“And Then It Sank…” The Development of an Oxygen Diffuser for Hydropower

By Mark H. Mobley, R. Jim Ruane, and E. Dean Harshbarger

ABSTRACT

Diffuser designs for aeration of hydropower reservoirs have progressed over the past 25 years with improved operation and reduced costs. The porous hose line diffuser design, developed for the Tennessee Valley Authority (TVA), has proven to be an efficient and economical aeration diffuser design at eleven applications. The line diffuser design transfers oxygen efficiently, and minimizes temperature destratification and sediment disruption by spreading the gas bubbles over a very large area in the reservoir. The development of the line diffuser was an iterative process that responded to site-specific requirements and design failures. Each successive application described in this paper provided new challenges and design improvements.

Introduction

Need for DO Enhancement

The water quality of reservoir releases has become a recognized issue for hydropower projects. Many Federal Energy Regulatory Commission (FERC) licensing requirements now include minimum dissolved oxygen standards; and, projects owned by Federal agencies like TVA and the US Army Corps of Engineers are under pressure by State agencies and private interest groups to improve water quality in the releases from their projects. In many reservoirs, solar energy heating causes a stable temperature stratification during the summer months when the warm surface water floats over the colder deep water, referred to as the hypolimnion. Oxygen demands near the sediments and in the water consume the dissolved oxygen (DO) in the hypolimnion, which is sealed off from the most significant sources of oxygen such as wind mixing and algae photosynthesis. Thus, depending on water flows and the magnitude of the oxygen demands, the hypolimnion can become oxygen depleted. If the DO levels are driven low enough, anoxic products like hydrogen sulfide and dissolved iron and manganese can reach troublesome levels in the water nearest the sediments. If this water is then withdrawn through hydropower intakes, the low DO water and anoxic products are released downstream.

Enhancement Alternatives

Each reservoir and hydropower project has site-specific characteristics that impact the need for and the means used to improve reservoir releases. Each project should be evaluated for site-specific requirements and then the best alternative or combination of alternatives should be applied. In 1997, TVA completed the Lake Improvement Plan, a five-year program to improve minimum flow and dissolved oxygen levels at sixteen hydropower projects (Brock and Adams, 1997). Several new and innovative aeration alternatives were developed and applied over the course of the program, including the porous hose line diffuser. The TVA program included 8 applications of turbine venting, 7 of oxygen diffusers, 2 of surface water pumps, 2 of air blowers, 2 of aerating weirs, and 1 application of auto venting replacement turbines. Several projects required combinations of up to three alternatives to meet target aeration requirements.

Reservoir Diffuser Concept

A reservoir diffuser distributes gas bubbles in the reservoir upstream of the turbine intakes to increase DO in the water that will be drawn out by hydropower operations, as shown in Figure 1. The diffuser systems are supplied with compressed air or oxygen from a supply facility located on shore. Pure oxygen gas is usually preferred to avoid potential total dissolved gas problems in the tailrace. The smaller, deeper, and more disperse the bubbles, the better the oxygen transfer efficiency. High oxygen transfer efficiency reduces the amount of gas and the size of the delivery system necessary to meet DO requirements. The placement of the diffusers and distribution of the oxygen input from the bubbles must be designed to meet site-specific water quality and water flow conditions to be effective.

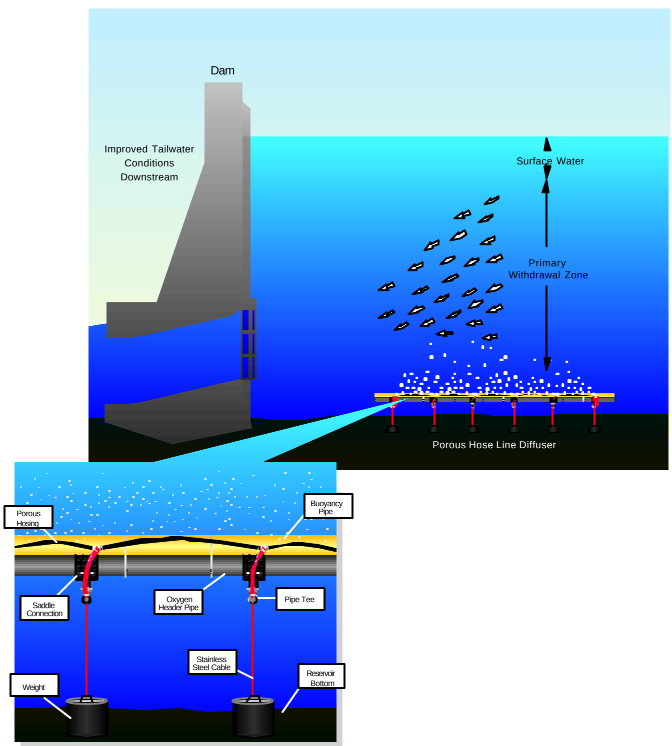

Figure 1: Diffuser Schematic (from Mobley, 1996)

Oxygenation within the reservoir can be an economical means to meet DO requirements for hydropower releases. The purchase of liquid oxygen is expensive, but other aeration alternatives may not be applicable at a specific hydropower site or may be insufficient to meet DO requirements. Oxygen diffuser systems are well suited for use as a topping-off system to augment other less expensive aeration systems that are unable to achieve the water quality objectives alone. Oxygenation within the reservoir can accomplish DO requirements without causing adverse effects on turbine generation, and is usually the only alternative that has the potential to eliminate anoxic products and DO demands that may cause water quality problems (e.g., a DO "sag" or decrease) in the releases.

Early Hydropower Installations Using Ceramic Diffusers

Fort Patrick Henry Dam, TVA: 1973

Some of the earliest research on reservoir diffuser systems for hydropower application was conducted by TVA at Fort Patrick Henry Dam (Ruane and Vigander, 1972). A pilot study and demonstration project were conducted from 1973 to 1976 (Fain, 1978). The installation used a liquid oxygen gas supply and ceramic diffusers that were mounted on diffuser frames supported by columns that extended from the reservoir bottom to the surface. The project provided good test data, but was discontinued due to an unrelated improvement in the incoming water quality conditions at the site and a subsequent loss of funding for the project.

Richard B. Russell Dam, U.S. Army Corps of Engineers, Savannah District: 1985

As a part of the original environmental commitments for the Richard B. Russell hydropower project, the Savannah District developed, designed, and installed a huge reservoir oxygen diffuser system (Mauldin et al. 1988). The system consisted of two distribution components, one for continuous operation approximately 1.5 miles upstream of the dam and one near the dam for instantaneous oxygen input during hydropower operation. The installation utilized 3,888 ceramic diffuser heads and provided a total capacity of 300 tons per day. The system has been operated since 1985 to meet a DO target of 6 mg/L in the releases. Oxygen costs have averaged around one million dollars per year (Peavey, 1994). Extensive maintenance using divers and replacement of the ceramic diffusers has been required over the years, but this system remains one of the largest oxygen diffuser installations in use today.

Design Similarities

Both of these early diffuser system designs used bottom-anchored diffuser frames. At Fort Patrick Henry, an intricate system of guy cables and buoys on the surface was used to position the diffuser frames. The diffusers at Richard B. Russell required divers for installation and maintenance. Both systems were equipped with ceramic diffusers to obtain the smallest bubbles and thus the most efficient oxygen transfer. Both systems also experienced clogging of the ceramic fine pore diffusers. The Richard B Russell system was equipped with a hydrogen chlorine gas injection system to clean the ceramic diffusers and the diffusers were replaced in 1991 with a self-cleaning membrane type. Experience at these projects indicated that ceramic diffusers and requirements for divers should be avoided.

Early Hydropower Installations Using Membrane Diffusers

Douglas Dam, TVA: 1988

In 1988, a pilot oxygen diffuser system was installed on Unit 4 at TVA's Douglas Dam. Three bottom-anchored, steel diffuser frames with adjustable legs to fit bottom topography were lowered from a catamaran crane in front of the intake of Unit 4. Each 6-meter by 10-meter (20-foot by 33-foot) frame supported 78 membrane diffusers, as shown in Figure 2. Oxygen transfer efficiencies of about 72% were measured late in the DO season of 1988 when weak stratification conditions existed (Mobley, 1989). DO improvements in the releases were about 2 mg/L. However, during the peak of the 1989 DO season, the oxygen improvement in the releases dropped to nearly zero. This was attributed to oxygen demands stirred up from near the reservoir sediments and mixed by the strong plumes induced by the diffusers. No clogging of the membrane diffusers was experienced, but the Unit 4 generator cooling system was clogged with sediment and organic growth due to the pumping action of the diffuser plumes. This necessitated outages for cleaning and chemical treatments to reduce organic build-up. This experience indicated a clear need for a means to spread the bubbles over large areas to reduce mixing and entrainment of oxygen demands from the sediments.

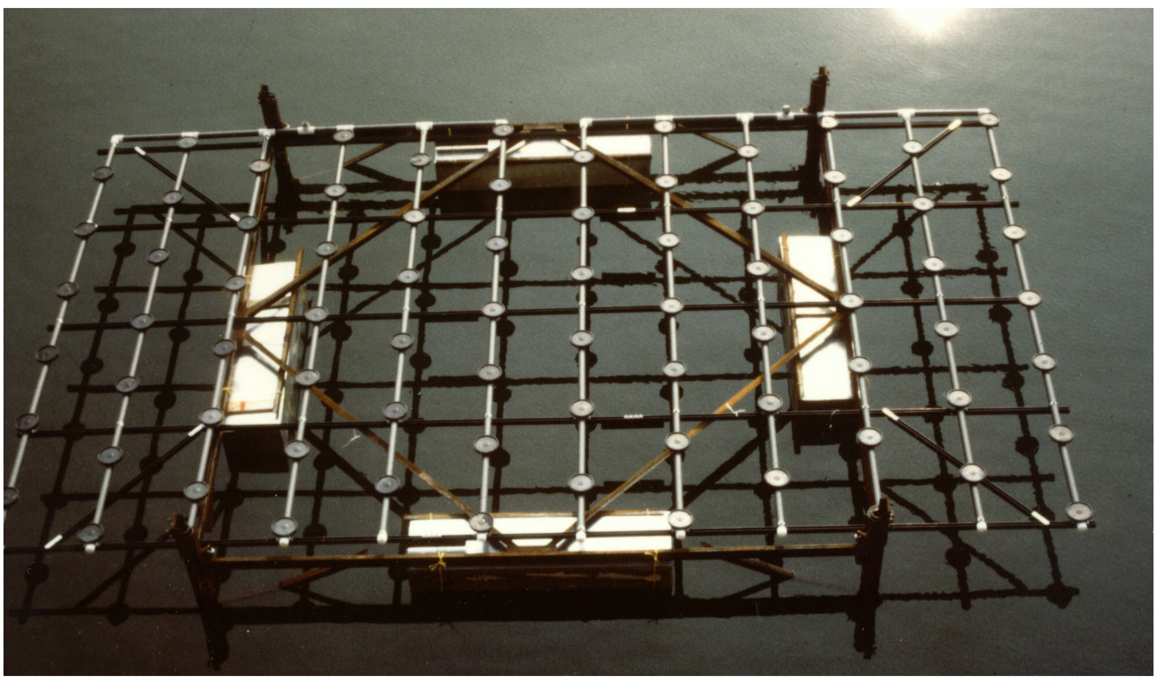

Figure 2: Membrane Diffuser Frame Installation at Douglas Dam

Early Hydropower Installations Using Porous Hose

Douglas Dam, TVA: 1991

In an effort to spread the diffused bubbles, a 122-meter by 36-meter (400-foot by 100-foot) PVC diffuser frame was built to support one hundred 15-meter (50-foot) long porous hoses. The hoses, used to distribute the oxygen bubbles, were common garden variety "soaker hose" made of recycled automobile tires. The hose stretches slightly under pressurization to allow gas or water flow through the walls. The diffusers were designed to have the same flow rate per 15-meter (50-foot) hose as in the 1989 design for a 9-inch membrane diffuser head, thus drastically increasing the distribution of the oxygen. The bubbles formed by the porous hose were observed to be of a similar size as the membrane diffuser (approximately 2 mm). Buoyancy chambers built into the PVC frame supported the entire frame and anchor assembly on the surface until the chambers were flooded to deploy the frame to the reservoir bottom. The huge frame required a fleet of small boats and ropes from the shoreline to position it in the forebay. Unfortunately, the PVC oxygen distribution header shattered due to stresses generated during the initial deployment, "and then it sank…"

Douglas Dam, TVA: 1993

Sixteen smaller PVC diffuser frames, measuring 30 meters by 36 meters (100 feet by 120 feet), as shown in Figure 3, were successfully deployed in Douglas Reservoir in 1993. There are eighty hoses per frame, for a total of over 19 km (12 miles) of porous hose. The system capacity is 3,060 cubic meters per hour (1,800 scfm or 110 tons/day) of oxygen. The redesigned oxygen distribution header was made of flexible hose. Elastic cords were used to attach anchors and absorb some bottom topography differences. These diffusers have been used since 1993 to provide up to 2 mg/L of DO improvement in the 453 cubic meters per second (16,000 cfs) peak hydropower flows of the four turbines at Douglas Dam. Although these diffusers are effective (Mobley and Brock, 1995), and are still in use, the frames and buoyancy connections were too unwieldy and expensive for future designs.

Figure 3: Aerial View of 16 Porous Hose Diffuser Frames in Douglas Reservoir

Installations Using Line Diffusers

Normandy, TVA: 1994

The next diffuser application at TVA was for a non-power reservoir where aeration was desired to remove dissolved metals and hydrogen sulfide in the reservoir through aeration and precipitation. For this application, a linear deployment was required to fit the diffuser in the deepest, most anoxic portion of the reservoir – in the old riverbed. A two-pipe line diffuser system was designed using a buoyancy pipe and gas supply pipe constructed of polyethylene (HDPE), as shown in Figure 1. With both pipes free of water, the entire pipe and anchor assembly will float on the surface and can be pulled with boats to the desired location. Elastic cords were used to attach the anchors and absorb some bottom topography differences. The diffusers were supplied with compressed air and were successfully deployed in a narrow curvilinear channel. Porous hose runs the entire length of the diffuser, distributing the air in small bubbles over as large an area as possible. This installation was the first for the line diffuser design and the clamp-on saddles used for hose connections were found to be expensive and leaky. The drilled screws to provide an orifice for flow control were also found to be expensive and unnecessary.

Blue Ridge, TVA: 1994

At Blue Ridge, a linear arrangement of four 550-meter (1,800-foot) long diffuser lines were deployed in the forebay to provide a 3 mg/L DO improvement using a 22,000 kg/day (400 scfm or 24 tons/day) oxygen system capacity. Steady-state effects of diffuser operation are shown in Figure 4. The design used small check valves at hose connections that were determined to be ineffective since the diffuser sank anyway when left overnight. The long linear arrangement of the diffusers was found to provide insufficient oxygen to the small minimum flow turbine, so an additional diffuser was installed immediately upstream of the intake tower.

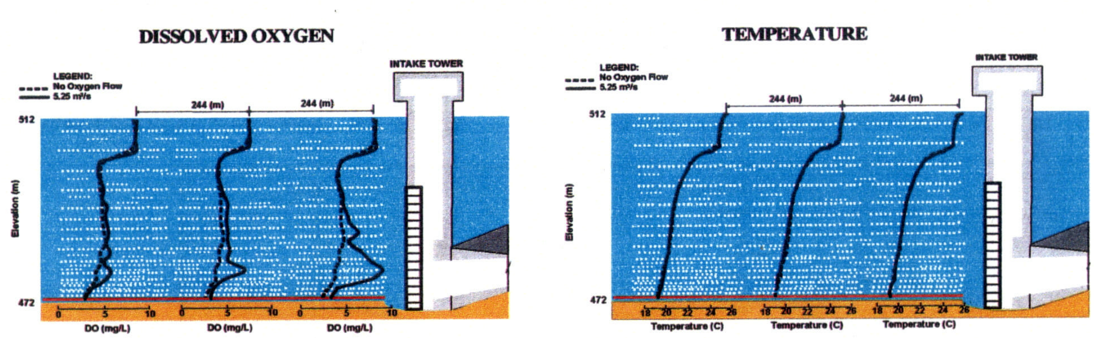

Figure 4: Results at Blue Ridge

Cherokee, TVA: 1994 and 1995

Peak hydropower water flows at Cherokee Dam can approach 20,000 cfs, and despite having operational installations of both turbine venting and surface water pumps, can require up to 2 mg/L of additional DO improvement from the line diffuser system to meet

4 mg/L in the releases. The system capacity is 136,000 kg/day (2,600 scfm or 150 tons/day) with 14,600 meters (48,000 feet) of line diffuser in the forebay. The system has automatic valves that open to provide a high rate of oxygen flow while the turbines are in use. When the turbines are off, a small amount of oxygen flow bypasses the valves to maintain a background buildup of DO in the reservoir. The oxygen input from the diffusers provided oxygenated cold water in the forebay that created a striped bass habitat during the warm summer season (Simmons, 1995). High concentrations of fish led to intense fishing pressure, but despite the repeated anchoring of boats in the area, no significant damage to the diffusers has been experienced. At this installation, the elastic cords for anchor attachment failed, allowing sections of the diffuser to float to the surface creating a boating hazard. A new anchor connection using stainless steel cables was retrofitted by re-floating each diffuser.

Embalse de Pinilla, Spanish Ministry of the Environment: 1995

The Embalse de Pinilla, a small reservoir north of Madrid, Spain, has only 5 MW of hydropower, but provides a source for an important water supply treatment facility. For this application, the reservoir oxygen diffuser was designed to reduce the chemical treatment required at the water supply plant by reducing organic loading and total dissolved metals through aeration in the reservoir. Local materials and labor were used for the installation.

Fort Loudoun, TVA: 1995

This mainstream Tennessee River dam has hydropower flows approaching 38,000 cfs, but required only a small boost in DO – mostly associated with reduced flows during weekends. The Fort Loudoun application, shown in Figure 5, included a single 3-km (10,000-foot) long line diffuser used to spread the oxygen input over the reservoir volume of an average day’s generation. The diffuser was equipped with progressive orifice sizes at the hose connections to obtain uniform flow over the entire length. The installation was complicated by intense recreational boat use and commercial navigation traffic. The elastic cord anchor connections were redesigned during this installation and retrofitted on the first diffuser.

Hiwassee, TVA, 1995

The original designs for the Hiwassee Reservoir diffuser system were to use air, but total dissolved gas (TDG) limitations in the tailrace shifted the design from air to oxygen. Hiwassee is a deep, narrow reservoir that caused some difficulties during deployment and retrieval of the diffuser lines. The mid-level hydropower intakes create a strong secondary thermocline in the reservoir that effectively limited the elevation of oxygen input from the diffusers placed in the old riverbed (Figure 6). The diffuser lines were retrieved and equipped with longer stainless steel anchor cables to suspend the line 18 meters (60 feet) above the reservoir bottom to place oxygen into the turbine withdrawal zone. The installation of an onsite pressure swing adsorption (PSA) oxygen generation system was attempted for this application, with unsatisfactory results. The diffusers are now supplied from a liquid oxygen storage tank.

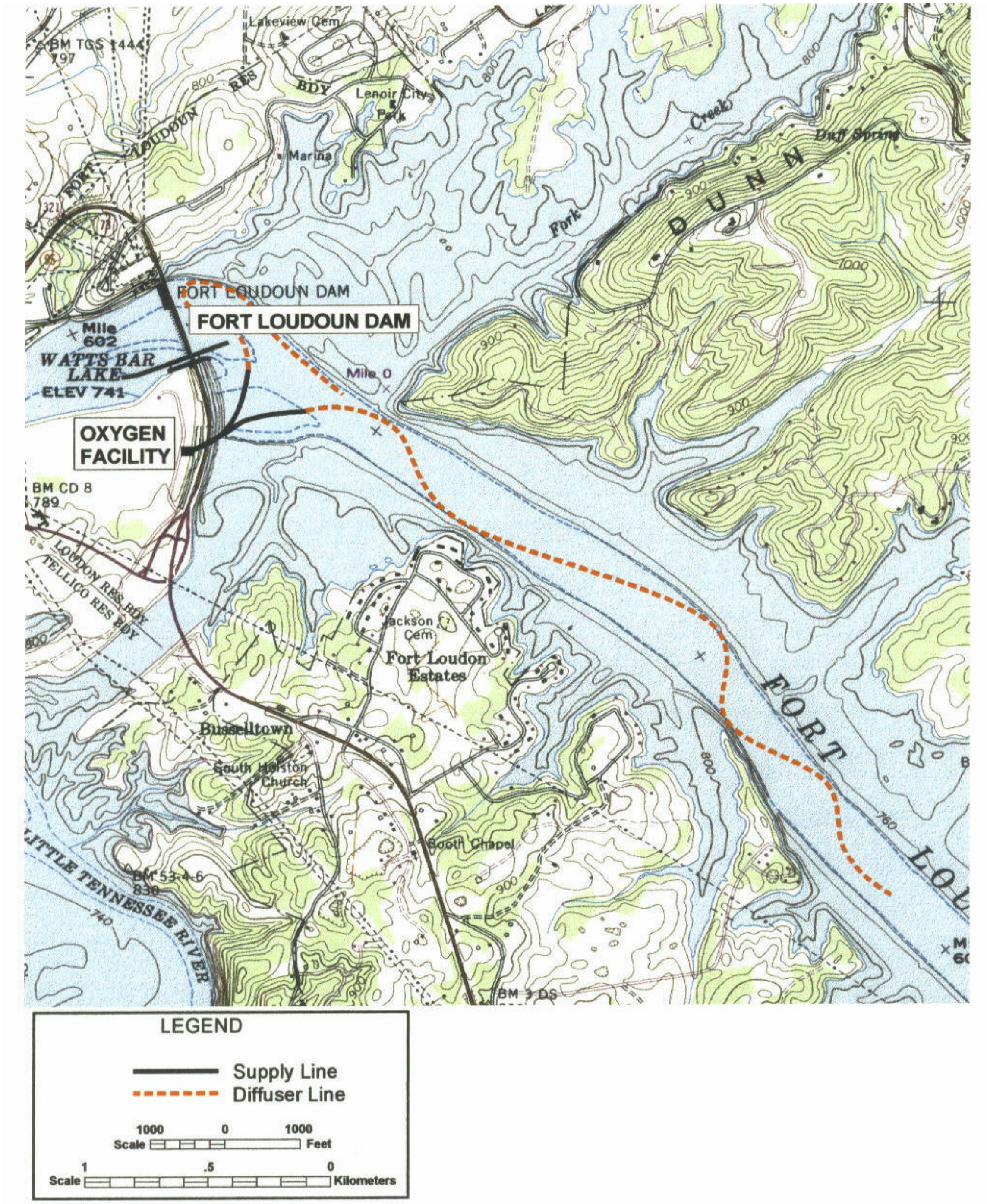

Figure 5: Fort Loudoun Diffuser Layout

Watts Bar, TVA: 1996

Watts Bar is another mainstream hydropower project with flows and oxygen requirements similar to Fort Loudoun. The diffusers were deployed to oxygenate an average daily flow volume and a more compact diffuser placement was utilized immediately upstream of the dam to provide for the increased oxygen needs during initial or single turbine operations. The multi-line diffuser design used in the immediate forebay (Figure 7) proved to be difficult to deploy and retrieve.

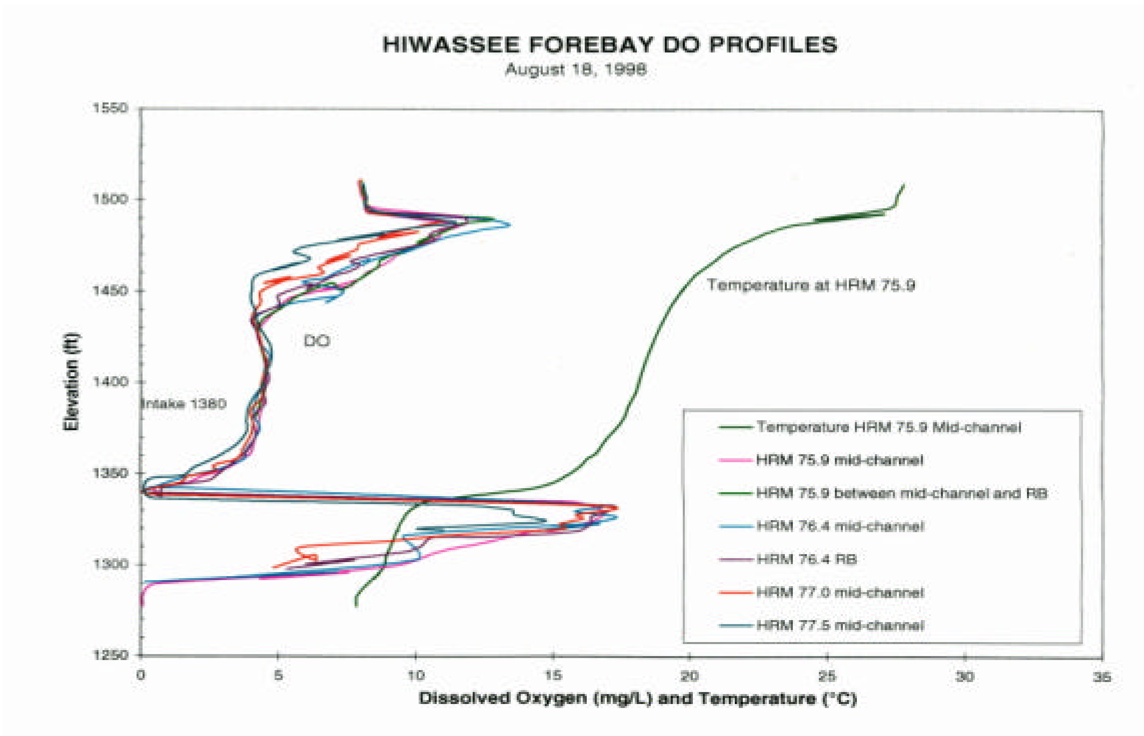

Figure 6: Effect of Secondary Thermocline at Hiwassee Reservoir on Oxygen Distribution

Buzzard Roost Hydroelectric Station, Duke Energy: 1997

The line diffuser at Buzzard's Roost was installed to provide enough oxygen input to allow Duke Energy to meet the FERC water quality requirements at the site. This installation included 2,750 meters (9,000 feet) of line diffuser in the shallow, excavated hydropower intake channel. The diffuser lines were placed within 6 meters (20 feet) of each other in only 12 meters (40 feet) of water, as compared to typical spacing of 30 meters (100 feet) in 30-meter (100-foot) depths.

Summary of Existing Line Diffuser Installations

A total of over 46 kilometers (153,000 feet) of line diffuser have been installed at the eight reservoirs described above and three other applications. The diffusers have required no maintenance other than inspection of the bubble pattern at the beginning of each season. Reservoir diffuser installations and other aeration applications have resulted in improved conditions in the hydropower tailwaters (Scott et al., 1996). Installation costs of line diffusers have been $25 to $30 per foot (Mobley, 1997) for a total of $300,000 to $2,000,000 for a typical hydropower diffuser installation. The costs for installation of a liquid oxygen supply facility would be of the same order as diffuser costs. Annual oxygen and operating costs range from $75,000 to $800,000.

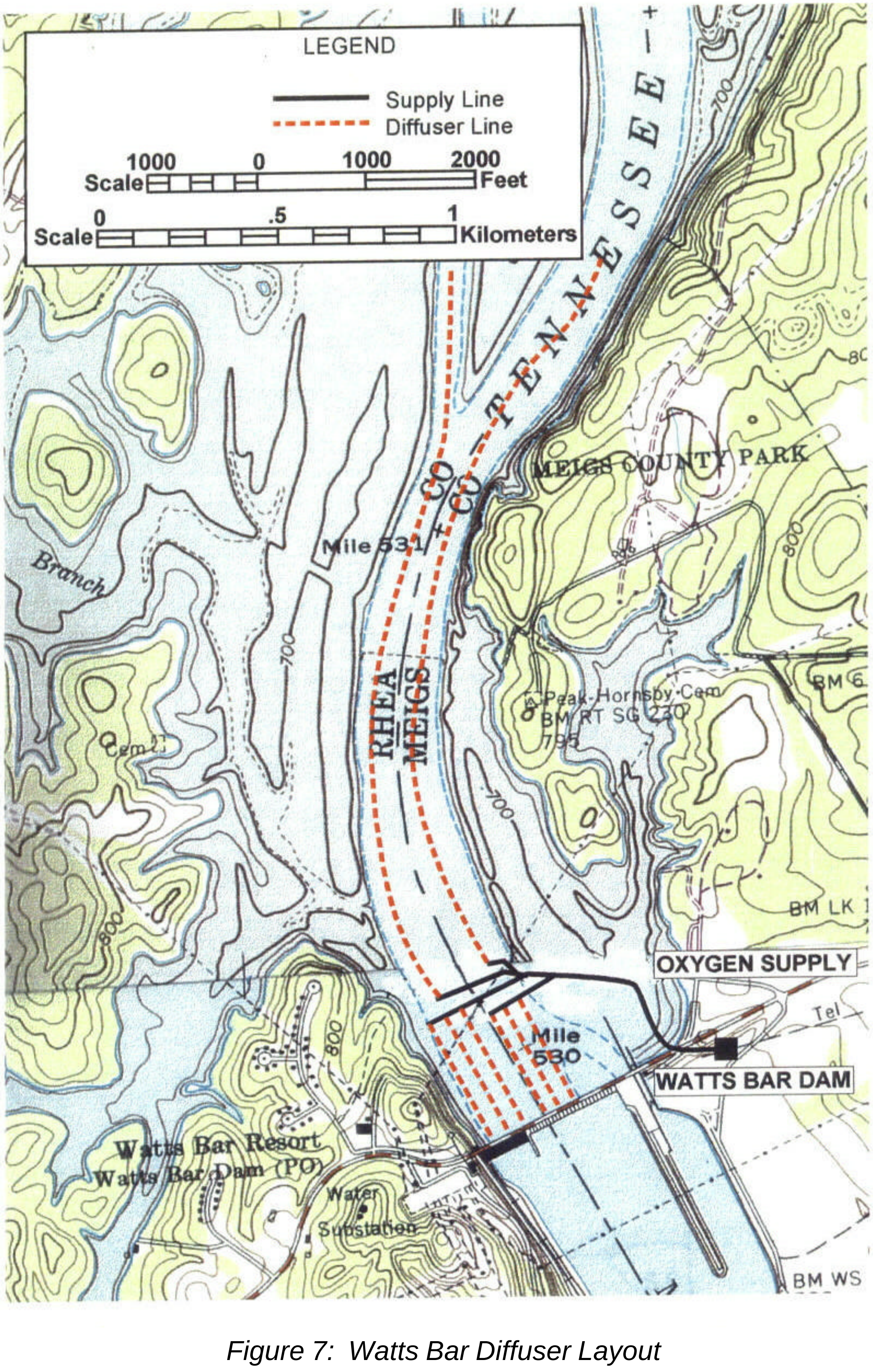

Figure 7: Watts Bar Diffuser Layout

Proposed Hydropower Diffuser Applications in Progress

Increasing complexity of diffuser application objectives has led to more frequent use of mathematical modeling techniques to predict bubble plume performance and reservoir conditions. New pre-processors and post-processors (Loginetics, 1999) allow the economical use of the CE-QUAL-W2 hydrodynamic model in the design of more applications. The use of these models for oxygen diffuser design is described in more detail in a related paper in the IAHR conference (Mobley, 2000).

Shepaug Dam, Connecticut Light and Power

A small reservoir with hydro turbine operations that are intermittent over each week required hydrodynamic modeling to predict the movement of the oxygen input at this proposed application to meet FERC requirements.

Richard B Russell, U.S. Army Corps of Engineers, Savannah District

A line diffuser installation is proposed to replace the original and modified diffuser systems. Costs of operation at decreased efficiencies and high maintenance costs justify the replacement (Mobley and Proctor, 1997).

J Strom Thurmond, U.S. Army Corps of Engineers, Savannah District

The multiple objectives of fish habitat creation and reservoir release improvements have justified the extensive use of hydrodynamic modeling to predict reservoir responses. The proposed diffuser location is almost 10 km upstream of the dam.

J Percy Priest, U.S. Army Corps of Engineers, Nashville District

Infrequent hydropower operation during the summer months (especially in low flow years) leads to build-up of high DO demands in the reservoir. A diffuser system to improve release DO must handle the demands and high turbine flows to be effective.

References

Brock, Gary W., and J. Stephens Adams, "A Review of TVA's Aeration and Minimum Flow Improvements on Aquatic Habitat," TVA Technical Paper 97-6, ASCE WATERPOWER '97, Atlanta, GA, August 5-8, 1997.

Fain, Theodoric, "Evaluation of Small-Pore Diffuser Technique for Reoxygenation of Turbine Releases at Fort Patrick Henry Dam," TVA Report No. WR28-1-32-100, October 1978.

Loginetics, 1999, http://www.logenetics.com/agpm.html, and personal communication with Gary E. Hauser.

Mauldin, Gary, Randy Miller, James Gallagher, and R. E. Speece, "Injecting an Oxygen Fix," Civil Engineering, March 1988, p54-56.

Mobley, Mark H., "Installation and Testing of an Oxygen Diffuser System at Douglas Dam, 1988," TVA Report No. WR28-1-20-108, October 1989.

Mobley, Mark H., and W. Gary Brock, "Widespread Oxygen Bubbles to Improve Reservoir Releases," Presented at 14th International Symposium of the North American Lake Management Society, Orlando, Florida, October 1994, Lake and Reservoir Management, 11(3):231-234.

Mobley, Mark H., and W. Gary Brock, "Aeration of Reservoirs and Releases Using TVA Porous Hose Line Diffuser," ASCE North American Congress on Water and Environment, Anaheim, CA, June 1996.

Mobley, Mark H., "TVA Reservoir Aeration Diffuser System," TVA Technical Paper 97-3, ASCE WATERPOWER '97, Atlanta, GA, August 5-8, 1997.

Mobley, M. H., and W. D. Proctor, "Richard B. Russell Forebay Aeration Using Line Diffusers: Cost Comparison with Existing System," TVA Engineering Laboratory, Norris, TN, WR97-2-760-104, May 1997.

Peavy, J. R., and J. M. Brubaker, "Richard B. Russell Lake and Dam Project: Oxygenation System," U.S. Army Corps of Engineers, Savannah District, February 1994.

Ruane, R. J., and Svein Vigander, "Oxygenation of Turbine Discharges from Fort Patrick Henry Dam," Prepared for Specialty Conference on Applications of Commercial Oxygen to Water and Wastewater Systems, University of Texas at Austin, 1972.

Simmons, Morgan, "Released Bass Dying Near Dam," Knoxville News-Sentinel, August 17, 1995.

Scott, Edwin M. Jr., Kenny D. Gardner, Dennis S. Baxter, and Bruce L. Yeager, "Biological and Water Quality Responses in Tributary Tailwaters to Dissolved Oxygen and Minimum Flow Improvements," TVA Environmental Compliance, Norris, TN, October 1996.

Authors

Mark H. Mobley, P.E., is Vice President of Engineering, Mobley Engineering Inc. Norris, TN - Lead the effort for development of the line diffuser and served as project engineer for diffuser installations and various aeration tests during 15 years experience at the TVA Engineering Laboratory. Recently founded Mobley Engineering Inc. to offer the design and installation of aeration systems for hydropower, water supply reservoirs, and other applications.

R. Jim Ruane – Reservoir Environmental Management, Inc., Chattanooga, TN-Participant in some of the early research on aeration of hydropower, with over 25 years experience at TVA. Founded REMI in 1995 to offer water quality and aeration assessments for hydropower and other utilities.

E. Dean Harshbarger is an Aeration Consultant in Norris, TN. He recently retired with 33 years of experience at the TVA Engineering Laboratory and over 20 years involved in aeration of hydropower releases. He served as Project Manager for twelve turbine venting and compressed air installations.