Widespread Oxygen Bubbles
To Improve Reservoir Releases

Mark H. Mobley
Tennessee Valley Authority, Engineering Laboratory,
P.O. Drawer E, Norris, Tennessee 37828

W. Gary Brock
Tennessee Valley Authority, Water Management Projects,
400 West Summit Hill Drive, Knoxville, Tennessee 37902

Abstract

This paper describes the installation and testing of an oxygen diffuser system in the forebay of TVA's Douglas Dam. The diffuser system is made up of plastic pipe frames and porous hoses that spread very small oxygen bubbles over a large area near the bottom of the reservoir. Operation of the system has demonstrated very high oxygen transfer efficiencies and a capacity to increase the hydropower discharge by 3 mg L^{-1} of dissolved oxygen.

Key Words: aeration, oxygen, diffuser

Douglas Dam is located on the French Broad River east of Knoxville, Tennessee. At normal summer pool elevation, the reservoir depth at the dam is about 38 meters (125 feet) and the impoundment contains over 173,000 hectare meters (1,408,000 acre feet) and is about 69 kilometers (43 miles) long. Douglas Dam has four Francis hydroturbine generating units each rated for 30 MW at a flow rate of 113 cubic meters per second (4,000 cubic feet per second). The average annual inflow is about 187 cubic meters per second (6,600 cubic feet per second). During the summer months the reservoir experiences strong thermal and dissolved oxygen (DO) stratification. The minimum DO in the summertime releases from Douglas is typically near 0 mg L^{-1}.

TVA has been developing and installing aeration systems on hydropower projects since the early 1970s (Ruane 1972, Fain 1978). Many different aeration technologies have been evaluated.

Several different arrangements and types of oxygen diffusers have been tested at Douglas Dam since 1988 (Mobley 1989).

The oxygen diffuser system described in this paper was installed in the forebay of Douglas Dam during 1993. A schematic of the system is shown in Figure 1. The general arrangement of the system is shown in Figure 2. Liquid oxygen is delivered by truck to a tank at the bulk oxygen storage facility on the site. Gaseous oxygen is supplied to the individual diffuser frames through piping from the bulk oxygen storage facility. The system includes sixteen diffuser frames that support over 19 kilometers (12 miles) of porous hoses to spread bubbles over an area of almost 18,000 square meters (4.5 acres). The diffusers efficiently oxygenate the reservoir metalimnion and hypolimnion layers with minimal upwelling or mixing.

The diffuser system is designed to provide up to 3060 standard cubic meters per hour (1800 standard cubic feet per minute, 4.5 tons per hour) of oxygen for a theoretical DO increase of 2 mg L^{-1} with all four hydroturbine units in operation. The exact amount of oxygen supplied by the system can easily be regulated to meet requirements. Average daily usage during August exceeds 50 tons per day. Since the oxygen system is expensive to operate, it was designed as a "topping off" system for Douglas. A surface water pump system is used to provide a baseline DO improvement to meet a target of 4 mg L^{-1} for the reservoir releases.

Diffuser System Construction

The diffuser system at Douglas is constructed of PVC pipe frames and porous hoses. Sixteen frames are located as shown in Figure 3. Each frame is approximately 30 meters by 36 meters (100 feet by 120 feet) and supports eighty hoses. The porous hoses are made of recycled tires and polyethylene (Aquatic Eco-Systems 1994). The frames keep the porous hoses extended to their 15-meter (50-foot) length and are provided with flotation to position the hoses about 6 meters (20 feet) above the reservoir bottom, as shown in Figure 4. A supply header is located along the central rib of the frame. Each hose connection to the header is equipped with an orifice plate to equalize the flow to each hose and minimize total flow disruption if a hose is ruptured.

The hoses are attached to the outer ribs of the frame using an elastic cord. Weights are equally spaced along the length of the frame and attached with elastic cords that are adjusted to match the bottom topography.

Diffuser System Deployment

Each pipe frame includes three buoyancy chambers that respectively: float the entire system on the water surface, match the sinking force of the underwater weights, and suspend the frame off the bottom. These chambers are labeled in Figure 4. Ropes were stretched across the forebay to control the location of each frame during deployment. The deployment buoyancy chambers nearly balance the weight of the frame underwater making it almost neutrally buoyant for the descent so that it can be controlled with ropes from boats on the surface. Once the frame is at the bottom, the deployment chambers are flooded, allowing the weights to sit on the bottom and anchor the frame in position. The permanent buoyancy chambers provide sufficient buoyancy to keep the frame floating above the bottom with or without oxygen flow to the diffusers. The buoyancy control hoses and supply hose connections are attached to a retrievable stainless steel cable on the bottom. Once deployed, the entire system is deep underwater with nothing visible from the surface except bubbles.

Bulk Oxygen Storage and Supply Lines

A liquid oxygen storage facility was constructed on the Douglas Dam Reservation to supply the diffusers. The liquid oxygen storage tank has a 75,000-liter (20,000-gallon) capacity and is mounted horizontally. It feeds ten ambient air vaporizers that are sized to handle the 850 liters per second (1,800 standard cubic feet per minute) gaseous oxygen flow rate. The oxygen is then distributed through four headers, each supplying four diffuser frames. Each of the headers is equipped with a flowmeter and remote-operated valve keyed to turbine unit operation. The flow to each diffuser is controlled with a pressure regulator in each line. Slightly different pressures are required to supply equivalent flows to each diffuser frame due to depth and supply line length variations. Copper supply lines are protected with a PVC containment pipe from the storage facility to the reservoir bank. Flexible hoses are anchored along the reservoir bottom to supply the diffusers.

Costs of Construction and Installation

The total cost for the oxygen system installed at Douglas Dam was about $2.5 million, with those costs split almost evenly between equipment related to the bulk oxygen storage facility and the diffusers in the reservoir. A new access road was built to the oxygen tank location. The road and concrete truck turnaround area was a significant portion of the total costs. The 75,000-liter (20,000-gallon) liquid oxygen storage tank, 10 ambient air vaporizers, and related equipment required to supply 850 liter per second (1,800 standard cubic feet per minute) was about $400,000 installed. The diffuser costs at Douglas include several test installations for design development. TVA is now installing a further developed design that is more economical to construct and has the potential to be more efficient because the oxygen bubbles are dispersed over an even larger area than described for the Douglas system. The costs of installing an oxygen diffuser system are site specific and will vary significantly depending on the needs of the individual project.

Costs of Operation

The oxygen diffuser system was operational in September, 1993 at the end of the low DO season. The operational costs for 1994 will include some start-up costs for adjustments, repairs to a supply hose that were damaged over the winter, and oxygen purchases. TVA has contracted for liquid oxygen deliveries at about $102 per thousand standard cubic meters ($70 per ton). Oxygen costs are about $312 per hour at the maximum design flowrate of the system at 51 standard cubic meters per minute (1800 standard cubic feet per minute). This flowrate could require up to 5 liquid oxygen deliveries per day if the hydro turbines are operated continuously.

Oxygen costs for August, 1994 were almost $125,000 or about $4,000 per day to provide a DO increase of about 1.5 mg L^{-1}. This aeration level was generally sufficient to meet the release DO target but was limited by a shortage of oxygen supply. Oxygen suppliers throughout the eastern US experienced a severe shortage of available oxygen this summer and most have resorted to rationing even their contracted customers. The supply situation is predicted to improve as additional capacity under construction by at least one supplier becomes available. However, complete reliance on contracted oxygen supply has shown some limitations. The price of delivered oxygen is also likely to increase due to increased demand. TVA is currently evaluating on-site production of oxygen for aeration purposes.

Diffuser Maintenance and Retrieval

Each diffuser frame can be retrieved by accessing the buoyancy chamber control hoses and floating the frame to the surface. The control hoses are attached to a stainless steel cable that is secured to the reservoir bank. This cable can be lifted with boats and winches to retrieve the hoses desired. These hoses can then be used to purge the buoyancy chambers and float the frame to the surface. Caution must be used since snagged anchors or uneven lifting can cause enough stress to break the frame. Once the frame is on the surface, broken hoses or fittings can be replaced and the frame re-deployed.

During the past two years of operation experience at Douglas, the porous hoses seem to resist clogging and maintain an even bubble distribution despite being inactive for about nine months each year. The only maintenance required on the diffusers thus far was one day's work by divers to repair a supply hose rupture.

Results

Tests of the oxygen system during 1993 and early 1994 have shown excellent results. Test measurements at Douglas include oxygen flow rates, water flow rates, DO at each turbine scrollcase, DO in the river downstream of the project, and forebay DO profiles. Dissolved oxygen improvements of up to 3 mg L^{-1} have been documented, as shown in Figure 5, with operation of all four turbines. Large increases in the DO content of the deep portions of the reservoir have been documented with very little effect on the reservoir temperature stratification as shown in Figure 6. The transfer of oxygen from the bubbles into the water is defined as the oxygen transfer efficiency. A high transfer efficiency reduces the cost of operation. The system has far exceeded the design efficiency of 80 percent with test results of over 90 percent efficiency.

References

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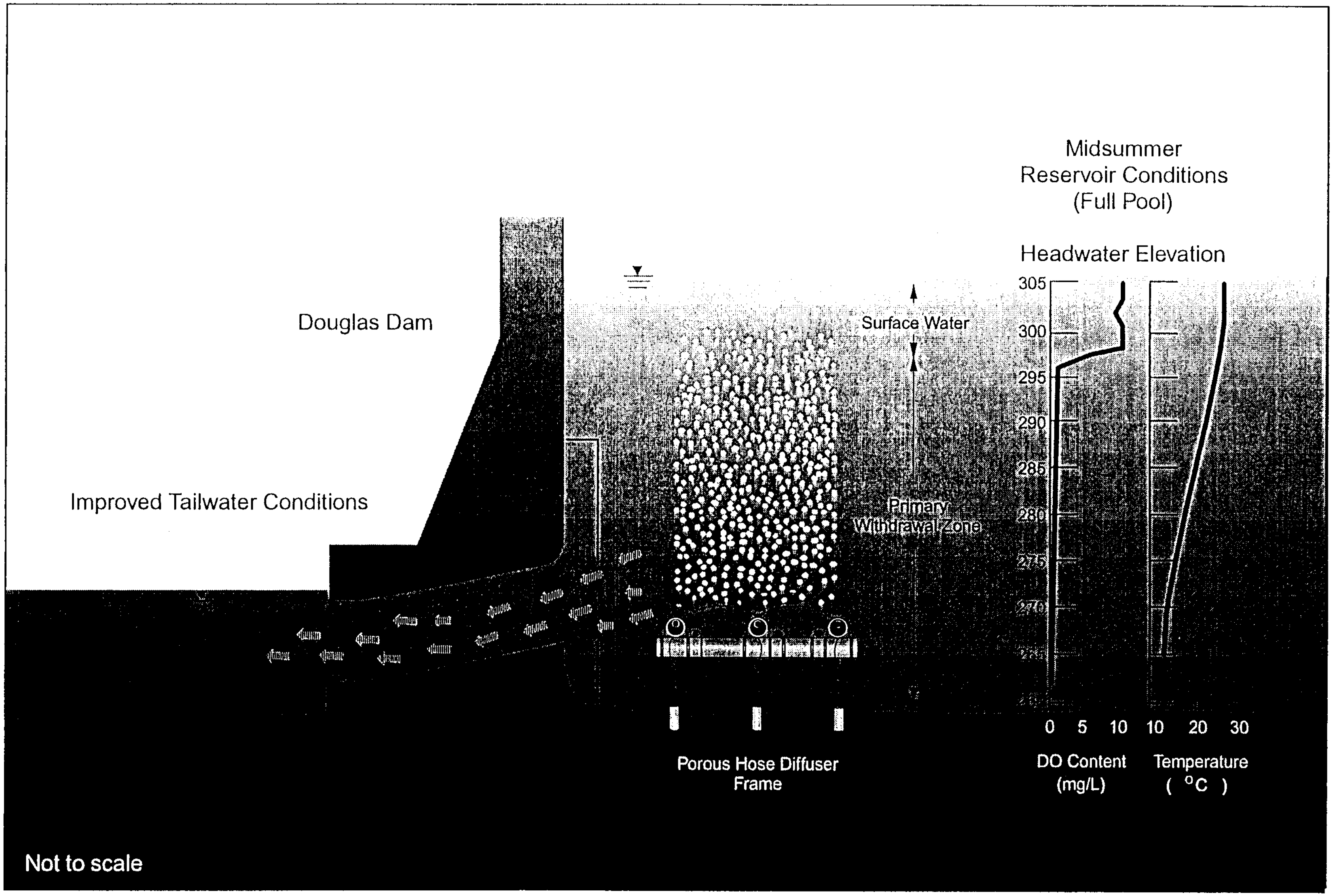
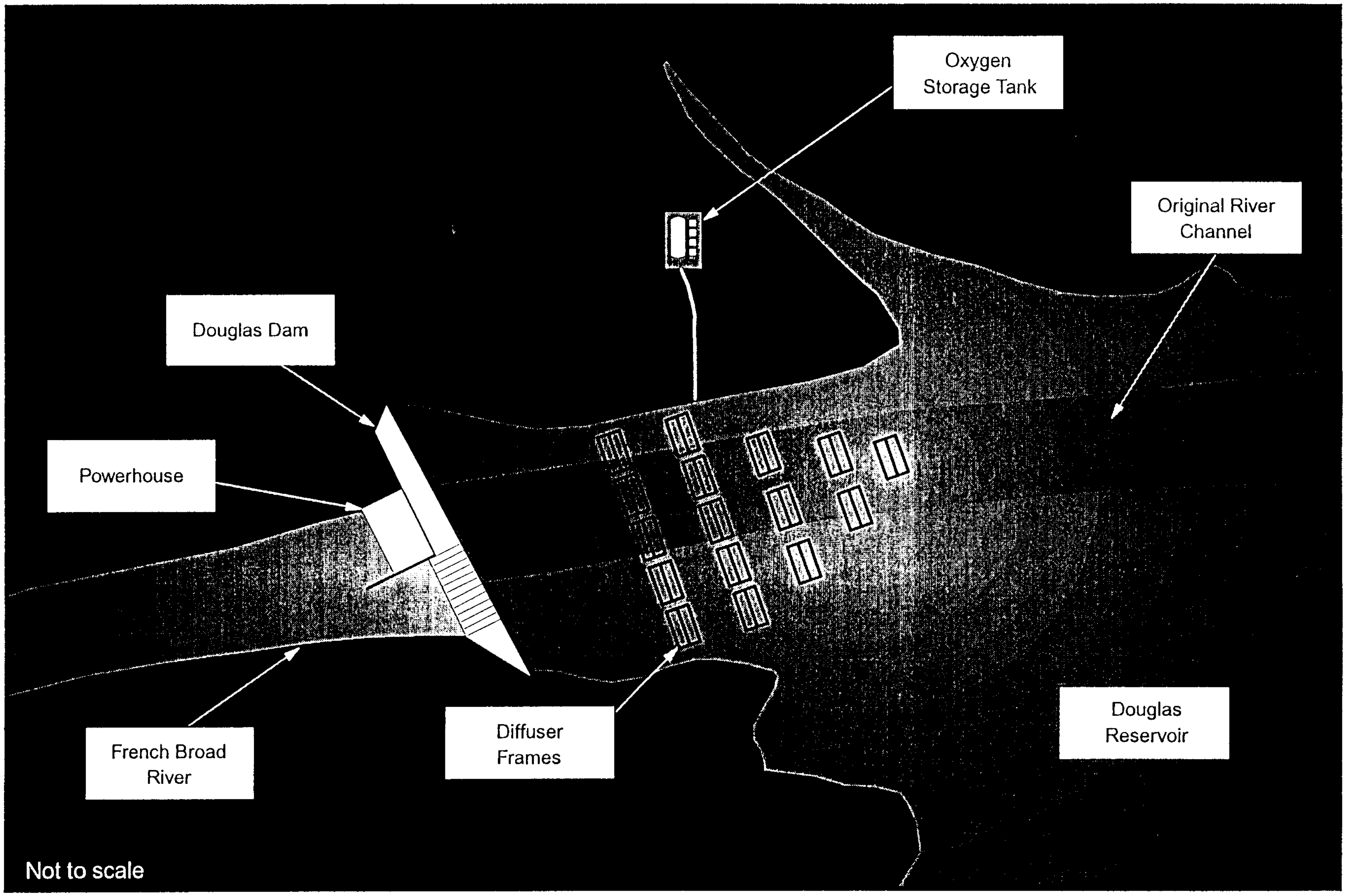
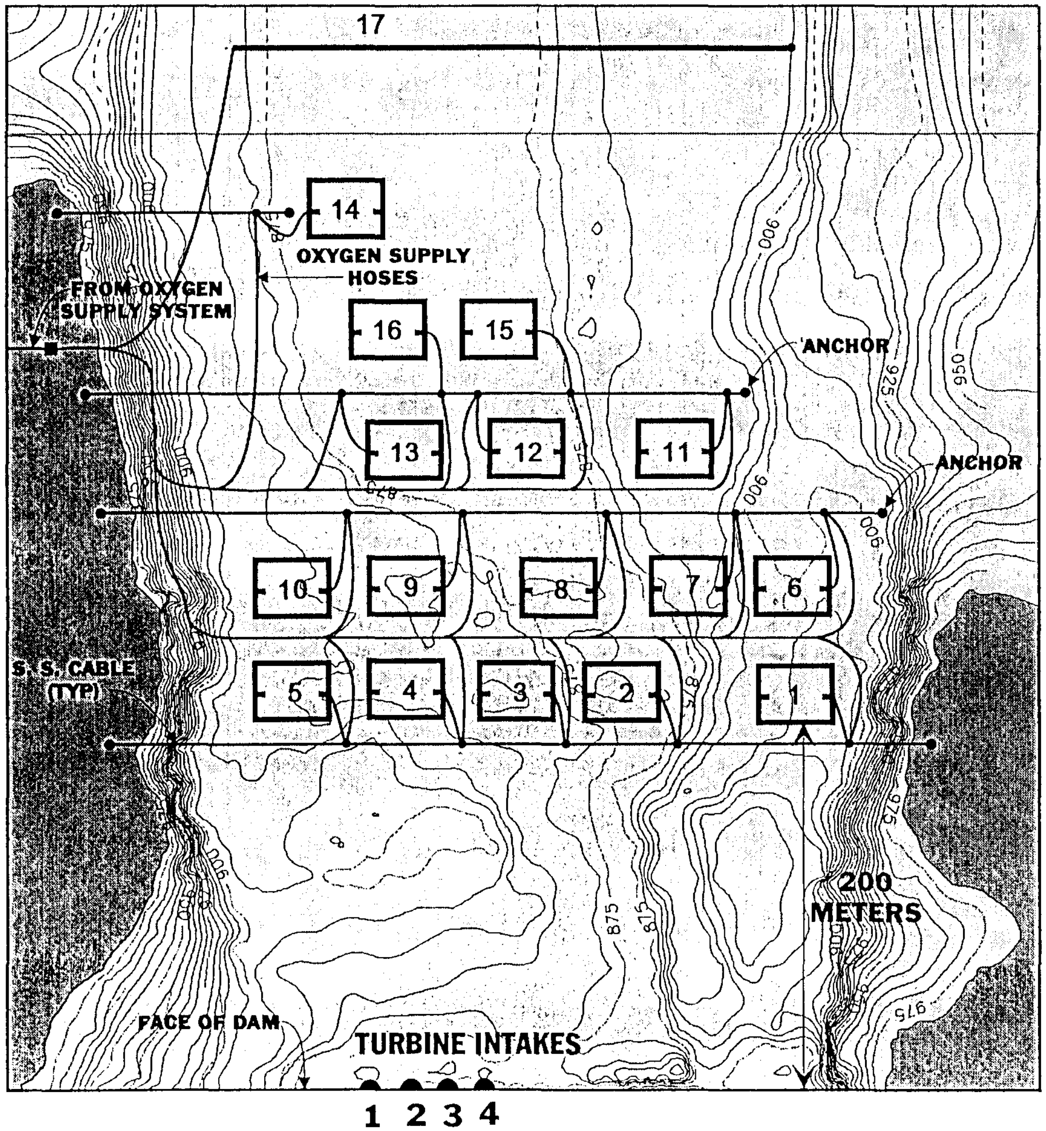
LIST OF FIGURES



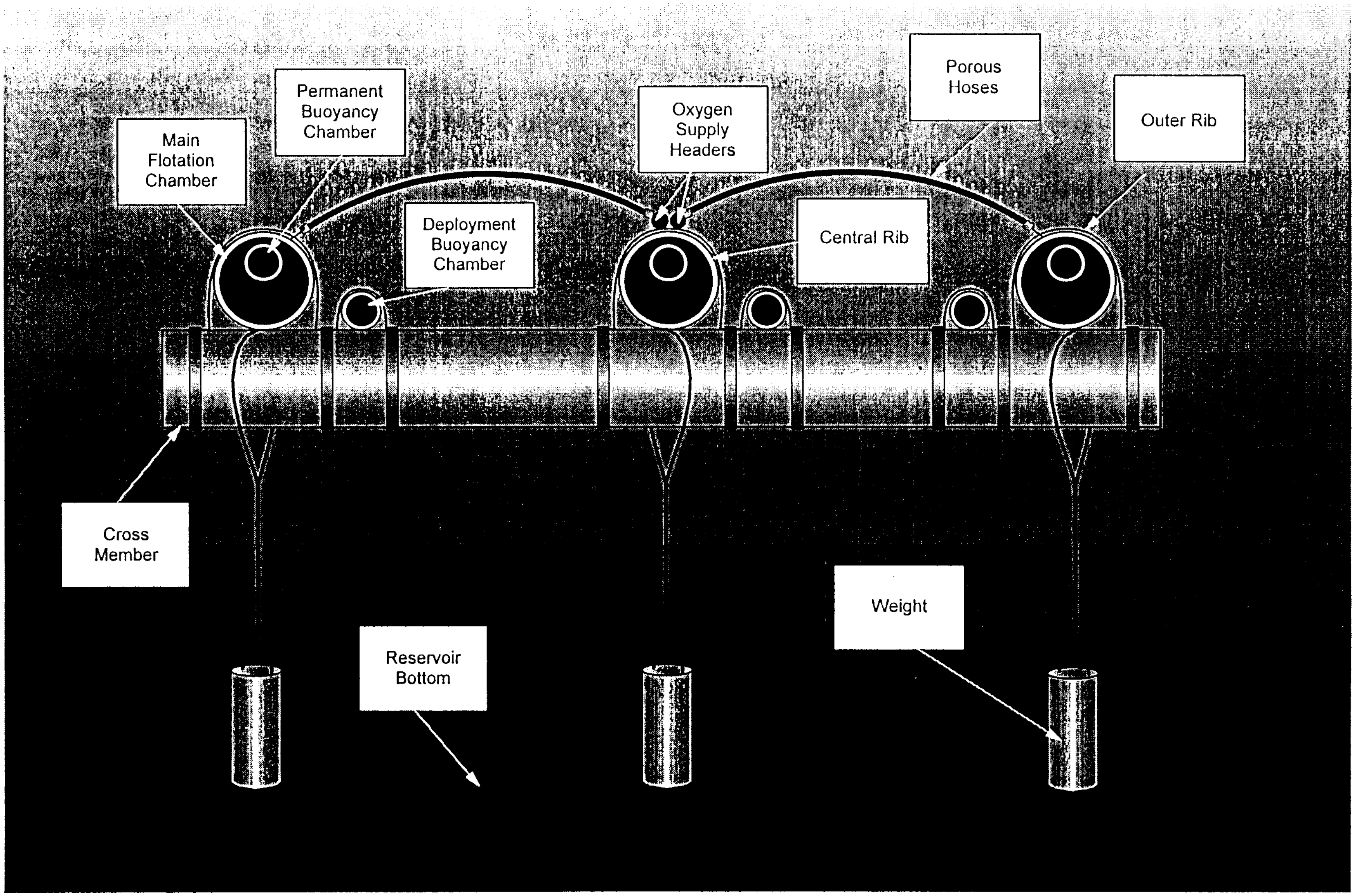
Midsummer
Reservoir Conditions
(Full Pool)
Headwater Elevation
Douglas Dam
Improved Tailwater Conditions
Surface Water
Primary
Withdrawal Zone
305
300
295
290
285
280
275
270
0 5 10
DO Content
(mg/L)
10 20 30
Temperature
(°C)
Porous Hose Diffuser
Frame
Not to scale



Oxygen
Storage Tank
Original River
Channel
Douglas Dam
Powerhouse
Diffuser
Frames
Douglas
Reservoir
French Broad
River
Not to scale

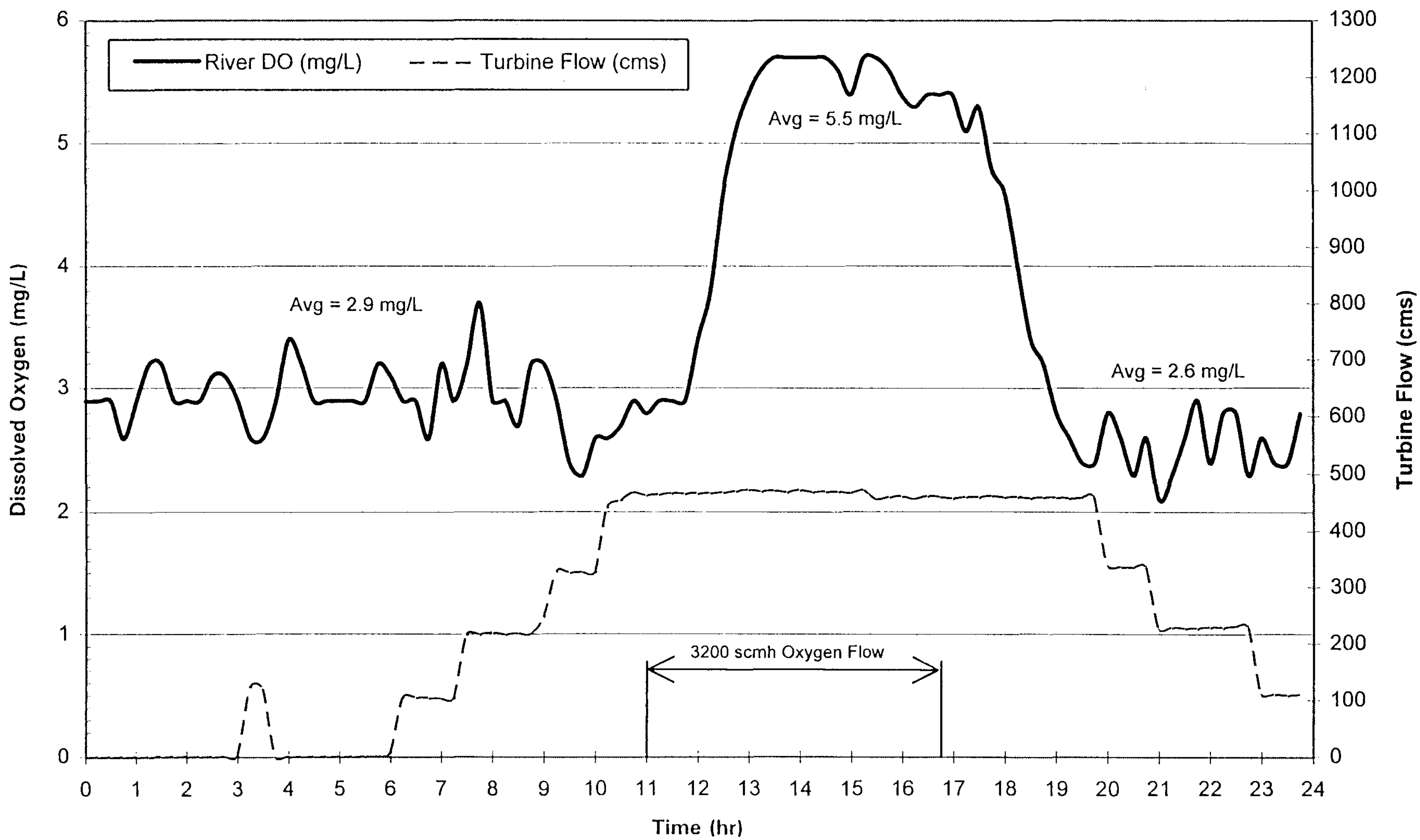


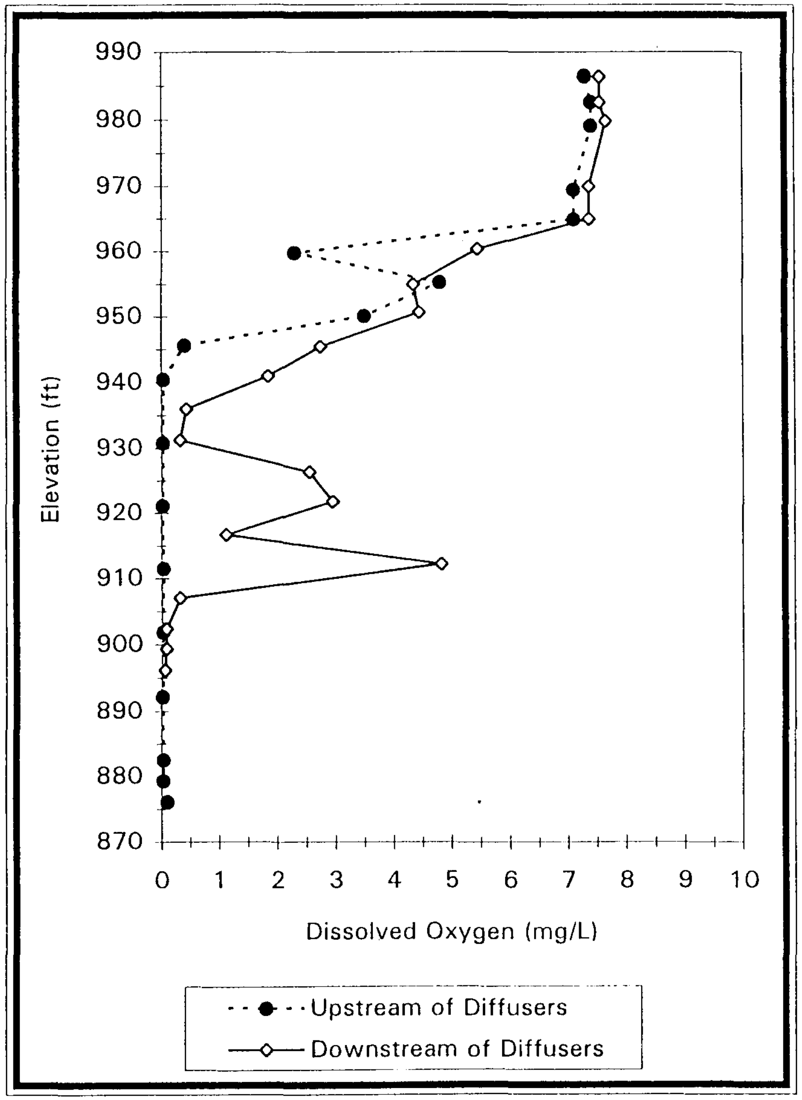
17
14
OXYGEN SUPPLY HOSES
FROM OXYGEN SUPPLY SYSTEM
16
15
ANCHOR
13
12
11
ANCHOR
10
9
8
7
6
S. S. CABLE (TYP)
5
4
3
2
1
200 METERS
FACE OF DAM
TURBINE INTAKES
1 2 3 4
875
900
925
950
975

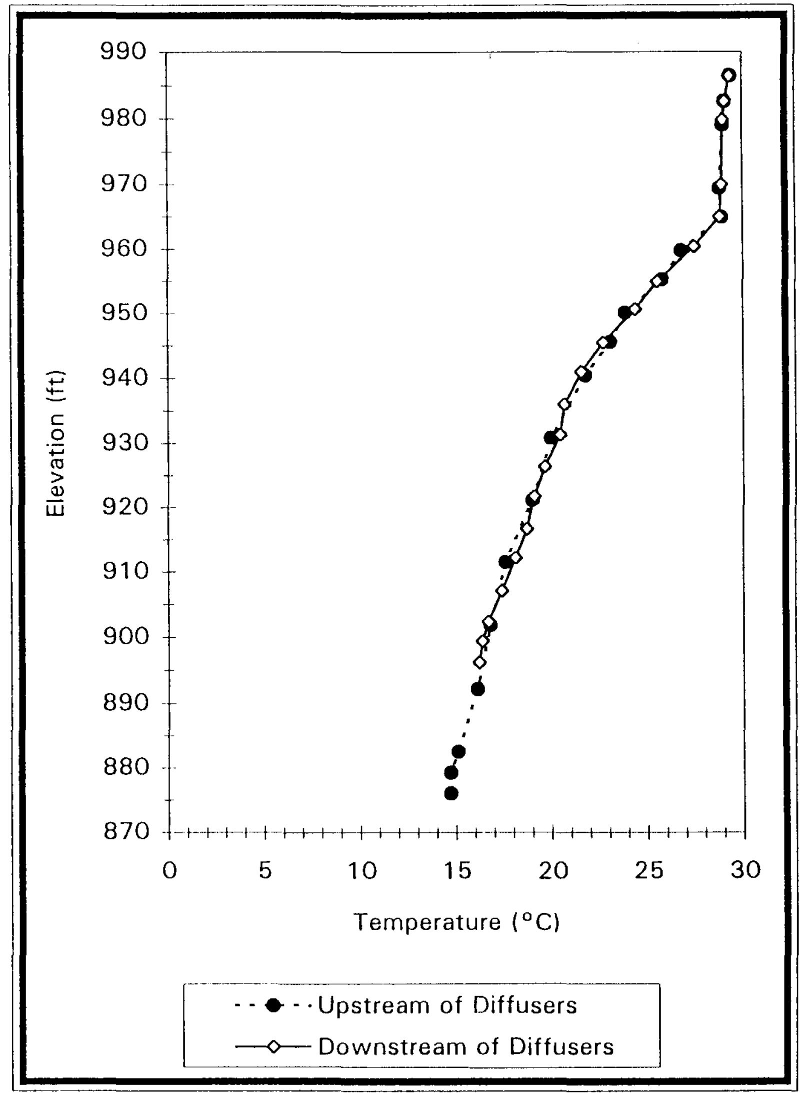

Main Flotation Chamber
Permanent Buoyancy Chamber
Deployment Buoyancy Chamber
Oxygen Supply Headers
Porous Hoses
Outer Rib
Central Rib
Cross Member
Reservoir Bottom
Weight

DOUGLAS DAM

Dissolved Oxygen in River 800 Meters Downstream of Dam




Elevation (ft)
Dissolved Oxygen (mg/L)
Upstream of Diffusers
Downstream of Diffusers


Elevation (ft)
Temperature (°C)
Upstream of Diffusers
Downstream of Diffusers