OXYGENATION OF TURBINE DISCHARGES FROM FORT PATRICK HENRY DAM

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Abstract

The Tennessee Valley Authority is investigating the use of oxygen injection through fine-pore diffusers for increasing dissolved oxygen concentrations in the turbine discharges from Fort Patrick Henry Dam. Oxygen injection is being considered either immediately upstream from the turbine intakes, so that the oxygenated water is drawn directly into the turbines, or immediately downstream from the "boil" area in the tailrace.

Research is being conducted in two phases: (1) selection of a diffuser for injecting the oxygen, and (2) selection of the best location for injecting the oxygen. In Phase I, various commercial diffusers are being evaluated for possible plugging problems and for oxygen absorption efficiency. Field and laboratory tests indicate that diffuser-plugging apparently is not a significant problem and that oxygen absorption efficiency approaching 100 percent can be achieved in a 42-foot height of bubble rise with several commercially available diffusers. In Phase II, a large-scale diffuser system will be evaluated at Fort Patrick Henry Dam during the summer and fall of 1973.

A full-scale system will be installed at the dam if results of this research show this method of reaeration to be technically and economically feasible.

INTRODUCTION

TVA is investigating the use of oxygen injection through fine-pore diffusers for increasing dissolved oxygen (DO) concentrations in the turbine discharges from Fort Patrick Henry Dam.

The dam is located on the South Fork Holston River at river mile 8.2 in Sullivan County, Tennessee, about 2.5 miles upstream from Kingsport, Tennessee, and 10.4 river miles downstream from Boone Dam (Figure 1). At normal maximum pool (elevation 1,263), the reservoir extends 10.3 miles

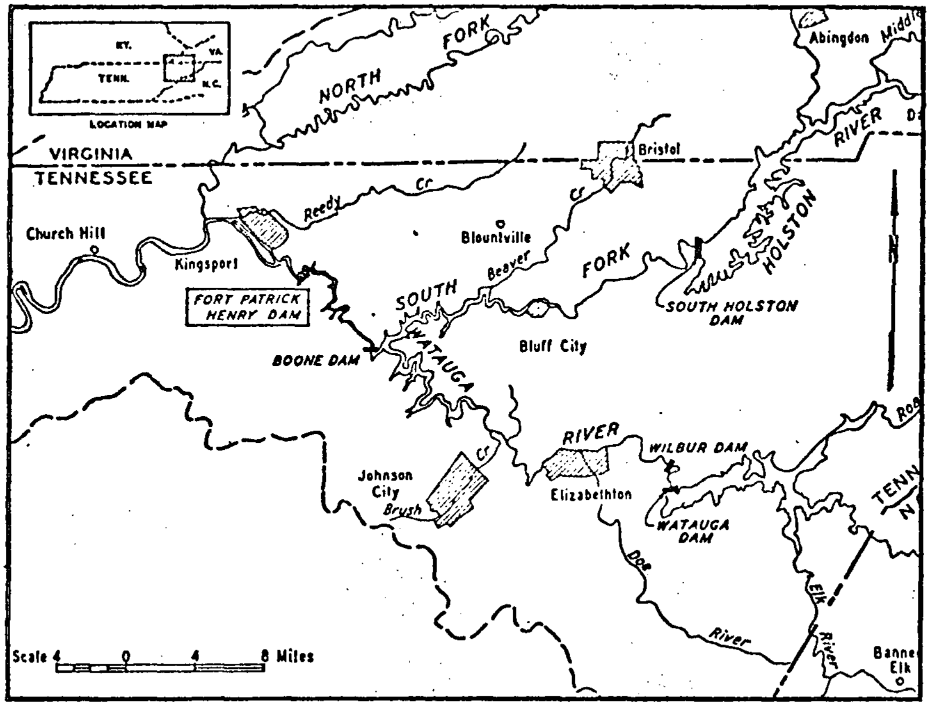

Figure 1. Map of Project Area

upstream and has a total volume of 27,100 acre-feet. The reservoir has 4,300 acre-feet of useful controlled storage between normal maximum pool level and normal minimum pool level (elevation 1,258). Average streamflow at Kingsport was 2,522 cubic feet per second during the period 1925–1970.

The dam is equipped with two hydraulic turbines, each of which has a generating capacity of 18,000 kw. Normal maximum discharge through each turbine is 4,400 cfs.

The maximum depth of the pool immediately upstream from the dam is approximately 70 feet. The thermocline during summer and early fall is usually 5 to 20 feet below the surface of the pool.

Low concentrations of DO occur in the turbine releases from Fort Patrick Henry Dam during the summer and fall each year (Figure 2). This problem is the combined result of water low in DO that enters Fort Patrick Henry Reservoir through low-level power intakes at Boone Dam upstream and an additional depletion of oxygen in the hypolimnion of the stratified Fort Patrick Henry Reservoir. This low DO problem adversely affects a reach of stream immediately below the dam that has been classified as a trout stream

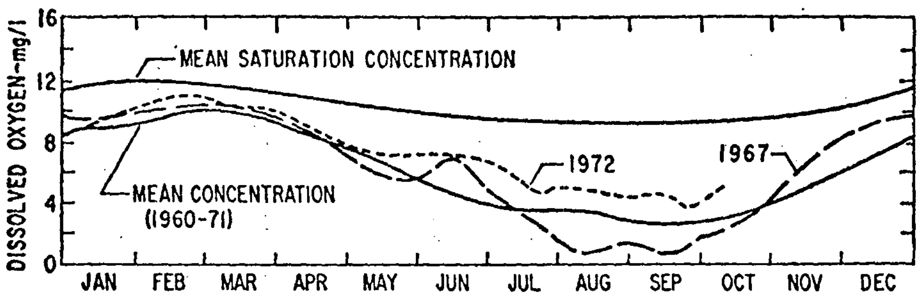

Figure 2. Dissolved Oxygen Conditions in the Turbine Discharge from Fort Patrick Henry Dam

by the State of Tennessee and also compounds a water pollution problem that exists downstream from Kingsport.

After an evaluation of various methods for increasing DO levels in reservoir releases (5), it was concluded that diffused air aeration in the tailrace or oxygen injection into the releases are the most promising methods for correcting this problem at Fort Patrick Henry Dam. Only those aeration methods that would not increase the temperature of the turbine releases could be considered because of the cold-water fishery downstream from the dam. This consideration automatically eliminated destratification of the reservoir and possibly other methods that might be more economical.

Oxygen injection was selected for further investigation, primarily because of the high power requirements (about five percent of the plant output) and high initial investment cost required to achieve high concentrations of DO by diffused air aeration. Using data on diffused air aeration in sewage treatment plants (4) and extrapolating to tailwater conditions, it was estimated that such an installation would require a minimum of 3,000 horsepower to drive the needed compressors and 15,000 fine-bubble diffusers such as those used in sewage treatment plants. The diffusers in the tailrace would cover an area about 100 feet wide and 250 feet downstream. Preliminary estimates for increasing DO in the turbine release to 6 mg/l indicate the total annual cost for oxygen injection ranges between $120,000 for upstream injection and $220,000 for downstream injection; diffused air aeration in the tailrace is about $220,000. The lower initial investment cost for oxygen injection was considered especially important because of the limited information available on aeration of reservoir releases.

This paper is divided into the following main sections: (1) Proposed Full-Scale Oxygenation System, (2) Evaluation of Commercially Available Diffusers, (3) Field Oxygenation Tests, (4) Discussion, and (5) Conclusions.

Proposed Full-Scale Oxygenation System

Oxygen can probably best be injected into the turbine releases from Fort Patrick Henry Dam by diffusing the oxygen through fine-pore diffusers. Amberg *et al.* tested injection of oxygen into a turbine system by means of a perforated sparge ring that encircled the turbine above the runner blade; the maximum absorption efficiency obtained was only 40 percent (1). In the proposed system, oxygen would be injected through diffusers placed either immediately upstream from the turbine intakes, so that the oxygenated water is drawn directly into the turbines (Figure 3), or immediately downstream from the "boil" area in the tailrace (Figure 4). The oxygen injection system would only operate when water was discharged through the turbines.

The most economical location for diffuser injection appears to be upstream from the turbine intakes. The greater depth of water has the advantages of allowing more contact time between the water and the gas bubbles and of increasing the ratio of the partial pressure of oxygen in the bubbles to that of dissolved nitrogen so that oxygen transfers into the water faster than dissolved

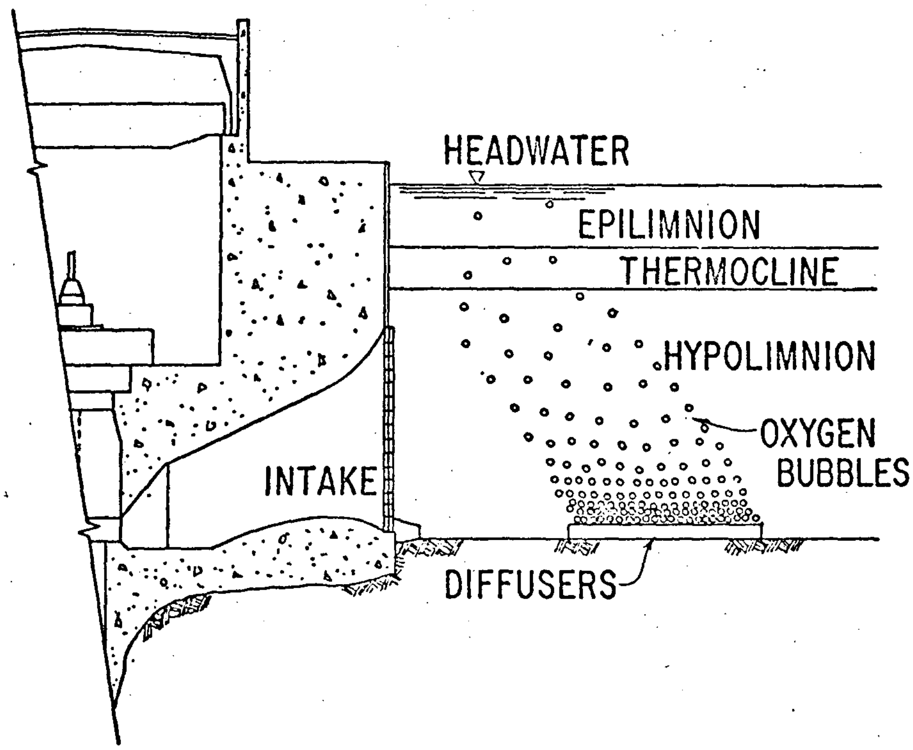

Figure 3. Oxygen Injection Upstream from Turbine Intakes

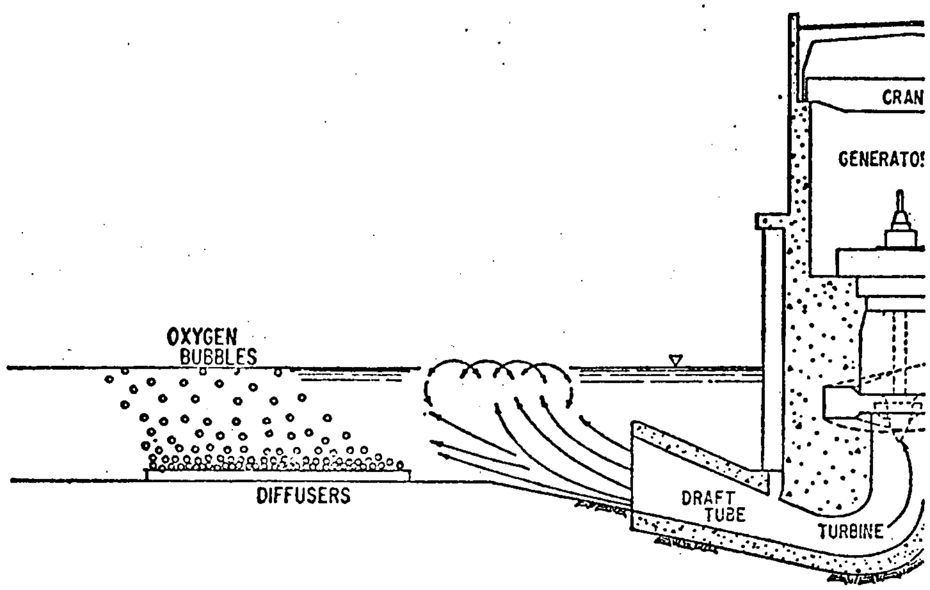

Figure 4. Oxygen Injection Downstream from Turbine Releases

nitrogen transfers into the oxygen gas bubbles. The ratio of the partial pressure of oxygen to that of nitrogen increases with increased depth because the partial pressure of oxygen in a bubble increases with depth while that for dissolved nitrogen generally remains the same at all depths. The combination of these factors allows more gas to be injected through a unit area of diffuser, thus reducing the size of the required diffuser system.

A disadvantage of upstream injection is that several problems may develop if all the oxygen is not absorbed by the time it reaches the turbines. These possible problems include a reduction in turbine efficiency, corrosion of the turbine and the associated discharge system, and adverse effects on pressure taps used to measure turbine discharge.

Injecting oxygen through diffusers downstream from the dam would not affect the turbine discharge system, but oxygen absorption efficiency may be lower because of the shallower water. Other disadvantages of downstream injection include the need for a larger diffuser system to inject larger volumes of gas (resulting from both lower absorption efficiency and less mass of oxygen per unit volume of gas, because of less pressure compared to upstream injection), waste of oxygen to the atmosphere or the need for capture and recirculation, and perhaps a somewhat greater consumption of electric power depending on the number of vaporization units required.

A liquid oxygen storage tank would be the source of oxygen gas because

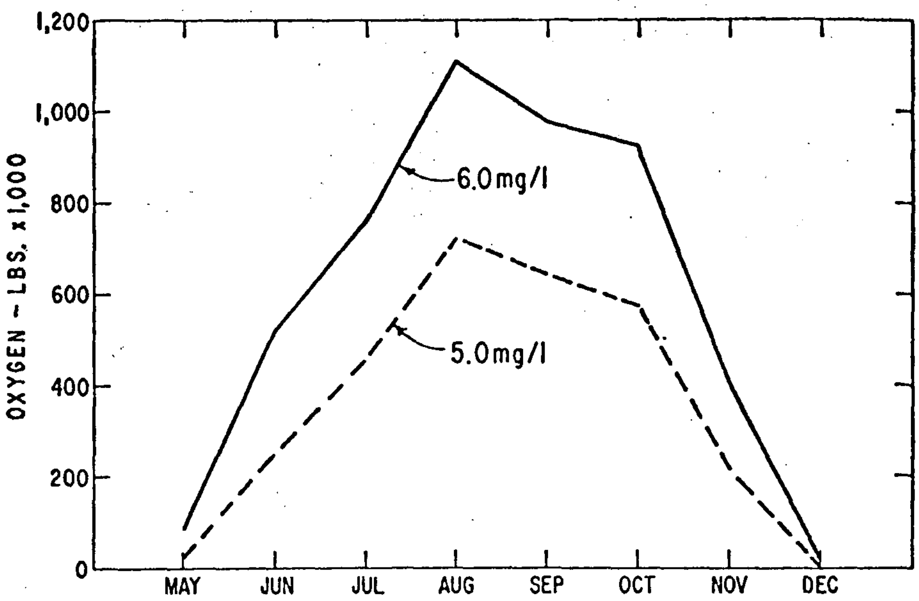

FIGURE 5. Average Monthly Oxygen Requirements at Fort Patrick Henry Dam (Based on 1960–1970 Records).

the oxygen requirement is seasonal, highly variable, and relatively low. The monthly demand for oxygen during an average year ranges from about 25,000 pounds to 1.1 million pounds, as shown in Figure 5. Oxygen would normally be required only six months of each year. The annual oxygen requirement ranges from 3.5 to 6.3 million pounds per year to achieve a DO concentration of 6 milligrams per liter and from 1.7 to 4.1 million pounds per year to obtain a concentration of 5 milligrams per liter (Table 1).

EVALUATION OF COMMERCIALLY AVAILABLE DIFFUSERS

Since only limited information is available on injecting oxygen into turbine releases by means of diffusers, special studies are required before designing a full-scale injection system. TVA is conducting these studies in two phases. In Phase I, commercially available oxygen diffusers are being tested in the field and in the laboratory to select a diffuser for Phase II. Diffuser selection will be based mainly on operation and maintenance considerations, oxygen transfer characteristics, and cost. For Phase II, which is discussed in the next main section, a large-scale diffuser system capable of increasing the dissolved oxygen concentration 2–3 milligrams per liter in the releases from one turbine will be installed at the dam and tested.

TABLE 1

Annual Oxygen Requirements for Turbine Discharges from Fort Patrick Henry Dam—1960–1970

Year	Oxygen Required to Provide the Following Minimum Downstream Dissolved Oxygen Concentrations, lbs/yr	
	5 mg/l	6 mg/l
	x 10^6	x 10^6
1960	3.51	5.73
1961	2.26	4.50
1962	3.20	5.15
1963	4.07	6.30
1964	3.13	5.33
1965	2.32	3.86
1966	3.68	5.58
1967	2.64	4.05
1968	1.71	3.55
1969	2.57	4.25
1970	2.42	4.46
Averages	2.86	4.80

Operation and Maintenance Tests

Diffusers can be clogged or plugged by one or more of the following: (1) silt and other solid material settling onto the diffusers, especially during periods when oxygen is not being injected, (2) biological organisms growing on the diffusers, (3) oxidation of chemically reduced ions or chemical compounds in the water on the diffusers, and (4) the diffusers behaving as filters when water enters the diffuser system during idle periods. To evaluate these possible problems, a small-scale field study was conducted in which oxygen was injected for various lengths of time through 14 diffusers (Table 2 and Figure 6) located on the bottom of the reservoir (Figure 7). Clogging characteristics of the various diffusers were evaluated on the basis of change in pressure drop across each diffuser (Figure 8). The diffusers were evaluated periodically during an eight-month period, and no apparent plugging problems developed. Several of these diffusers will be tested for possible changes in transfer efficiency. Sediment has accumulated on the diffusers

TABLE 2

Diffusers Evaluated Under Reservoir Conditions For Possible Maintenance Problems

Diffuser Number	Diffuser Description	Length (in)	Width or OD (in)	Wall Thickness (in)	Pore Size (μ)	Testing Time (days)
1	Steel Disk	-	8-3/4	1/8	5	246
2	Steel Disk	-	8-3/4	1/8	10	152
3	Alumina Cylinder	6	2-9/16	11/16	≈15-≈20	246
4	CEVIAN-N Plastic	20	2-5/8	1/2	27-50	246
5	Alumina Cylinder	24	2-1/2	11/16	60	152
6	Alumina Plate	10-1/8	10	1	60	75
7	Alumina Plate	10-1/4	10-1/2	1	164	75
8	Alumina Cylinder	24.	2-1/2	11/16	240	11
9	Aluminum Alloy Plate	12-1/2	2-1/2	-	3-4	64
10	Aluminum Alloy Plate	12-1/2	2-1/2	-	1-1/2—2	164
11	Aluminum Alloy Plate	12-1/2	2-1/2	-	2-3	112
12	Aluminum Alloy Plate	38	2-1/2	-	1-1/2—2	142
13	Alumina Cylinder	6	2-1/2	11/16	5-10	94
14	Alumina Cylinder	6	2-1/2	11/16	8-15	94

several times but has always been removed by applying a high gas flow rate to the diffusers. In addition, no plugging or clogging resulted when the eight diffusers having the smallest pores were left idle for two weeks.

The water quality conditions under which the diffusers were evaluated are summarized in Table 3. Field testing of these diffusers probably will be continued during the summer and fall of 1973.

To supplement the field tests for evaluating diffuser plugging that might be caused by oxidation of chemically reduced ions and compounds, oxygen was injected through the smallest pore diffuser (Table 2) in a tank of water

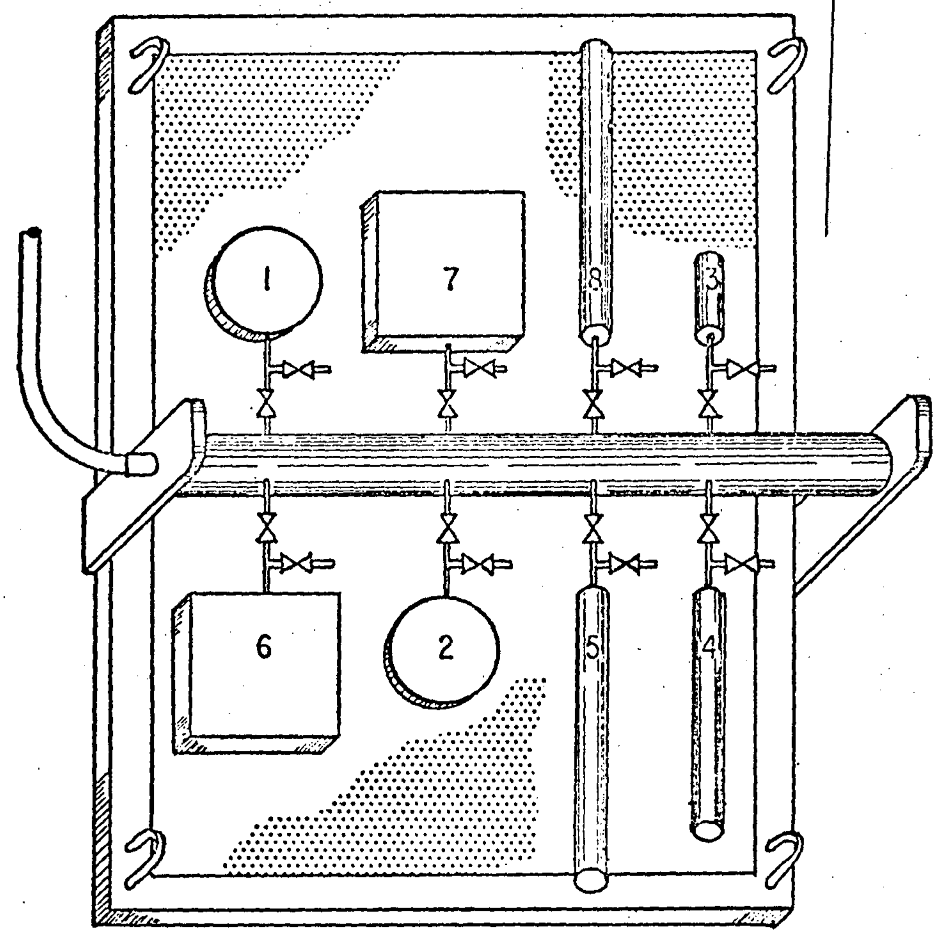

Figure 6. Phase I Diffuser System (Numbers on diffusers refer to those diffusers described in Table 2)

(Figure 9) that contained ferrous iron. The diffuser did not clog after being tested intermittently 8 hours a day for about 2 months for a total of 317.5 hours. The oxygen flow rate per diffuser unit during the test was 0.093 standard cubic feet per minute per square foot of diffuser surface, which is about the same as that recommended by the manufacturer.

The amounts of ferrous iron and fresh water added to the tank were adjusted so that ferrous and total iron concentrations were held at about 1.6 and 7.4 milligrams per liter, respectively. A pH of about 7 was maintained in the tank by adding sufficient phosphate buffer to neutralize the acid formed from oxidation of ferrous iron and the acid used to preserve the ferrous iron standard.

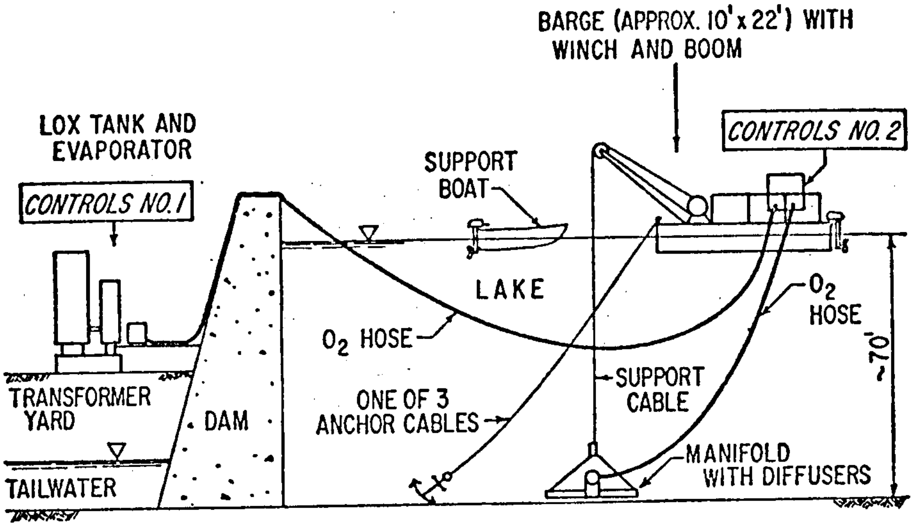

Figure 7. Fort Patrick Henry Dam Aeration Project General Lay-Out

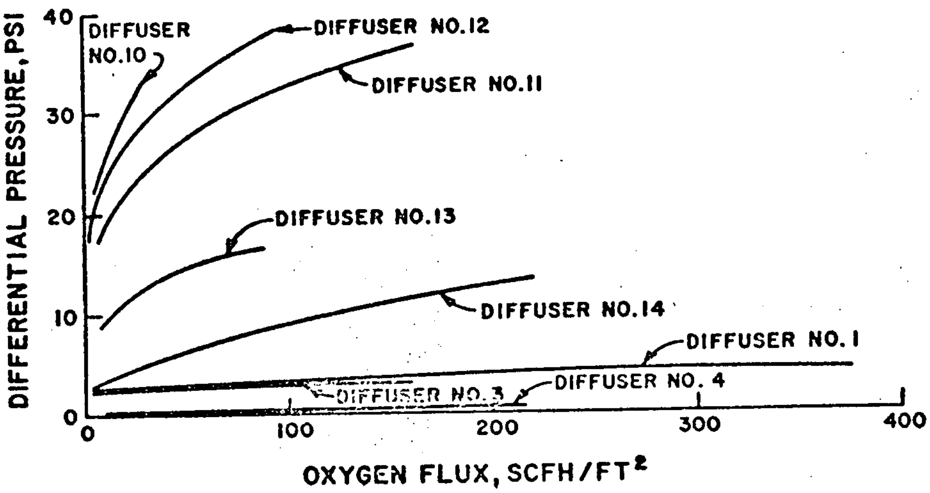

FIGURE 8. Graphical relationships between pressure drop and oxygen flow rate per unit area of diffuser for several of the diffusers tested during the field maintenance tests (Refer to Table 2 for descriptions of the diffuser numbers.)

Although the pressure drop across the diffuser did not change significantly, an iron plate formed on the diffuser surface. Tests are planned to determine whether this plating will affect the transfer efficiency of the diffuser. A possible solution to this plating problem may be the periodic injection of hydrogen chlorine gas for dissolving the iron on the diffuser.

Table 3

Water Quality Conditions in Fort Patrick Henry Reservoir (South Fork Holston River Mile 8.2)

Date	Time ET	Depth ft.	Water Temp. °C.	DO mg/l	5-Day 20°C. BOD mg/l	Turb. JCU	Nitrogen* Org. mg/l	Nitrogen* NH_3 mg/l	Nitrogen* NO_2 mg/l	Nitrogen* NO_3 mg/l	Phosphate Sol. mg/l	Phosphate Tot. mg/l
5-24-72	8:40 a.m.	•	14.0	7.5								
5-23-72	9:20 a.m.	1	19.0	13.6	5.1	1	0.40	<0.01	0.02	0.40	0.09	0.14
		10	14.4	11.2	5.6	2	0.53	<0.01	0.02	0.47	0.02	0.20
		20	14.2	10.2	4.4	2	<0.01	0.03	0.01	0.65	0.04	0.11
		25	13.4	8.7	3.8	1	0.33	0.02	0.01	0.66	0.01	0.12
		45	12.3	7.2	2.7	3	0.17	0.14	0.01	0.69	0.04	0.09
	11:00 a.m.	73	12.0	6.9	3.2	5	0.16	0.15	0.01	0.73	0.08	0.11
5-23-72	2:00 p.m.	•	13.0	7.8	3.1	2	0.27	0.13	0.01	0.71	0.12	0.10
5-23-72	2:01 p.m.	•	13.0	7.8	3.3	2	0.21	0.13	0.01	0.71	0.08	0.11
5-30-72	8:15 a.m.	•	14.0	6.7								
6-6-72	8:30 a.m.	•	15.0	8.0								
6-13-72	10:45 a.m.	•	14.0	7.4								
6-20-72		•	15.0	6.8								
6-27-72	8:30 a.m.	•	-	5.0								
6-27-72	9:50 a.m.	1	17.6	6.8	1.4	2	0.29	0.11	0.02	0.87	0.02	0.06
		10	15.7	5.4	1.2	3	0.16	0.11	0.02	0.90	0.02	0.11
		20	14.5	4.9	1.1	3	0.20	0.11	0.02	0.92	0.03	0.11
		30	14.3	4.8	1.5	3	0.16	0.10	0.02	0.93	0.03	0.06
		45	14.0	4.7	<1.0	4	0.15	0.10	0.02	0.93	0.03	0.09
	11:05 a.m.	71	13.7	4.6	1.0	5	0.16	0.09	0.03	0.96	0.02	0.08
7-4-72	10:15 a.m.	•	14.0	6.9								
7-11-72	11:45 a.m.	•	15.0	6.2								
7-18-72	8:45 a.m.	•	15.0	5.6								
7-25-72	10:20 a.m.	1	22.1	11.9	6.6	1	0.46	<0.01	0.01	0.41	0.02	0.08
		10	15.5	5.1	3.2	2	0.33	0.04	0.02	0.84	0.02	0.09
		20	15.0	4.9	2.5	1	0.24	0.04	0.02	0.93	0.03	0.08
		30	15.0	4.5	2.7	3	0.29	0.05	0.02	0.99	0.06	0.10
		40	14.8	4.4	2.3	2	0.29	0.05	0.02	1.1	<0.01	0.09
		55	14.6	4.0	2.3	5	0.31	0.05	0.02	1.1	0.04	0.14
	12:00 p.m.	65	14.5	3.6	2.6	2	0.32	0.04	0.01	1.1	0.05	0.15
7-25-72	8:15 a.m.	•	17.0	4.4								
8-1-72	9:00 a.m.	•	16.0	4.7								
8-8-72	11:15 a.m.	•	17.0	4.9								
8-15-72	8:45 a.m.	•	16.0	4.9								
8-22-72	8:20 a.m.	•	17.0	4.4								
8-29-72	11:20 a.m.	1	22.1	11.9	2.6	3	0.45	<0.01	0.03	0.72	0.02	0.12
		10	17.3	5.9	1.6	4	0.35	<0.01	0.01	0.96	0.01	0.09
		10	17.3	5.9	1.5	4	0.39	<0.01	0.01	0.97	0.01	0.10
		20	16.4	4.8	1.3	5	0.28	<0.01	0.01	0.97	0.02	0.02
		40	16.0	3.8	1.0	6	0.20	<0.01	0.01	0.10	0.04	0.09
		60	15.5	3.7	<1.0	15	0.29	0.02	0.03	1.0	0.05	0.17
	12:02 p.m.	70	15.5	3.5	1.1	24	0.32	0.03	0.03	1.0	0.05	0.23
9-5-72	12:30 p.m.	•	16.0	4.3								
9-12-72	8:15 a.m.	•	16.0	4.5								
9-19-72	9:30 a.m.	•	16.5	4.1								
9-26-72	9:30 a.m.	•	17.0	3.7								
10-3-72	12:30 p.m.	•	10.0	4.3								
10-3-72	5:50 p.m.	1	21.5	7.6	4.7	10	0.40	<0.01	0.02	0.85		0.28
		10	16.7	5.1	1.7	10	0.22	<0.01	0.02	0.89		0.22
		20	15.9	4.5	2.0	7	0.20	0.01	0.02	0.93		0.11
		30	15.5	4.2	1.8	8	0.22	<0.01	0.02	0.93		0.12
		40	15.5	4.2	1.4	7	0.24	<0.01	0.02	0.93		0.12
		50	15.5	4.2	1.2	10	0.24	<0.01	0.01	0.92		0.12
		60	15.3	4.3	1.3	10	0.24	<0.01	0.01	0.90		0.15
	7:09 p.m.	70	15.3	4.0	1.6	15	0.20	<0.01	0.01	0.92		0.17
10-10-72	8:45 a.m.	•	16.0	4.5								
10-17-72	10:00 a.m.	•	17.0	5.0								
10-25-72		•										

*Nitrogen: Values shown are mg/l nitrogen in the forms listed.
•Indicates sample was taken from turbine system scrollcase.

TABLE 3 (continued)

Water Quality Conditions in Fort Patrick Henry Reservoir
(South Fork Holston River Mile 8.2)

Date	Time ST	Depth ft.	pH	Total Hardness ($CaCO_3$) mg/l	Ca mg/l	Mg mg/l	Iron Fe^{++} mg/l	Iron Total mg/l	Manganese Mn^{++} mg/l	Manganese Total mg/l	Sulfide mg/l	SO_4 mg/l	Specific Conductance at 25°C micromhos/cm	Solids Dissolved mg/l	Solids Suspended mg/l
5-23-72	8:40 a.m.	•					0.06	0.36		0.05	<0.03				
5-23-72	9:30 a.m.	1	8.9	99	28	7.0	0.06	0.06	<0.01	0.01	<0.03	7	170	120	11
		10	8.4	95	27	6.8	0.04	0.10	<0.01	<0.01	<0.03	7	170	120	5
		20	8.0	90	29	6.6	0.03	0.11	<0.01	0.02	<0.03	7	170	110	3
		25	7.5	97	26	6.6	0.06	0.11	<0.01	0.02	<0.03	7	160	110	16
		45	7.2	86	24	6.3	0.07	0.26	<0.01	0.04	<0.03	7	160	120	7
	11:00 a.m.	73	7.2	96	27	6.9	0.08	0.62	<0.01	0.07	<0.03	7	160	110	9
5-23-72	2:00 p.m.	•		86	24	6.4	0.06	0.34	<0.01	0.05	<0.03	7	200	210	3
5-23-72	2:01 p.m.	•		86	24	6.4	0.09	0.29	<0.01	0.05	<0.03	7	200	210	6
5-30-72	8:15 a.m.	•					<0.01	0.19		0.09	<0.02				
6-6-72	8:30 a.m.	•					0.15	0.18		0.02	<0.02				
6-13-72	10:45 a.m.	•					0.02	0.11		0.05					
6-20-72		•					0.06	0.13		0.04	<0.02				
6-27-72	8:30 a.m.	•					0.01	0.35		0.04	<0.02				
6-27-72	9:30 a.m.	1	7.3	82	23	6.0	0.04	<0.05	<0.01	<0.01	<0.02	14	200	220	9
		10	7.1	79	22	5.9	0.03	0.06	<0.01	<0.01	<0.02	12	200	110	5
		20	7.4	80	22	6.0	0.03	0.06	<0.01	0.01	<0.02	13	200	100	<1
		30	7.3	79	22	5.9	0.04	<0.05	0.01	0.01	<0.02	13	200	110	3
		45	7.5	83	23	6.1	0.03	0.10	0.02	0.02	<0.02	13	190	110	11
	11:05 a.m.	72	7.5	82	23	5.9	0.05	<0.05	<0.01	<0.01	<0.02	12	190	100	10
7-4-72	10:15 a.m.*	•					0.09	0.43		0.05	<0.02				
7-11-72	11:45 a.m.	•					0.04	0.43		0.03	<0.02				
7-18-72	8:45 a.m.	•					0.01	0.36		0.08	<0.02				
7-25-72	10:30 a.m.	1	6.8	73	20	5.7	0.02	0.07	<0.01	<0.01	<0.02	14	180		9
		10	6.9	75	21	5.5	0.03	0.27	<0.01	0.05	<0.02	16	180		5
		20	6.9	75	21	5.5	0.07	0.75	0.01	0.05	<0.02	14	180		3
		30	6.8	72	20	5.4	0.06	0.38	0.01	0.06	<0.02	15	180		8
		40	6.8	77	21	5.9	0.06	0.33	<0.01	0.06	<0.02	15	180		9
		55	6.8	77	21	5.9	0.05	0.41	<0.01	0.07	<0.02	14	180		8
	12:00 p.m.	65	6.8	78	21	6.3	0.06	0.40	0.03	0.09	<0.02	14	180		11
7-27-72	8:15 a.m.	•					0.05				<0.02				
8-1-72	9:00 a.m.	•					0.10	0.81		0.38	<0.02				
8-8-72	11:15 a.m.	•					0.01	0.34		0.04	<0.02				
8-15-72	8:45 a.m.	•					<0.01	0.58		0.08	<0.02				
8-22-72	8:30 a.m.	•					0.04	0.25		0.31	<0.02				
8-29-72	11:20 a.m.	1	8.4	89	26	5.9	0.02	0.10	0.05	0.10	<0.02	16	140	90	<10
		10	7.2	89	26	5.9	0.02	0.70	<0.01	0.05	<0.02	15	140	80	23
		20	7.2	86	25	5.7	<0.01	0.25	0.01	0.04	<0.02	14	140	70	13
		30	7.0	89	26	5.8	0.01	0.36	<0.01	0.07	<0.02	15	140	60	21
		40	6.9	91	27	5.7	0.01	0.32	0.02	0.08	<0.02	14	140	70	18
		60	6.9	87	25	5.9	0.13	1.2	0.09	0.20	<0.02	14	140	80	29
	12:02 p.m.	70	6.9	92	27	6.0	0.12	1.8	0.14	0.27	<0.02	14	150	90	36
9-5-72	12:30 p.m.	•					0.24	0.48		0.10	<0.02				
9-12-72	8:15 a.m.	•					0.02	0.27		0.10	<0.02				
9-19-72	9:30 a.m.	•					0.04	0.29		0.07	<0.02				
9-26-72	9:30 a.m.	•					0.02	0.35		0.07	<0.02				
10-3-72	12:30 p.m.	•					0.22	0.64		0.05	<0.02				
10-3-72	5:30 p.m.	1	7.6	83	23	6.3	0.04	0.34		<0.02	<0.02	13	150	100	7
		10	7.2	80	22	6.2	0.06	0.41		0.02	<0.02	13	170	100	6
		20	7.1	80	22	6.2	0.03	0.25		0.03	<0.02	14	170	100	4
		30	7.1	80	22	6.2	0.02	0.24		0.03	<0.02	13	170	100	5
		40	7.1	84	23	6.4	0.02	0.35		0.03	<0.02	14	170	100	4
		50	7.1	83	23	6.3	0.02	0.41		0.03	<0.02	12	170	100	9
		60	7.2	86	24	6.3	0.07	0.67		0.07	<0.02	12	170	100	19
	7:09 p.m.	70	7.8	84	23	6.5	0.10	0.71		0.07	<0.02	12	170	100	16
10-10-72	8:45 a.m.	•					0.06	0.32		0.05	<0.02				
10-17-72	10:00 a.m.	•					0.01	0.30		0.04	<0.02				
10-25-72		•					0.03	0.25		0.05	<0.02				

*Indicates sample was taken from turbine system scrollcase.

Oxygen Transfer Efficiency Tests

The oxygen transfer efficiency of various diffusers depends mainly on pore size, uniformity of pore size, spacing of pores, and gas flow rate per unit of diffuser. The theoretical aspects of gas transfer have been discussed by numerous investigators (2) (3) (6) but information is not available for predicting the aeration transfer efficiencies of various commercially available diffusers having pore sizes in the range desirable for use with oxygen.

The oxygen transfer efficiency for diffusers can best be determined by con-

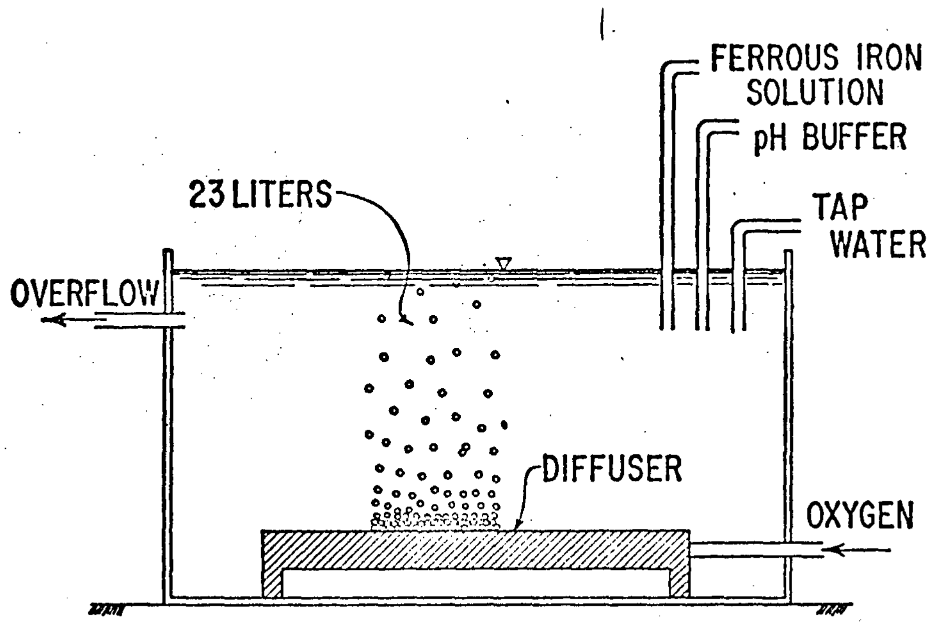

Figure 9. Chemical Plugging Test Tank

ducting laboratory studies using a tank to simulate the conditions under which the diffusers will be used. The transfer efficiency is defined as the ratio of the oxygen absorbed by the water to the oxygen supplied through the diffuser for set conditions of DO and temperature. Other factors that affect transfer efficiency include height of bubble rise, gas flow rate through the diffuser, concentration of dissolved nitrogen, geometry and hydraulic characteristics of the tank, and water quality conditions in the tank.

Transfer efficiency may be determined by the following three techniques:

$$\text{Transfer Efficiency} = \frac{\text{total oxygen absorbed}}{\text{total oxygen supplied}} = \frac{(C_2\text{-}C_1)V_t}{W} \qquad (1)$$

where (C_1) and (C_2) are the initial and final DO concentrations, respectively, for the test; (V_t) is the volume of water in the tank; and (W) is the weight of oxygen supplied.

$$\text{Transfer Efficiency} = \frac{\text{rate of oxygen absorption}}{\text{rate of oxygen supplied}} = \frac{(dc/dt)V_t}{W/t} \qquad (2)$$

where (dc/dt) is the rate of oxygen absorption determined by methodology developed by Ippen and Carver (2), and (t) is the period of oxygen supply.

$$\text{Transfer Efficiency} = 1 - \frac{\text{total oxygen unabsorbed}}{\text{total oxygen supplied}} = 1 - \frac{V_g \rho}{W} \qquad (3)$$

where (V_G) is the volume of oxygen gas collected at the top of the water column, and (ρ) is the gas density.

The first technique is easiest to use but the results are applicable only to those situations where the initial and final DO concentrations are the same as those for the original tests. The applicability of this technique is especially limited for air aeration, because transfer efficiency is very dependent on DO concentrations; however, when oxygen is used in place of air, this technique is applicable over a wider range of DO concentrations.

The second technique is perhaps the most difficult to use in oxygenation tests because it requires measuring the oxygen uptake rate, which in turn requires measuring the DO in the tank during the test. Measuring DO in the tank is difficult if oxygenation occurs in only part of the tank and if this oxygenated water is not mixed with that in the remainder of the tank. The advantage of this technique, however, is that the results are applicable for all DO concentrations within the range tested.

The third technique requires collecting gas at the top of the water column and analyzing it for oxygen content. This technique should be used in combination with the first to provide a check on the results. An important advantage of this technique for oxygenation tests is that the amount of dissolved nitrogen stripped from the water during testing may be determined easily without the need for on-site instruments for continual dissolved nitrogen analysis. One disadvantage of this technique as applied in the past is that the results are applicable only in the same manner as those from the first technique because only initial and final measurements are taken, and therefore are not applicable for intermediate concentrations of DO.

To compare the relative oxygen transfer efficiencies for various commercial diffusers, a tank (Figure 10) was constructed at TVA's Engineering Laboratory in Norris, Tennessee. The tank was designed for a 45-foot depth to simulate approximately the minimum height of the hypolimnion in Fort Patrick Henry Reservoir. A diameter of 7 feet was selected so that the volume of water in the tank would be sufficient to limit the rate of DO increase during testing to about 1 milligram per liter per minute so the rate of DO increase might be measured. The size of this tank should also reduce effects of the wall of the tank and thus possibly reduce the amount of error in scaling up results.

The tank is equipped with a pump for mixing the contents, a filter for cleaning the water, a nitrogen gas injection system for adjusting the concentration of dissolved nitrogen in the water before tests, and a gas collector that may be adjusted to various heights of the water column. The gas collector system allows continuous measurement and analysis of unabsorbed gas while a test is in progress which may allow the determination of rate of oxygen absorption.

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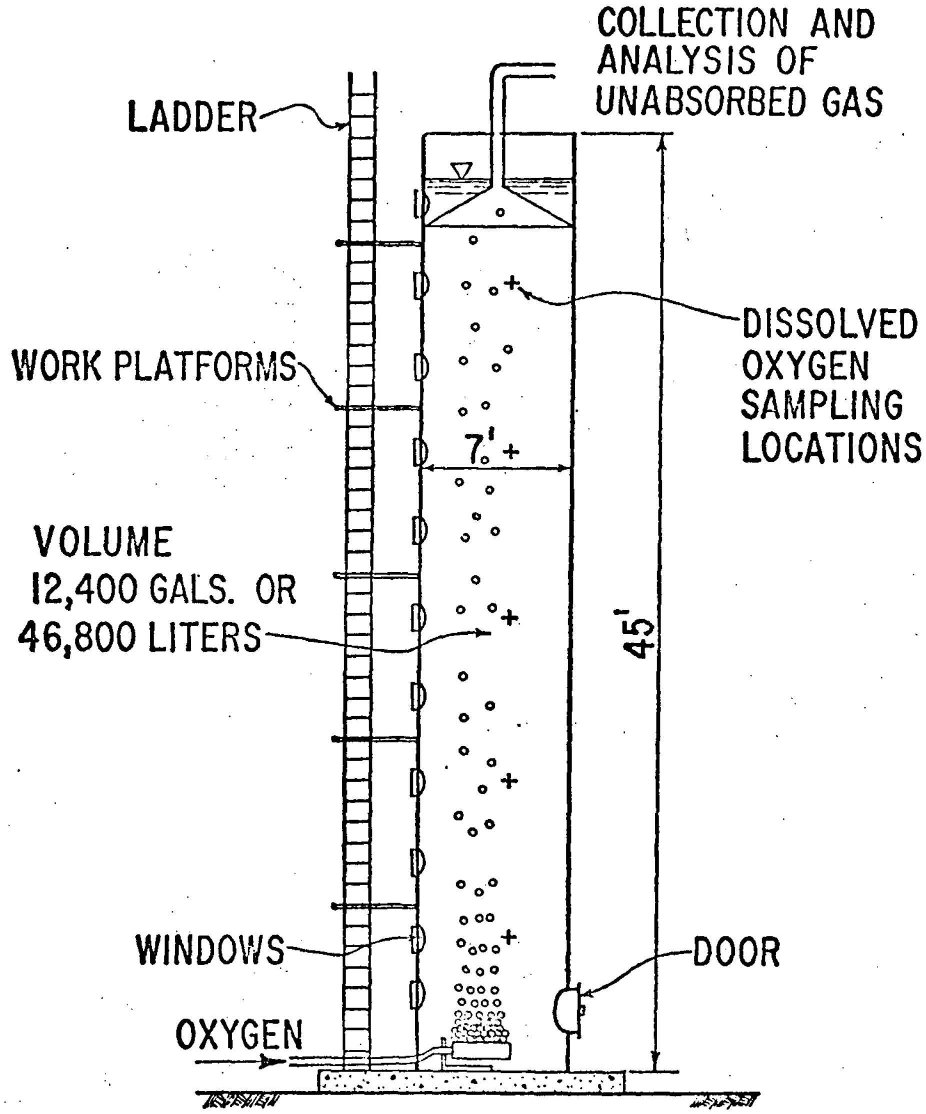

Figure 10. Tank for Measuring Aeration Transfer Efficiencies of Diffusers

(This determination would allow use of the second equation noted above, and the results would be applicable to all concentrations of DO within the range tested.)

The amount of oxygen gas injected can be measured by integrating measurements from the orifice flow meter and by weighing the amount of oxygen used from a small medical supply bottle. Before each test, DO is reduced to about 0.5 mg/l by chemical reduction (sodium sulfite is used with a cobalt catalyst).

Much of this equipment was just recently added to the tank and final diffuser evaluations have not yet been conducted. Preliminary tests, however, have been conducted on six diffusers by the first technique for determining transfer efficiency without the benefit of the gas collector, nitrogen injection system, and weight measurement system for the amount of oxygen gas injection. The approximate final DO in the tank water following each test was 6.0 mg/l . Another limitation to these results is that gas flow rate measurement at very low rates (<0.2 scfm) apparently was in error. These preliminary tests, however, indicate that for a 42-foot height of bubble rise the transfer efficiency is essentially the same (Figure 11) for all the diffusers tested. In general, the results indicate that transfer efficiencies approaching 100 percent are possible at low gas flow rates and the minimum efficiency is 50 to 60 percent for high gas flow rates. The results also indicate that bubble size is not significant within the range tested for a 42-foot height of rise and that a significant amount of oxygen transfer occurs while the gas bubble is forming on the diffuser especially at low gas flow rates.

After all equipment has been installed, more accurate tests will be con-

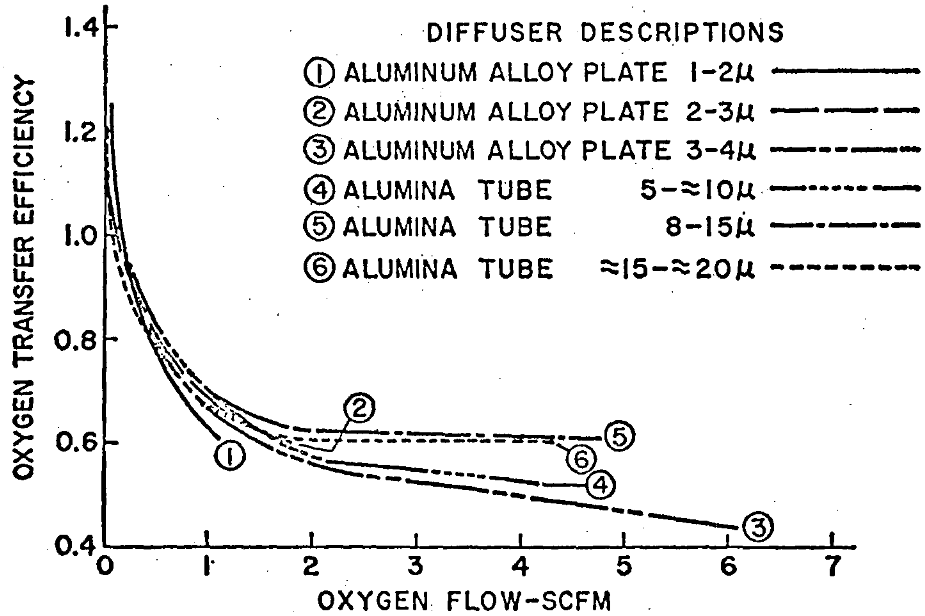

Figure 11. Preliminary Results of Oxygen Transfer Efficiency Tests (Diffuser numbers 1–3 were plates with a surface area of about 0.2 square feet and diffuser numbers 4–5 were tubes with an outside diameter of 2½ inches and a length of 1 foot.)

ducted, and the preliminary tests will be checked. Oxygen transfer efficiency will be determined by the gas balance technique and, if possible, the ratio of the rates of oxygen absorption to oxygen supply technique will be used. Oxygen transfer tests then will be conducted at various depths to insure that a reasonable distribution of oxygen absorption is attained within the entire 45-foot depth to avoid supersaturation of oxygen with respect to the atmosphere within the first 10 to 20 feet of bubble rise. Such supersaturation might allow the gas to be stripped from solution after passing through the turbines which possibly could cause loss of oxygen and increased rates of corrosion of the draft tube.

Other Considerations for Selecting Diffusers

Since high transfer efficiencies have been measured for several diffusers, selection of a diffuser probably will be based on total system costs, maintenance, and possible problems of installation and operation. Several possible installation and operational problems will be evaluated in the tank at the Engineering Laboratory to determine (1) time required to obtain gas flow through the diffusers following periods of idleness, (2) effect of horizontal velocities, (3) effect on efficiency of a small degree of inclination of the diffuser, and (4) the effect on efficiency of iron oxidation on the diffuser and other plugging that may have occurred on the diffusers during the field operation and maintenance tests. When water enters the diffuser during periods of idleness, it may have to be displaced before gas can pass through the diffuser. The effect of diffuser inclination on transfer efficiency will be investigated because diffuser system installation might be expensive if the system has to be leveled.

Other considerations for choosing a particular diffuser should include cost and ease of cleaning. Although cost estimates are not yet available for all the diffusers being evaluated, cost apparently decreases with increasing pore size up to the maximum pore size thus far evaluated for transfer efficiency (Diffuser No. 6 in Figure 11); after that, diffusers with larger pores apparently cost the same regardless of pore size. Tube diffusers appear to be the easiest to clean because they can be dismantled. The plastic diffuser made of CEVIAN-N is not as fragile as the alumina tube diffusers.

FIELD OXYGENATION TESTS

After a diffuser has been selected in Phase I, a large-scale diffuser system, capable of increasing the dissolved oxygen concentration 2–3 milligrams per liter in the releases from one turbine, will be installed in the reservoir for Phase II. Phase II will be conducted during the summer and fall of 1973. The field installation probably will consist of a diffuser system that can be moved to various locations by means of a barge similar to that used in Phase I (Figure 7).

Work to be done in Phase II includes the following:

1. Determine the best location for injecting the oxygen, i.e., in front of the turbine intake or in the tailrace. It is important to determine the best location for the diffusers upstream from the turbines to avoid bubbles entering the turbine system. If bubbles enter the turbine system and affect power operations, or other unforeseen problems develop with upstream injection, downstream injection will be evaluated.
2. Evaluate oxygen transfer efficiencies under field conditions.
3. Evaluate problems associated with oxygenation by this method, such as corrosion of the turbine discharge system or reduction in power production efficiency.
4. Obtain additional information for use in designing a full-scale demonstration project.
5. Schematically design a full-scale installation if results obtained show this method of reaeration to be feasible technically and economically.

Discussion

Oxygen injection through diffusers, compared with other alternatives, appears to be an economical method of increasing DO concentrations in the turbine releases from reservoirs where downstream temperatures must not be increased. Preliminary results of this study indicate (1) maintenance and operation of the diffusers apparently is not a major problem in that clogging or plugging of the diffusers has not occurred during testing, (2) approximately 100 percent absorption of the oxygen injected can be attained at low gas flow rates and in sufficient depths, and (3) oxygen injection is at least as economical as diffused air aeration in the tailrace.

Although this method appears to be the least cost alternative for Fort Patrick Henry Dam, it is important to note that this method is not the most economical in all cases. Each dam needs to be investigated for its specific physical conditions and DO requirements (5). For dams where there is a large annual requirement for addition of DO, diffused air aeration with its high capital cost may be more economical because of low operational costs. Oxygen injection, with high operational cost but lower capital cost, is more economical where oxygen requirements are relatively small. Long-term operation of several very promising techniques of aeration probably will be necessary to determine the economics of such systems.

Oxygen injection into turbine releases also may be used as a supplementary (or peaking) system in conjunction with other aeration methods that may be more economical for normal turbine releases but that may not be dependable for maintaining a minimum DO concentration when higher turbine release rates are necessary. For example, oxygen injection could be used with diffused air destratification either by injecting oxygen through a separate diffuser system similar to the one proposed for Fort Patrick Henry Dam or by injecting oxygen through the diffusers used for destratification. The latter technique would increase the DO throughout a large volume of water immediately upstream from the dam and would not require the cost of a supplementary diffuser system for peak discharges. Before a separate diffuser system is used for oxygen injection in a peaking system, it might be necessary to investigate the possibility that sedimentation and biological growths might clog the diffusers if left idle over long periods of time. Oxygen might also be used to enrich the gas mixture for diffused air aeration in the tailrace. Such a combination of these two techniques could reduce the capital cost required for diffused air aeration.

A considerable amount of research is needed before even the more promising techniques should be applied to reservoirs on a large scale. Many reservoirs will need such systems in the near future to meet state water quality standards, but unless the possible aeration methods are properly investigated, vast sums of money may be spent unwisely.

Conclusions

1. After various methods of increasing DO levels in reservoir releases had been investigated, TVA concluded that diffused air aeration in the tailrace or diffused oxygen injection into the releases are the most promising methods for correcting the problem at Fort Patrick Henry Dam. Oxygen injection was selected for further investigation primarily because of the high power requirement and high initial cost of diffused air aeration.
2. Upstream diffuser injection probably is more economical than downstream injection; however, if upstream injection adversely affects the turbine system, downstream injection may be more economical.
3. Liquid oxygen storage tanks probably would be more economical than on-site oxygen generation because the oxygen requirement is highly variable, seasonal, and relatively low.
4. Fourteen commercially available diffusers were operated in Fort Patrick Henry Reservoir for various lengths of time during an eight-month period, and no apparent clogging or plugging occurred.

5. The diffuser with the smallest pore size that is commercially available did not clog after being operated for over 300 hours in water that contained a relatively high concentration of ferrous iron.
6. To compare the relative oxygen transfer efficiencies for various diffusers, a 45-foot high tank was constructed. Although installation of auxiliary equipment is not yet complete, preliminary tests indicate that high absorption efficiencies can be attained at a low gas flow rate per unit of diffuser.
7. Selection of a diffuser should include considerations for total system costs, possible installation problems, operation and maintenance problems, and transfer efficiency.
8. Large-scale field studies are proposed for 1973 in which the best location will be determined for an oxygen injection system.

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