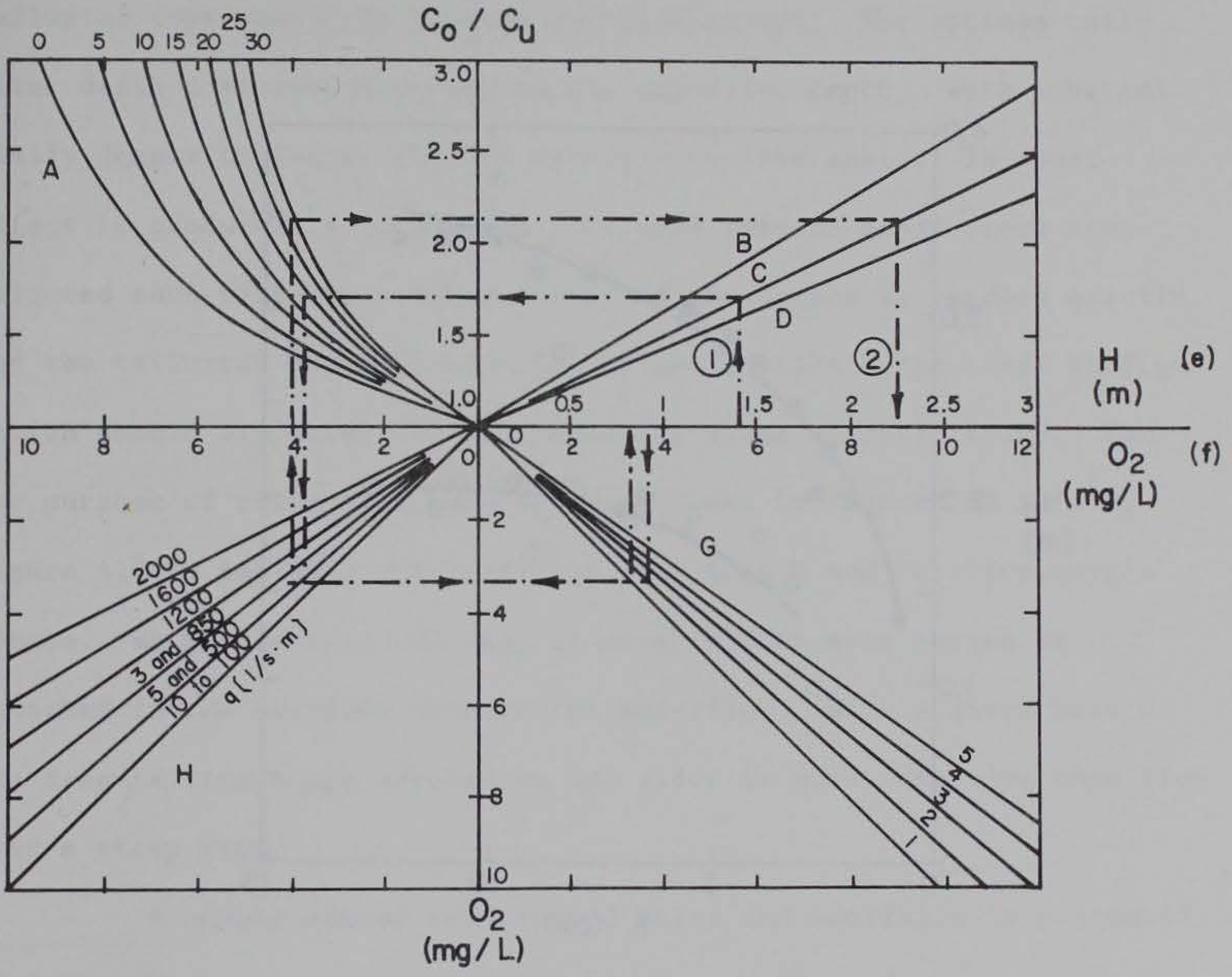
C_O mg/L oxygen concentration in headwater
C_U mg/L oxygen concentration in tailwater
C_S mg/L saturation concentration according to Fig. A1

Figure A8. Oxygen uptake on a single-step fall (overflow).



a. multi-step bed fall
b. three-step bed falls

Figure A9. Oxygen uptake at three-step fall (cascade).



a. water temperature
b. moderate load
c. medium load
d. wastewater flow
e. total fall head
f. O_2 transfer
g. number of steps
h. loading

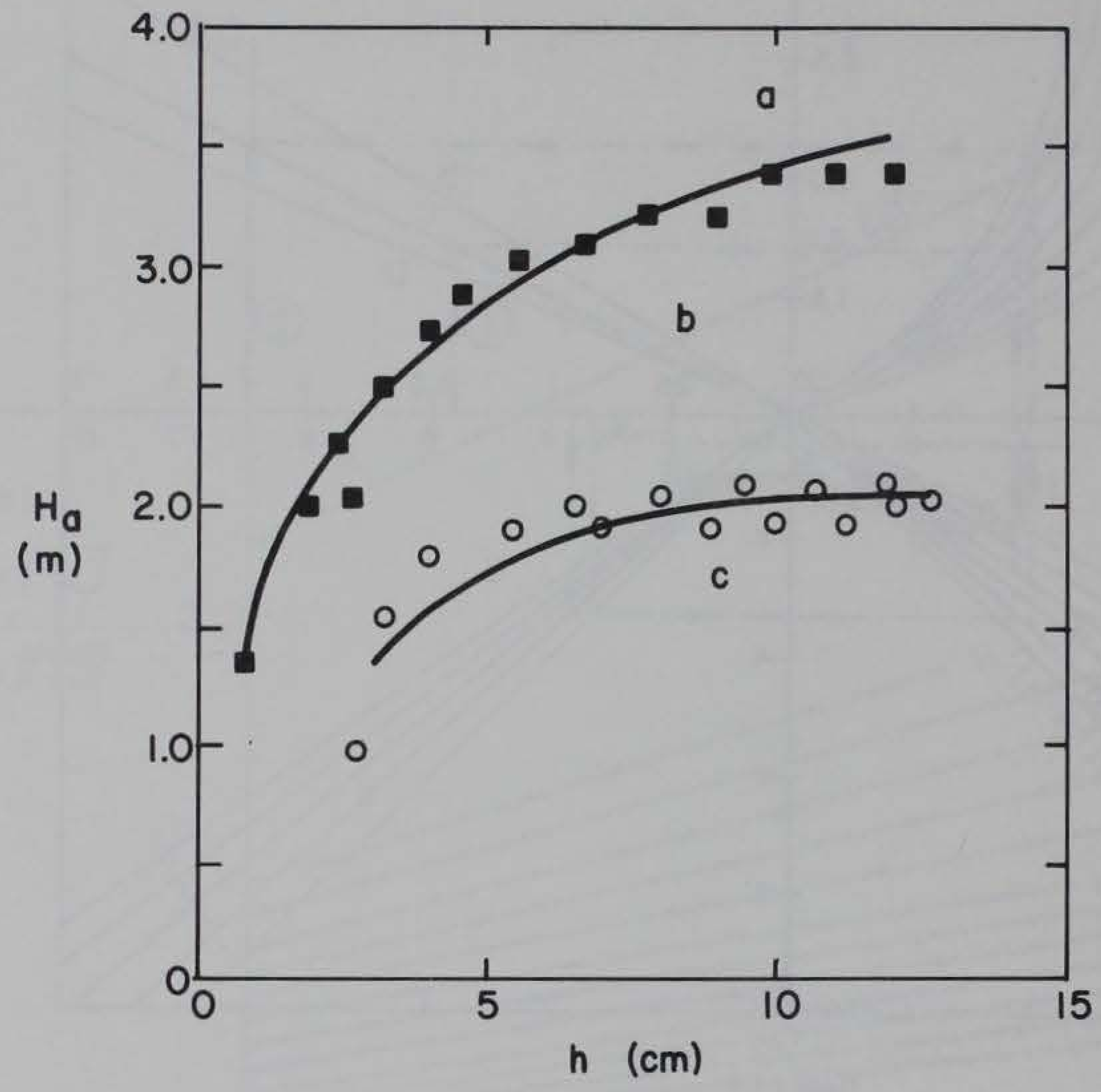
Figure A10. Diagram for determination of oxygen uptake at overfalls and cascades (related to a 100% deficit).

Example 1: at T = 20°C, q = 500 L/s.m, H = 1.4 m and C_0 = 2.3 mg/L we obtain for a moderately loaded body of water an O_2 transfer of 3.3 mg O_2/L. Thus

$$C_U = C_0 + \frac{C_S - C_0}{C_S} \text{ (oxygen transfer)}$$

Example 2: At T = 30°C, q = 750 L/s.m, C_0 = 1.5 mg/L and C_U = 4.5 mg/L there results in moderately loaded water a two-step cascade where H (total) = 2.3 m.

$$O_2 \text{ transfer} = \frac{C_S}{C_S - C_0}(C_0 - C_U) = 3.8 \text{ mg } O_2/\text{L}.$$



a. linear
b. overfall crest
c. interrupted (profile)

Figure All. Fall head H_A to so-called breaking point (h = thickness of nappe at overflow).

to the breaking point, and can only be increased through very careful overfall design to about 3.5 m.

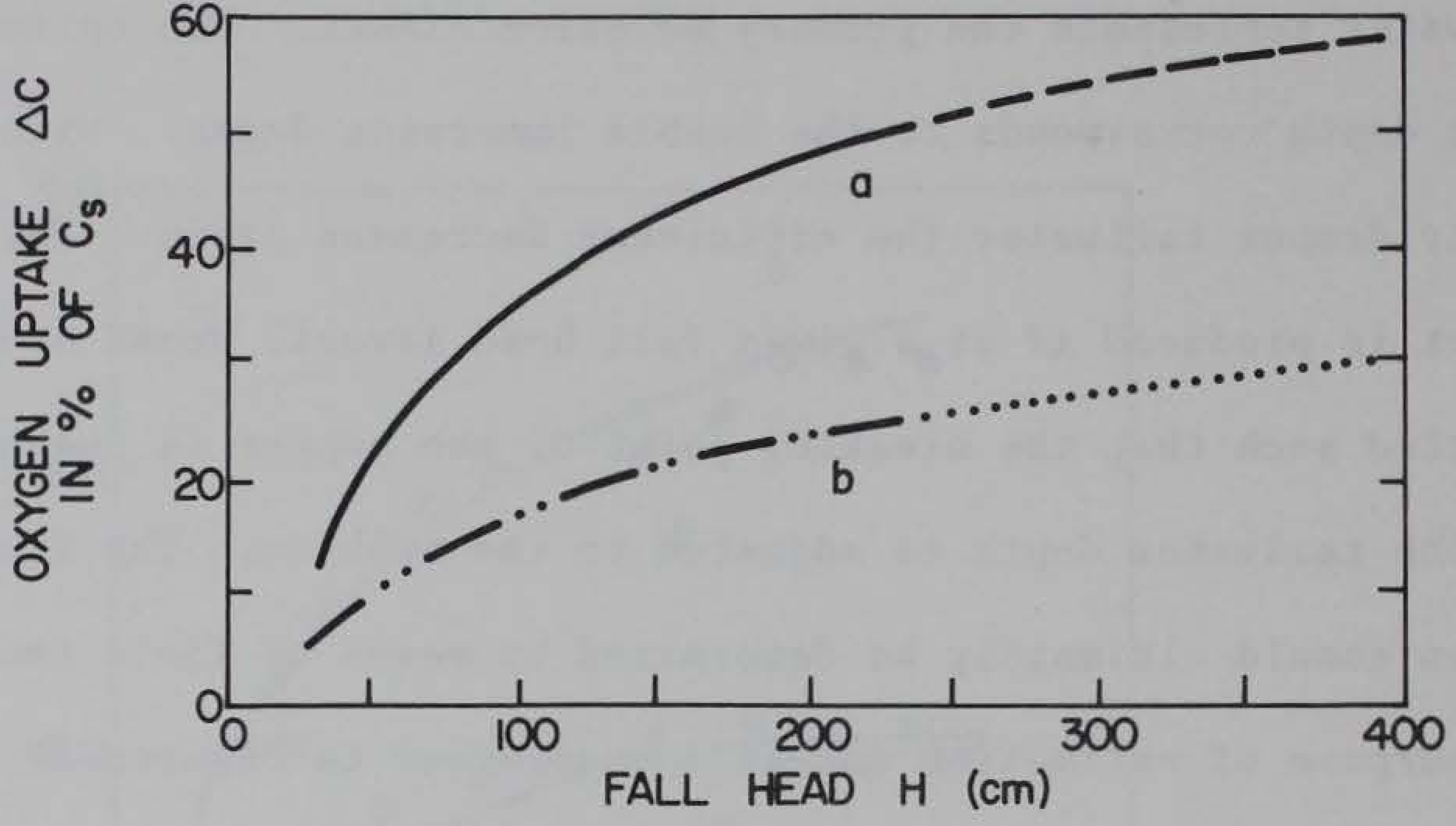
Evaluations show that the uptake through air bubbles in the tailwater represents the primary aeration effect. The optimum tailwater depth corresponds to the bubble immersion depth. With substantially deeper tailwater the efficiency decreases again. The best effect is produced if at a given fall head several broad steps are selected such that the breaking point of the nappes is reached exactly, and the tailwater depth is adjusted to the bubbles. The ideal configuration should ultimately be determined by means of field tests. For the purpose of estimation and as a supplement to Figures A8 to A10, Figure A12 is included which relates fall head H and relative oxygen uptake. We should also add that at movable dams more oxygen is absorbed in the overflow than in the underflow. With a given head H, the free-falling nappe aerated on two sides is more effective than flow over a steep ramp.

A comparison of constructed weirs and overfalls is presented in Table A7.

4.4 Surface Aerators

The surface aerators were originally conceived for use in sewage treatment plants. They spray oxygen-poor water, usually while making use of an additional rotation motion, over the surface. Of critical importance for effectiveness is the generation of the greatest possible number of boundary surfaces.

The most important types of machines are



a. overfall
b. smooth chute or race

Figure A12.

Table A7. Weirs, Overfalls

Weir Name River	Type	Configuration	H m	Co mg/L	Cu mg/L	T °C	B m	Q_w m^3/s	kg O_2/h	*) kWh/kg O_2	Reference
Spillenburg Ruhr	2-step fixed	Step 1 1:5 Step 2	1.2 1.6				300	20	151	3.57	Albrecht e.a. 1973
Kettwig Ruhe	Sector w. overfl.	1:1	5.9				90	20	495	2.33	Albrecht e.a. 1973
Kahlenberg Ruhr	Roller underfl.	Double fall	4.5				430	20	393	2.63	Albrecht e.a. 1973
Baldeney Ruhr	Roller underfl.	1-step hydraul. jump, small counter sill	8.75				33	20	570	3.02	Albrecht e.a. 1973
Werne Lippe	Fixed chute w.	1:1	1.8				100	20	101	3.45	Albrecht e.a. 1973
Beckinghausen, Lippe	Fall Weir	Overflow Gate	2.6				30	20	323	1.59	Londong 1973
Duisburg Ruhr	Fall Weir	Overflow Hook Gate	5.6				15	20	635	1.69	Londong 1973
	Trough Cascade								0.88	0.85	Bundesanst. f. Gew.schutz 1976
Laboratory	Fall Weir	Sheet crest jet diffusers	0.1-0.6							0.56-0.83 0.45	Kayser e.a. 1975
Nature	Fall W.		2.6-5.5							1.67	Kayser e.a. 1975
	Fall W.									1.33	Irving 1974*
Laboratory	Fall W.	Sheet crest	0.1-0.6	2.1-3.5	2.6-6.1	14.1		2.34 (L/s)	0.04-0.3	0.75-0.59	Albrecht 1971
			0.1-0.6	3.2	4.5-6.0	13.8		7.28 (L/s)	0.14-1.00 (g /h)	0.69-0.57	
			0.1-0.6	2.6	2.8-5.9	14.7		13.7	0.10-2.15 (g /h)	1.79-0.50	
			0.1-0.6	3.7	4.3-6.7	14.7			0.55-3.48 (g /h)	0.48-0.46	
Laboratory	Cascade	5-step	1.0							0.87	Avery e.a. 1978
			1.5							1.08	
	Fall w.	Sharp Crest	0.5							0.76	
			1.0							1.03	
			1.5							1.28	
	Hydr. Jump	Dip Wall Underfl.	0.5							0.72	
			1.0							0.96	

*) Power = $\rho_w \cdot g \cdot H \cdot \eta \cdot Q_w$ ($\eta=0.8$)
*Cited in original text but not in original list of references

- aeration rollers,
- devices with subaqueous pumps, and
- spray cones or centrifugal aerators.

The spray cones rotate around a horizontal axis. They are equipped with small vanes or buckets which churn up the surface water at speeds of 1 to 3 m/s. Diagonally placed buckets make possible an additional inherent motion of the roller axis around a fixed point.

The spray cones rotate at 30 to 50 revolutions per minute and generate at the spreading buckets a circumferential velocity of 3 to 5 m/s.

Surface aerators can be used in rivers or mounted on bridges or rafts. Their effectiveness increases with increasing surface flow velocity. Surface aerators are very safe and dependable to operate and are not endangered by floating refuse. On the other hand, the following disadvantages should be listed:

- interfering element for navigation,
- environmental deterioration due to noise and visual appearance,
- foam formation on the surface,
- difficulty aerating the entire width and depth of the river.

4.5 Use of Pure Oxygen

The use of oxygen gas is well known in sewage treatment plants. In connection with river aeration, however, no conclusive data is yet available. The method is currently being studied for standing water. The oxygen gas is introduced in bubble form as in diffused air aeration. Combinations with shaft aeration are also conceivable. In this case, a mixed stream of gas and water is first fed downward through a pipe against the bubble-rising direction.

Since air is a gas mixture which contains only about 21 percent O_2, the oxygen concentration in oxygen gas is accordingly 5 times greater. Because of the BOD dissolution rate, only about 0.2 to 0.3 percent oxygen is required compared to the water flow. It is therefore also conceivable that the oxygen could be introduced through fine nozzles or filter mats (bubble size 1 to 2 mm) upstream from turbines. Influencing of the machine efficiency need not be feared, due to the small amount added. The formation of intensive cavitation nuclei must be further investigated. Since oxygen is costly, the oxygen price and the transportation and storage costs for liquid oxygen tanks will ultimately determine the overall economic efficiency of this process.

4.6 Other Methods

There are methods which are used primarily at cooling water and sewage water outlets which can actually also be used for flowing water as supplementary processes, or in general in the case of low flow. If holes are drilled into a Venturi nozzle, air is sucked in through the holes and forms bubbles in the water. Even a pressure head of 1 m is sufficient for aeration. By appropriately selecting the holes, an effective, fine-bubble mixed flow can be generated. Particularly high efficiency is achieved if the mixed jet is introduced under water and is directed downward.

The advantage of the Venturi nozzle lies in the low capital investment and operating costs. A disadvantage is that the air transfer is very much a function of flow. Virtually constant waterflows are necessary for economical operation.

The so-called shaft aerator represents a further development. The water and air mixture is conducted downward vertically in a pipe and then fed to the surface again. Since the saturation value of the oxygen increases with rising pressure, its transfer into the water is further promoted. This method is suited to fall heads less than 1 m and requires only limited maintenance.

Another method involves spraying water over the surface through perforated or slit pipes equipped with nozzles. The oxygen gets into the water through the large total surface of all drops and through the entrained air bubbles on the water surface. In order to avoid plugging, the water passes first through coarse and fine screens. In these systems, optimum benefits are also only reached if the flow is virtually constant.

Other methods which are used for deeper, stagnant water are presented in Table A8.

Table A8. Other Selected Aeration Methods

Process	Location	Specifications	kg O_2/h	kWh/kg O_2	Comments	Reference
Oxygen Gas	Neef Power Plant, Moselle	Headwater depth min. 2 m, filter candle grates, openings 25 μ, bubbles 2 to 4 mm	282	2.14	0.26 DM/kg (total cost 30 operating days per year)	Bundesanstalt f. Gewässerkunde 1976
Deep water aeration	Rappbode (pre-dam)	Mixed air lifters (shaft aerators)	2.2	3.8		Klapper 1976
Deep water aeration	Falloren	Depth 18 m	12.5	1.1-1.3		Bucksteeg et al. 1978
Deep water aeration	Wahnbach Dam	Riser pipe with diffuser + riser	120	1.2	0.13 DM/kg (total cost)	Bernhardt 1978
Surface aerator	Baldaney intake power plant	Spray cones	41	1.25	0.51 DM/kg (total cost)	Imhoff, Wolff 1971
Atomization	Lac du Bret Lausanne	Perforated pipe L = 10 m, D = 300 mm, water on horiz. cover, then drops falling back		4.68		Eckholdt 1962
Filter mat	(sewage eng.)	Depth 4 m	584	0.63		Eckholdt, 1962
Surface aerator	Passaic River			1.29		Raney et al. 1973
Surface aerator	Delaware River			1.89		Raney et al. 1973
Diffuser		Mech.		1.80		Irving 1974*
Diffuser				0.85		Irving 1974

*Cited in original text but not in original list of references.

Table A8. Other Selected Aeration Methods (Continued)

Process	Location	Specifications	kg O_2/h	kWh/kg O_2	Comments	Reference
Water jet air suction device		H = 6.92 m, Q_w to 30 m^3/s		1.47	$C_{initial}$ = 6.0 mg/L	Dietrich 1963
Fire fighting nozzle	Mouth of the Thames			1.25	Highly polluted water	Bernhardt 1978
Surface aerator	Mouth of the Thames	Rot., immersing bevel wheel		0.89	Highly polluted water	Bernhardt 1978
Atomization	Mouth of the Thames	Jets upward + falling back		0.74	Highly polluted water	Bernhardt 1978
Box Aerator	Mouth of the Thames	Pipe aeration in box, 3 m below water level		0.17	(In box) not gen[eral]	Bernhardt 1978
Brush Aerator	Sewage eng.	Aeration tank with rot., submerged brushes. Adjustable downflow baffle		0.17-0.53	Pure water brushes min. speed, otherwise idle energy too high	Hoerler 1963
BSK* turbine	Sewage eng.	Vertical-axis cone with "overtooth" on surface	4-15	Approx. 15	Rotation direction jerking or dragging	

*Abbreviation unexplained - Translator's Note.

5. FINAL OBSERVATIONS

5.1 Comparison of Stream Aeration Systems

Table A9 is a tabular comparison of the aeration systems described in this report. Along with the power comparison (kWh/kg O_2), physical and operational effects are also listed according to key words. The evaluation of advantages and disadvantages makes it possible, finally, to define more closely the logical applications for each aeration method.

Besides blowing air into the deepest layers, it is also possible, using pumps or vertical-axis propellers, to circulate the stratified water body in such a way that oxygen-deficient water rises toward the surface where it is brought in contact with the atmosphere or an additional aerator. Another possibility involves generating temperature-related density differences by introducing cold water into warm zones or vice versa. The resulting convection currents are able to rearrange the water layers.

5.2 Comparison in Relation to Transfer Efficiency: kWh/kg O_2

It is actually not surprising that the surface aerators adopted from sewage engineering have the best ratio between power to be expended in kWh and transferred oxygen in kg O_2. They attain values of 0.3 to 1.5 kWh/kg O_2. The other processes such as atomizer, Venturi tubes, or diffusers, etc., which are also more suited for small areas, show very large variation in the corresponding values and must accordingly be able to be adapted in very subtle ways to the expected boundary conditions from case to case.

Table A9. Survey Table

Turbine Aeration	Physical Parameters Utilized	Effect on Efficiency of Turbine	Place and Type of Application	Additional Installations Cost Effects	Later Installation	Maintenance Operation
Without air supply	Residual turbulence tailwater	0		0		
Air with screen	Pressure, residence time, turbulence	Up to 2% air component approx. 0	Above river power plant, pipes	Blower or similar device, pressure balance, long lines	Rel. simple	Possible stopping up
Air - overpressure after screen	Pressure, residence time, turbulence	Up to 2% air component approx. 0	Kaplan + Francis inlet injection	Compressor valve holes wall	Only near inlet	Frequent switching on and off
Air - runner plane and draft tube	Turbulence	Reduction draft tube recovery	Runner plane draft tube self-priming	Feed lines press. control turb. shutdown during inspection	No	Difficult

Turbine Aeration (Continued)	kWh/kg O_2	Advantages	Disadvantages	Functional Installation
Without air supply	0	Very small aeration effect in tailwater	Possible churning up of sediments	--
Air with screen	Generally 1.0 +/- 0.4 in Kaplan and Francis turbines	Turbine untouched	Rel. expensive additional machinery necessary	Existing plants, vertical axis turb., so that no air in high points
Air - overpressure region after screen	Ditto	Air stream directed against runner	Ditto + leaktightness	New horizontal or diagonal axis turbines
Air - runner plane and draft tube	Ditto	Self-priming	Access difficult for installation + inspection	Francis turb. better (lower draft tube loss); development possibilities open: input points, deflectors
		All: water jet included, electricity personnel	All: tied to fixed point in longitud. river profile dependent on flow	

Table A9. Survey Table (Continued)

Process	Parameters Utilized	Additional Equipment Cost Effects	Servicing Operation	kWh/kg O_2	Advantages	Disadvantages	Functional Installation
Diffused air aeration	Pressure water depth, residence time (diffusion)	Compressor, pipelines, valves, filters (rafts)	Clogging	1.20-3.45	Mobile, dosable, does not interfere w. PP operation	Installation cost, maintenance, obstruction to navigation	Standing and flowing water, if possible canalized, depth over 1-2 m
Weirs, overfalls							
Movable weirs	Fall head, nappe breakup	No equipment water loss		2.6 ± 0.4	Can be regulated		Navigation canals
Fixed overfalls	Fall head turbulence		None	Approx. 1.6 (model from 0.5)	No maintenance	Cannot be regulated, less effective at low flow	Aeration cooling water or treated wastewater jet
Cascades, Bed steps	Turbulence		None	0.85-1.1	Good O_2 transfer, no maintenance	Cannot be regulated, great width	Undammed river sections, fall heads 30 cm + greater, not only constant flow
Surface aerator	Turbulence water drop surface	Rollers centrifuges, spreading buckets, pumps, etc. suspension	Floating refuse	0.3-1.5	Mobile, dosable	Noise, foam, navigation obstruction, only small area	Locations with high flow velocity (surface) and high O_2 depletion, depth approx. 1.5 to 5 m.

Table A9. Survey Table (Continued)

Process	Parameters Utilized	Additional Equipment Cost Effects	Servicing Operation	kWh/kg O_2	Advantages	Disadvantages	Functional Installation
Atomization	Fall head drop surface	Screens, sieves, pumps, feed lines	Clogging	0.75-4.70	Mobile, dosable, locally intensive	Fall head cannot be be varied	High fall head, approx. constant flow (cooling water)
Diffuser, Venturi	Pressure turbulence	Pumps, pipelines, screens, filters	Little	1.3 ± 0.5	Mobile, locally very effective	For small flows and areas, noise	Cooling water, wastewater even with small fall head, constant flow
Shaft aerator	Pressure, residence time	Pumps, pipes, possibly screens	Little	1.3-3.8	Low space requirement, locally very effective	Effect more local, noise, deposition of suspended matter in pipe	Small fall head, small space
Pure oxygen	Pressure, residence time, solubility	Storage, tanks, pipelines, valve, etc.	Problem dosage	(2.1)	Good O_2 transfer (turbine efficiency not affected)	Expensive	With small flow and short installation time "emergencies"

Of interest is the fact that the turbine aeration method, at about 1.0 ± 0.4 kWh/kg O_2 is in second place in this analysis. It is also obvious that the systems which utilize flow turbulence primarily attain the best efficiencies. Of these processes, the systems which do the best are those which were tested at higher oxygen deficiencies.

Diffused air aeration, which is based primarily on diffusion, yields somewhat poorer results. Its advantage lies ultimately in its mobility.

Weirs and overflows are highly dependent on the form of the overfall crest, which is adjusted to the flow, and on the structure of the tailwater. As is apparent, peak values of oxygen uptake efficiency can be reached--usually at experimental weirs. However, if in practical operation the breaking point should be too high or the flume shape in the tailwater should not be adapted to the bubble immersion depth, then more negative results will be obtained very quickly at fixed weirs and cascades.

Only limited data is available on stream aeration with pure oxygen. The method is familiar from sewage engineering and has been investigated in recent years primarily in connection with deep, standing water.

5.3 Comparison in Respect to Water Flow

Critical oxygen conditions occur with low water or with highly fluctuating flow. Not all aeration systems which are favored on the basis of transfer efficiency or total cost can satisfy these natural conditions equally, however. The cheapest system, the fixed weir overfall, achieves its optimum effect on oxygen transfer only with a certain water flow. Since it is difficult to design for low water, its area of application tends to involve controllable, rather constant influx from the cooling plants of thermal power plants or from the final settling tanks of sewage treatment plants.

The movable weir could be adapted in principle to the influx, but normally it is designed from different standpoints.

Turbine aeration is already somewhat more versatile. With flow that fluctuates for short periods or with low water flow, however, turbining can normally not be used.

Diffused air aeration has increased flexibility. However, it should be kept in mind that at low water the water depth, and thus the residence time for the air bubbles, can become too small. Since the diffused air aerators are designed for a certain pore or filter size, certain limits are imposed on their ability to adapt to great variations in flow.

The use of surface aerators can be advocated, primarily in cases of low influx. However, although their effectiveness on the water surface increases with rising water flow due to the increased surface velocity, the deep action is at the same time reduced in cases of rising water level to the extent that this method is generally not as effective as the other methods when there is strong water flow.

If the goal is to achieve (a) great adaptability to quickly changing water levels and at the same time (b) intensive action at low water or with other oxygen bottlenecks, then a combination of two different methods should not be completely ruled out. For example, one possibility would be to install in the headwater of an overfall weir a Venturi tube or a surface unit as supplementary equipment.

5.4 Comparison with Respect to Installation Location

Aerated turbines and weirs or cascades are locally fixed. They consequently achieve the best transfer rates when they include the entire channel flow. In contrast, diffused air aerators, pure oxygen systems, or the various types of surface aerators are basically mobile and can be used at more precisely defined locations, particularly in cases of very long reaches. A good possibility is also a combination of stationary turbine aeration and mobile surface or diffused air aeration.

5.5 Position of Turbine Aeration in Relation to the Other Known Methods

The survey and comparison of measured values reveals that turbine aeration is one of the most effective methods. However, we should not forget that the very high efficiencies of oxygen uptake apply to that water flow range for which the plants were designed. Sucking in air in the negative pressure region does require less additional equipment, but is highly dependent on the turbine water flow. If air bubbles are added upstream from the intake funnel, then the flexibility of overall aeration can be increased. This, however, requires additional equipment.

In general we can state that the more tightly an aeration system is bound to particular inflow volumes, then the more important detailed information about oxygen BOD_5 patterns becomes. For this reason, one would hardly want to select the turbine aeration method without having available systematic series of measurements of water quantity and quality over many years. Stream aeration solely by means of turbines can be viewed critically in the following cases:

1. Highly polluted water which is in an unstable equilibrium between the aerobic and anaerobic state. Turbine operation cannot allow for changing light and temperature conditions;
2. Very high oxygen requirements for certain fish. There is a danger that salmonids such as trout, salmon, etc., will collect below the turbine and will not survive the sudden drop in oxygen when the turbines are shut down;
3. When water is low, the turbines cannot operate. This is critical for the river as a receiving body and fish water;
4. Deaerated and heated cooling water or untreated wastewater is discharged in batches. In such cases previous oxygenation of these influxes is not indicated.

If we disregard the limitations listed above, there are still very significant, to some extent already tested, possibilities for using turbines as aeration units. We assume that when the air supplied represents no more than two percent of the water volume, it will have no noticeable effect on turbine efficiency. Even today, air bubble streams are used to regulate smooth operation and to combat cavitation.

6. PROSPECTS FOR FURTHER DEVELOPMENT

Of the systems treated in this report, the turbine aeration systems and the surface and deep water aerators seem most likely to offer further opportunities for development. Since the last two methods named tend to lead to new developments when very specific, generally unchanging and locally limited boundary conditions exist, they will not be treated in the following.

With regard to the further development and adaptation of turbine aeration, the following areas of concentration, listed in sections 6.1 to 6.5, emerge.

6.1 Testing of Other Input Points

The observations in Chapter 4.1.3 already indicate the possibility that, purely from the standpoint of boundary surface renewal (thorough mixing and also residence time of the individual air bubbles) the addition [of air] in the annular gap and from the rotating turbine vanes could result in an increased efficiency of oxygen uptake or a correspondingly reduced air demand. Questions concerning the rotational stability of the rotating parts, due to local pressure fluctuations on turbine or housing or due to the regulation of the air feed, would have to be answered by engineering studies. Since no model similarity can be achieved due to the air bubbles and since, therefore, use of model turbines is not possible, tests with real turbines are necessary.

6.2 Systematic Studies of Smooth Operation, Inherent Frequencies, Efficiency Variations, Cavitation, and Rust

The common statement that turbine efficiency is only changed insignificantly with an air supply of two percent or less is highly simplified. Certainly important differences depending on machine type and input point will result in the case of exact in situ measurements. The same also applies to smoothness of operation and cavitation limits.

6.3 More Exacting Adaptation of Known and New Air Supply Systems to the Different Types of Turbines

In the literature only a few individual cases of already constructed turbine aeration plants are described. We are a long way from any kind of systematic classification which relates the type of air supply system to the turbine type. Tests and series of measurements dealing with a Francis turbine, a Kaplan turbine, and a tubular turbine would represent an important step forward.

6.4 Quantitative Data Showing Which Boundary Conditions Rule Out a Certain Turbine Aeration Method from an Engineering Standpoint or Make It Economically Infeasible

Turbine aeration methods are relatively versatile, within certain limits. These limits can probably already be defined at this time by the turbine manufacturer together with the energy producer. For example, from historical data of water quality and water quantity it is possible to estimate the annual aeration time and the number of additional starting and stopping procedures and possible interruptions for inspections. The same is true for the cost of additional equipment. Depending on the relations between water quality and minimum requirements for oxygen content or between inflow and turbined water volume, it is possible that better suited locations for oxygenation than the dams of river power plants will be found.

6.5 Search for Combination Possibilities with Secondary Systems

If it happens that an existing or planned turbine aeration system will not meet the demands of particular oxygen problems, then it is conceivable that a secondary system might be considered. A mobile diffused air or surface aeration system could be considered as a balance to the locally fixed turbine aeration system. These secondary systems would be used in small areas, for example in natural fish collection pools or in the headwaters of a dam, for short periods of time. The economic efficiency can be interesting for the reason that these secondary or reserve aerators can be selected only for narrowly limited boundary conditions and because they can be used primarily in cases when turbine aeration would be inefficient to operate.

In this connection the reader is also referred to the possible combination of turbines and pure oxygen aeration.

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APPENDIX B: SUPPLEMENTAL REFERENCES

Additional aeration references published primarily since 1970 are presented for the following categories:

1. Turbine venting to benefit machine operation
2. Gas transfer tests and measurements
3. Stream aeration
4. Gas transfer theory
5. General aeration
6. Aeration systems

Because of the relevance of gas bubble disease to reaeration efforts, a list of references on that subject is also provided under category 7, gas bubble disease. See References (Section 6.0) for availability.

1. TURBINE VENTING TO BENEFIT MACHINE OPERATION

Title	Reference
Penstock Intake Vortex and Related Turbine Operation Model Studies	Dexter and Zeigler (1978)
Analysis of Air Vents on Penstock Emergency Gates	Falvey (1977)
Comparison of Draft Tube Surging of Homologous Scale Models and Prototype Francis Turbines	Fisher *et al*. (1980)
Influence of the Amount of Bubble Nuclei on Cavitation Tests of a Francis Turbine	Henry (1978)
Influence of a Method of Air Admission and Pressure Surges in Draft Tube Models of Axial Hydroturbines	Isaey (1961)
Vibrations of the Bolarque Dam	Kenn *et al*. (1979)
Air Supply Into Draft Tube of Francis Turbine	Nakanishi and Ueda
Flow Aeration to Prevent Cavitation Erosion	Quintela (1980)
Studies of a Method to Prevent Draft Tube Surge in Pumped Turbines	Seybert *et al*. (1978)
Efficiency Improvement by High-Pressure Shroud Aeration of Turbines and Pumps on 75,000-hp Turbine	Sproule and Koeller (1969)
Methods of Controlling Turbine Draft Tube Vibrations and Stability	Thicke (1980)
On the Measurement of Void Fraction in Hydraulic Fluid with Entrained Bubbles	Tsuji and Matsui (1978)

Title	Reference
A Contribution to Influencing the Part Load Behavior of Francis Turbines by Aeration and Sigma Value	Ulith (1968)
Contribution to Clarifying the Inception of Nonstationary Flow Phenomena in the Draft Tube of High Specific Speed Francis Turbines Operating at Part Load	Ulith *et al*.
Measurement of the Frequency Domain of a Francis Turbine in Waters with Different Air Content and Air of Different Densities	Walter (1979)
Hydraulic Performance Evaluation and Potential Payback	Whippen (1978)
Reduction of Pressure Fluctuations in Penstocks at Pumped-Storage Plants by Injecting Air Under the Runner	Zolotov *et al*. (1976)

2. GAS TRANSFER TESTS AND MEASUREMENTS

Title	Reference
The Comparability of Oxygenation Capacity Measurements	Bingel (1977)
Proposed Modifications of K_2--Temperature Relation	Brown and Stenstrom (1980)
Analysis of Supersaturated Air in Natural Waters and Reservoirs	D'Aoust and Clark (1980)
Testing and Data Analysis of Diffused Aeration Equipment	Ewing *et al*. (1979)
Field Testing for Oxygen Transfer and Mixing in a Static Mixer Aeration System	Gilbert and Libby (1978)
Measurement of Physical Oxygen Input into Natural Streaming Waters Using Tracers	Guenthart *et al*. (1980)
Reaeration Tests, Outlet Works Beltsville Dam, Pohopoco Creek, Pennsylvania	Hart and Wilhelms (1977)
Aeration of the River Main with Pure Oxygen	Hollweg and Thron (1978)
Dissolved Nitrogen Measurements at Clarks Hill Reservoir, Georgia-South Carolina	Merritt and Leggett (1981)
Tracer Measurement of Aeration Performance	Neal and Tsivoglou (1974)
Alternative Choices in Measurement Systems for Artificial River Aeration	Olgac *et al*. (1980)
Laboratory Studies of Gas Tracers for Reaeration	Rathbun *et al*. (1978)
Estimating the Gas and Dye Quantities for Modified Tracer Technique Measurements of Stream Reaeration Coefficients	Rathbun (1979)

Title	Reference
Oxygen Transfer Parameter Estimation	Stenstrom *et al.* (1981)
Surface Aeration Equipment Field Testing Versus Shop Testing	Stukenberg and Wahbeh (1978)
Tracer Measurement of Reaeration: Application to Hydraulic Models	Wilhelms (1980)

3. STREAM AERATION

Title	Reference
The Reaeration of Rivers	Cleary (1966)
Artificial Aeration of Rivers	Eckoldt (1962)
Artificial River Aeration According to R. von Wolff, Results of the Experiments at the Saar River Hydroplant METTLACH, 1964	Eckoldt (1966)
Mean Air Concentration of Self-Aerated Flows	Falvey (1979)
Aeration of the River Main with Pure Oxygen	Hollweg and Thron (1978)
Oxygenation Tests with Oxygen Gas in Rivers	Hollweg (1980)
Oxygen Aeration at Fixed Weirs	Hutarew and Topal-Gokceli (1975)
How Does One Compute Artificial Stream Reaeration?	Imhoff (1969)
Engineering Methodology for River and Stream Reaeration	JBF Scientific Corporation (1971)
River Water Aeration with Pressurized Air and Oxygen	Markofsky (1980)
Optimal Control of Artificial Aeration in River Networks	Olgac *et al*. (1977)
Alternative Choices in Measurement Systems for Artificial River Aeration	Olgac *et al*. (1980)
Investigation of Method of Stream Improvement	Palladino (1961)
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Title	Reference
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4. GENERAL AERATION

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5. GAS TRANSFER THEORY

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Mass-Transfer Model for Aeration	Holyand (1979)
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6. AERATION SYSTEMS

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Oxygen Transfer at Hydraulic Structures	Avery and Novak (1978)
Field Testing for Oxygen Transfer and Mixing in a Static Mixer Aeration System	Gilbert and Libby (1978)
Model-Prototype Air Demand for Gated Tunnel Flows	Harshbarger *et al.* (1979)
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7. GAS BUBBLE DISEASE

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