The Role of Failure in Success – **Or . . . Try, Try Again**

Mark Mobley, P.E.

The Role of Failure in the Development of Successful Dissolved Oxygen Enhancement Techniques

In his book "*To Engineer is Human – The Role of Failure in Successful Design,*" Dr. Henry Petroski has an entire chapter entitled "Falling Down is Part of Growing Up." In that chapter and in the book, Dr. Petroski explores how failure is a necessary part of engineering design and how lessons learned from failure can lead to advances in technology, improvements in understanding and… growing up. When my brother-in-law gave me the book, I read it from cover to cover. Dr. Petroski's message was right on target for my situation. Many of my recent designs at the Tennessee Valley Authority (TVA) Engineering Laboratory had ended in failure and I needed some encouragement to help me concentrate on learning from them to improve my future designs.

Working at an engineering laboratory, we were often experimenting with new designs and new technology, pushing the envelope and exploring a range of "what if" scenarios. These experiments sometimes pushed designs to failure but most were conducted on physical scale models in controlled conditions in the laboratory. The designs my team and I were working on were much more visible and public since they were large, full-scale installations at a hydropower dam.

Crashing cranes and heavy equipment

At Douglas Dam in the mid-1980s and eventually 15 other hydropower projects over the next decade, TVA was implementing water quality enhancements through the Reservoir Release Improvement Program. I was assigned to review and test the application of Garton pumps at Douglas Dam. Garton pumps (or surface water pumps) were large floating propeller pumps that looked like 15-foot-diameter ceiling fans. The idea was for the pumps to push the warm surface water that is high in dissolved oxygen (DO) content down into the deep withdrawal zone of the hydroturbine to dilute the cold anoxic water that is released during summertime stratified conditions.

The pumps had been invented and developed by Dr. James Garton at Oklahoma State University. It turned out that a full-scale test of three pumps had been conducted at Bagnell Dam by Union Electric Company with some promising results in release DO improvement. But their floating platform design was insufficient to withstand the wave action of the Lake of the Ozarks, so the pump equipment had been removed, surplused, and was lying in a scrap yard at the dam. I convinced my boss that we could buy the surplus equipment, redesign the floating platform, and test them at Douglas Dam. The pump equipment included a 30 HP electric motor and gearbox to drive the 15 foot long driveshaft attached to the propeller. Since this shaft was fixed in the gearbox, we built scaffolding to support the new floating platforms 20 feet or so off the ground so that the pump equipment could be mounted. The assembled pumps were to be lifted by a crane and moved across the dam to be lowered into the reservoir. But ignoring our flagmen and instructions, our crane operator did not lower the load from scaffolding height before he moved the crane over the rough ground of the construction site. The crane overturned, falling onto a smaller crane and smashing our first surface water pump on the ground. Miraculously, no one was hurt but the incident was captured on film by a professional TVA photographer (Figure 1).

This was not a design failure but a failure to communicate our plans clearly to the operator (and make sure he followed them). Eventually, with replacement parts, a new crane (and a different operator), we got three pumps installed and tested. The resulting DO improvement led to two more pilot test designs and eventually permanent installation of nine surface water pumps at Douglas and Cherokee dams that are still in operation today.

Spread it out – Development of the line diffuser design

My next assignment was to investigate the use of pure oxygen gas to further increase the DO in the releases at Douglas Dam. The surface water pumps had achieved about 2 mg/L of increase but more was needed to reach the desired target of 4 mg/L in the releases. Oxygen diffusers had been tested by TVA in the late 1970s and were being used by the U.S. Army Corp of Engineers at the Richard B. Russell hydropower project. Both systems used fine pore ceramic diffusers to create very small bubbles for optimized oxygen transfer from the bubble to the water but the diffusers were prone to clogging, creating a significant maintenance problem. To address this problem, my design team and I chose a laser slit diffuser disk used in waste water treatment and designed a frame and deployment method (Figure 2). The diffuser and deployment all worked well. We installed three frames directly in front of Unit 4 for testing. We achieved an initial DO increase of about 2 mg/L with

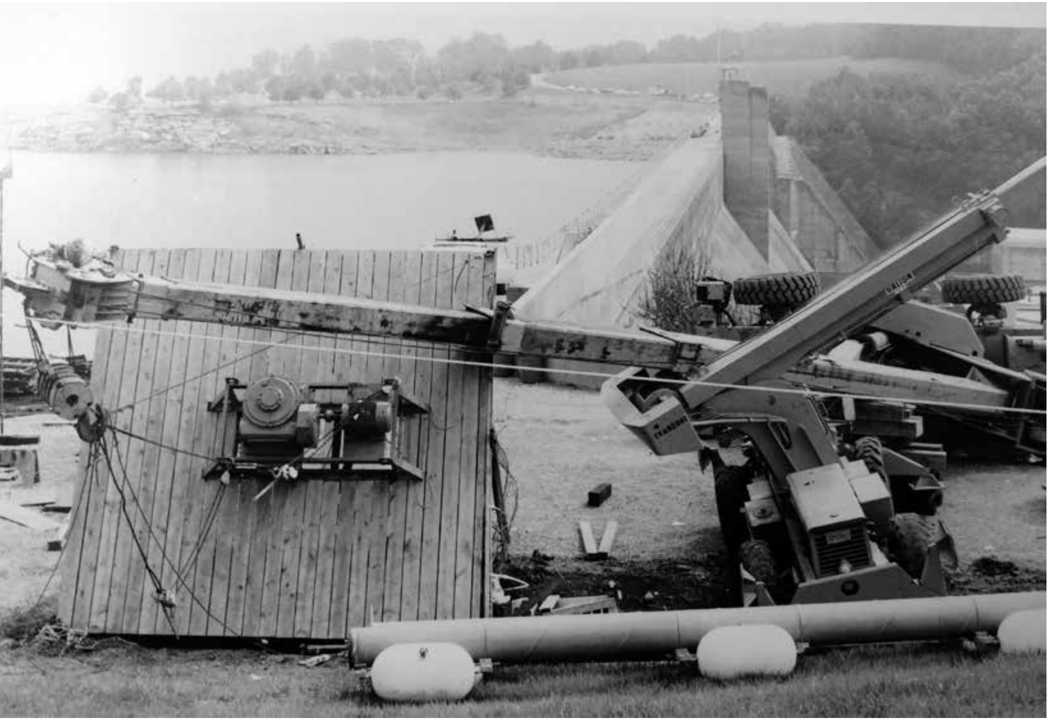


Figure 1. Overturned crane and smashed equipment at Douglas Dam.

Figure 2. Compact diffuser design.

72-percent oxygen transfer efficiency, but the strong bubble plumes stirred up and entrained bottom sediments that increased oxygen demands, eventually zeroing out our overall DO addition and clogging the raw water cooling system in the hydro plant (Figure 3). I was not popular with the plant operators.

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. Looking to replace the diffuser disk design, my team came up with garden variety "soaker hose" made of recycled automobile tires. The hose stretches slightly under pressurization to allow gas or water flow through the walls and made beautiful bubbles in the laboratory. We designed the hose to have the same flow rate per 50-foot hose as in the 1989 design for a 9-inch membrane diffuser head, thus drastically increasing the distribution of the oxygen. Of course that meant the frame to support the hoses had to be extra-large as well. In 1991, we constructed a 400-foot by 100-foot floating frame of PVC pipe to support 100 porous hoses (Figure 4). 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, some of the PVC pipes shattered due to stresses generated during the deployment allowing uncontrolled water into chambers needed for buoyancy. "And then it sank…" The entire frame immediately sank irretrievably to the bottom.

Eventually, in 1993 with program support for a new design, 16 smaller PVC diffuser frames, measuring 100 feet by 120 feet, were successfully deployed in Douglas Reservoir. Each frame supports 80 hoses for a total of over 12 miles of porous hose. Although these diffusers were effective and capable of providing up to 2 mg/L of DO improvement in the 16,000 cubic feet per second peak hydropower flows of the four turbines at Douglas Dam, the frames and buoyancy connections were too unwieldy and expensive for future designs.

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), with porous hose running the entire length of the diffuser, distributing the gas in small bubbles over as large an area as possible. This installation was the first of the line diffuser design. It was successfully deployed in the narrow

Figure 3. Manual cleaning of raw water heat exchangers.

Figure 4. PVC frame diffuser.

curvilinear channel and is still in use today.

This design, developed through so many failures, led to the successful application of line diffuser aeration and oxygenation systems in more than 50 lakes and reservoirs for enhancement of hydropower releases, water supply and fish habitat. Persistence pays off!

Getting rid of hydrogen sulfide and only hydrogen sulfide

After leaving TVA to found Mobley Engineering, Inc. (MEI), I was involved in a DO enhancement project in 2004 at the Lake Wallenpaupack hydroelectric project for Pennsylvania Power and Light (PPL). At this project, the powerhouse and turbines are some 3.5 miles downstream of the dam releasing water directly into the Lackawaxen River. Turbine venting, drawing air directly into the water flow beneath the turbine, had been successfully implemented to increase the DO of the hydropower releases. But the localized air intake caused the hydrogen sulfide (H_2S) in the water flow to degas immediately at the hydropower plant and waft strong rotten egg odors along the river to the very nice riverfront houses with nice patios and decks. Needless to say, the neighbors were not happy with PPL even if they were now meeting their state water quality DO standard.

A team from Kleinschmidt Associates and Reservoir Environmental Management Inc., determined that up to 196 cfs of H_2S laden water was being withdrawn during hydropower operations and that an aeration equivalent to 2 mg/L would be sufficient to oxidize the H_2S in the reservoir before it was moved into the hydropower withdrawal. A Mobley Engineering Line Diffuser aeration system was designed and installed with operation instructions for an air flow of 176 standard cubic feet per minute (scfm) to aerate the incoming H_2S during turbine operation and 12 scfm to maintain DO levels during long periods of no generation.

Upon operation, the aeration system immediately eliminated H_2S odors in the releases – a very public and popular success. This went on very well until the next summer when our team got a call from PPL complaining of very turbid, rusty-looking water in the releases (Figure 5). The beautiful Lackawaxen River was murky and reddish downstream of the hydropower plant. This was a very obvious and public failure. With a couple of site visits and review of operations, it was discovered that the operators thinking that "if a little air was good then more would be better" had left the aeration system in full operation during non-generation periods leading to the aeration of not only H_2S but some of the very high dissolved iron content of the reservoir causing the rusty, turbid water in the releases. Careful operation of the aeration system has provided relief from H_2S odors without objectionable turbidity ever since.

Super-saturation without scouring

Building off our successful side stream super-saturation (SSS) system

Figure 5. Turbid hydropower release into the Lackawaxen River.

installation in Falling Creek Reservoir for the Western Virginia Water Authority in 2012, a team from MEI, Gantzer Water Resource Engineering and Burgess & Niple extrapolated the design for a much larger system for the Wolf Creek Reservoir for the City of Barberton Ohio in 2015.

With a SSS system, cold water is removed from the bottom of the reservoir, pumped through a pressurized oxygen contact chamber (Speece Cone) and redistributed into the hypolimnion of the reservoir. The trick is to distribute the highly oxygenated (DO content sometimes over 100 mg/L) supersaturated water back over the bottom of the reservoir without degassing the oxygenated water or mixing the reservoir. At Falling Creek, we used eductor nozzles to mix the super-saturated water with four times the volume of ambient water in a jet. This diluted the oxygenated water from super-saturated conditions and spread the oxygen placement in the hypolimnion. At Barberton, we upsized the nozzles for the higher flows and without knowing better, deployed the piping system on a much softer reservoir bottom. The system performed as expected at first, dramatically increasing DO levels. But the goal of the application was reduction of manganese (Mn), and the system was showing unexplained spikes of high soluble manganese. Wondering if our nozzles had somehow gotten twisted into pointing into the sediments, the city hired a dive team for an inspection. They found that our pipe anchoring system had sunken completely into the sediments instead of holding the pipe some distance above and that there was a two-foot-deep, six-foot-long hole scoured out of the sediments at every nozzle. Well, it was back to the blackboard (or whiteboard) for the engineers (Figure 6). We kicked around several new designs and then tested new nozzles in a local lake to determine the nozzle that provided the best mixing and least jet (Figure 7). Last

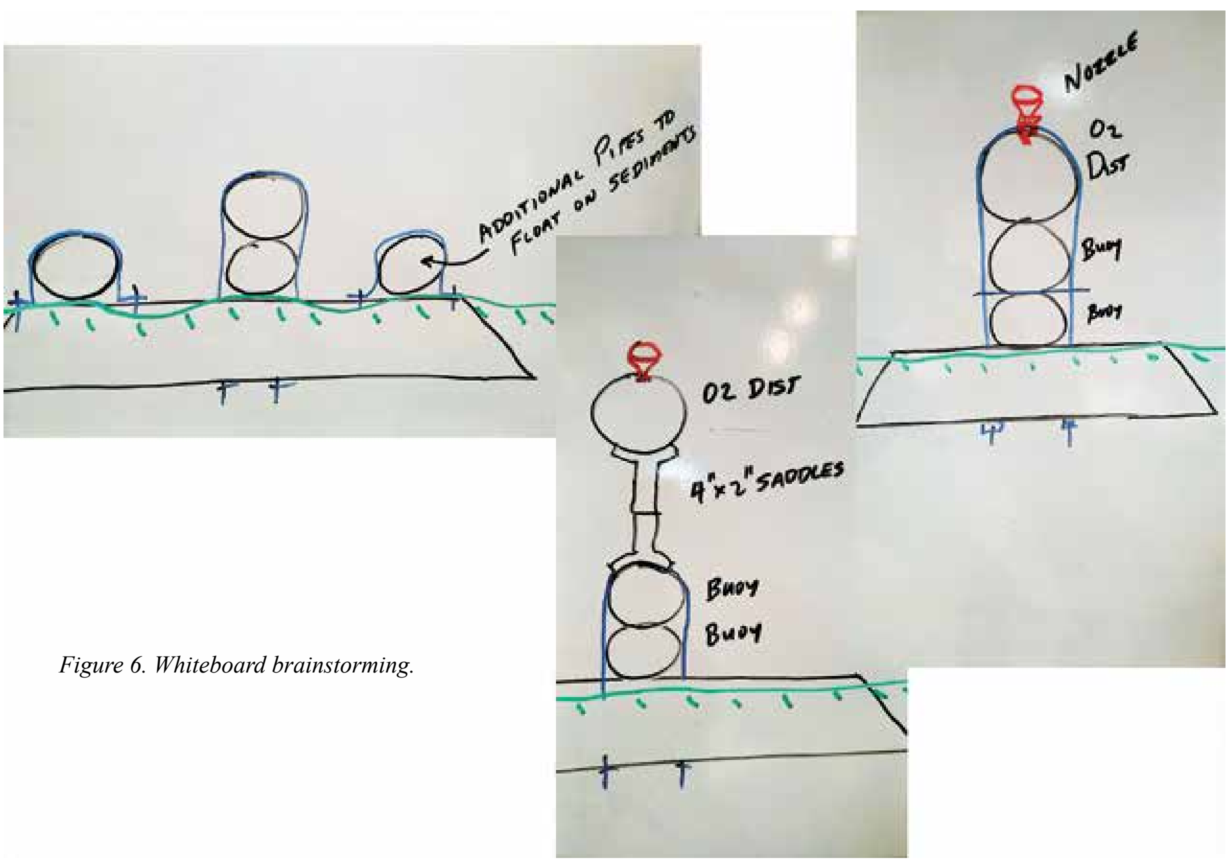


Figure 6. Whiteboard brainstorming.

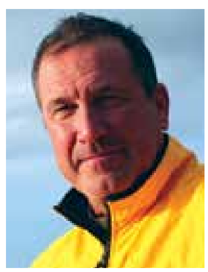
Figure 7. Nozzle test.

year, we modified the distribution piping with additional piping and new nozzles. Results were much improved with the lowest Mn levels yet measured, but the oxygen supply equipment suffered a long term shutdown and we will have to wait until the system is fully operational again to claim complete success with this design.

"No one *wants* to learn from mistakes, but we cannot learn enough from successes to go beyond the state of the art."

Dr. Petroski asserts that failure is a necessary part of innovation – that new technologies require at least some element of risk. These days we can minimize those risks with complex computer models, but at some point you have to go build it and see if it works. And we learn from our mistakes.

Petrowski, Henry. 1985. *To Engineer is Human – The role of Failure in Successful Design,* St. Martin's Press, New York.



Mark H Mobley, P.E., founded Mobley Engineering, Inc. in 1999 after 16 years with the Tennessee Valley Authority Engineering Laboratory. He has been responsible for the installation of over 50 reservoir diffuser systems using compressed air or oxygen to enhance drinking water, hydropower releases and fish habitat. He can be reached at: Mobley Engineering, Inc., PO Box 600, Norris, TN 37828; 865.494.0600 ofc; 865.806.8050 mobile; mark@mobleyengineering.com.