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DISSOLVED OXYGEN ENHANCEMENT AT DEER CREEK POWERPLANT

By

Tony L. Wahl

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MEMORANDUM

To: Regional Director, Salt Lake City, UT
Attention: UC-773 (Young), UC-722 (Miller)

From: Philip H. Burgi
Chief, Hydraulics Branch

Subject: Summary Report on Dissolved Oxygen Tests at Deer Creek Powerplant (Hydraulic Research)

Researchers from the Hydraulics Branch recently participated in turbine aeration tests at Deer Creek Powerplant to improve dissolved oxygen concentrations downstream of the powerplant in the Provo River. We have completed our analysis of the test data and have prepared the enclosed summary report. The report includes discussions of aeration effectiveness, power losses caused by aeration, and the feasibility of establishing permanent turbine aeration at the site. The report also discusses advantages, disadvantages, and costs of other aeration alternatives.

If you have any questions please contact Tony Wahl at (303) 236-6146.

Philip H Burgi

Enclosure

cc: Projects Manager, Provo UT, Attention: PPO-103 (Frandsen)
(w/encl)

bc: D-3751 (PAP file) D-3750 D-5850
D-3752 D-3421
(w/encl to each)

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D-3752 (Wahl)
(w/o encl to each)

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Dissolved Oxygen Enhancement at Deer Creek Powerplant

Report on Turbine Aeration Testing - August 9-12, 1993

Prepared by: Tony L. Wahl

INTRODUCTION

Deer Creek Dam and Powerplant are located at the head of the Provo River Canyon, about 15 miles northeast of Provo, Utah. The powerplant contains two Francis-type turbines rated at 2475 kW, each. The two units each discharge about 300 ft^3/s at full load. Water levels in the tailrace below the powerplant are controlled by a small 3-bay gate structure. The rated head on the powerplant is 120 ft and the maximum head is 140 ft. During the late summer months dissolved oxygen (DO) concentrations in the water discharged from the powerplant typically reach very low levels, well below a desirable 4-6 mg/L concentration beneficial for water quality and aquatic habitat. The low DO concentrations affect the Provo River downstream of the dam, a heavily used blue ribbon trout fishery. Although fish kills have not been documented, fish do abandon a 1-2 mile reach of the river in the late summer months.

Several alternatives are being considered for improving DO concentrations downstream of Deer Creek Powerplant, including shifting of reservoir releases to the spillway and/or outlet works, installation of aeration weirs in the river reach, and aeration of the flow through the turbines. The turbine aeration concept was tested at the powerplant during August 9-12, 1993, to evaluate the feasibility and effectiveness of this option.

CONCLUSIONS AND RECOMMENDATIONS

1) Air injection into the turbines is an effective method for increasing DO concentrations downstream of Deer Creek Powerplant. Turbine aeration could readily be implemented to obtain DO concentrations of 4-5 mg/L downstream of the powerplant, even under the most severe low DO conditions.
2) Observations of bearing temperatures and shaft runout did not indicate any adverse effects of air injection on the mechanical behavior of the turbines or generators.
3) Air injection was especially effective up to a 4 percent injection rate (air volume at standard temperature and pressure/water volume), with a 10 percent increase in aeration efficiency for each additional percent air. Above a 4 percent injection rate, the benefits of additional air began to decrease.
4) The most desirable location for air injection is through the headcover. Pressures required for air injection through the headcover are low enough to make an axial flow blower feasible for a permanent installation. Injection pressures required for the snorkel tube location are excessively high for the required airflow rates. Although not expressly tested, air injection at the draft tube throat (through the mandoor) should also be effective, but would require additional modifications.
5) Unit 1 should be investigated to determine and remove the source of blockage in the air line leading from the vacuum breaker valve to the headcover.
6) Efficiency losses at the 55 and 60 percent wicket gate settings were between 0.3 and 0.7 percent for each 1 percent air injected into the turbines. For estimating power losses caused by turbine aeration, a 0.5 percent efficiency loss was assumed for each 1 percent air injected.
7) At a 35 percent wicket gate setting air injection increased turbine efficiency. It is likely that air injection could increase turbine efficiency at wicket gate settings of 50 percent or lower.

8) Using the tailrace control gates to increase DO concentrations is less effective than turbine aeration. A 3-ft drop over the gate structure produced only half the aeration achieved with 4 percent air injection into the turbines. Power losses for a 3-ft increase in tailrace level would be 2.5 percent at the powerplant's rated head of 120 ft.
9) Natural aspiration through the headcover (simply removing the vacuum breaker valve or blocking it open) could provide some benefit. At the 55 percent wicket gate setting tested, natural aspiration produced DO increases comparable to that achieved by raising the tailrace control gates (about 20 percent aeration efficiency). At higher wicket gate settings the airflow rate will probably be reduced and the waterflow rate will be increased, producing lower percentage airflow rates and lower aeration efficiency. Natural aspiration could also be combined with manipulation of the tailrace control gates to obtain additional DO improvement. However, using the tailrace gates to raise the tailrace water level might reduce natural aspiration for some operating conditions.
10) Additional pressure measurements made on the units at various operating conditions would make it possible to estimate airflow rates and aeration achievable at wicket gate settings that were not tested (especially near full load). These measurements could easily be made by local personnel. Making these measurements is strongly recommended, especially if the natural aspiration alternative is considered for permanent use.
11) Other alternatives for DO enhancement such as oxygen injection in the penstock or construction of aeration weirs in the river would likely be more difficult and/or more expensive to implement. A preliminary analysis showed that a series of six 65-ft long weirs with a free drop of 0.5 meters each would be required to achieve aeration similar to that obtained with turbine aeration.
12) In any option involving aeration using atmospheric air (including turbine aeration), the possibility for nitrogen supersaturation in the tailrace should be considered. Measurements of dissolved nitrogen concentrations were not made in these tests.
13) Another detailed test could be conducted in the summer of 1994, focusing on the alternative that appears most feasible for permanent use. The question of nitrogen supersaturation could also be addressed as part of this test.

TEST SUMMARY

Test Preparations and Powerplant Modifications

The tests were originally scheduled for late August or early September, but were moved up to early August to accommodate scheduled maintenance and rehabilitation work in the powerplant switchyard. To make the test effective it was desirable to achieve at least a 2 mg/L DO increase through the turbines. Based on past research in this area, this required that we have the capability to inject up to 5 percent air [volume flowrate of air at standard temperature and pressure (101.3 kPa, 15°C), divided by volume flowrate of water]. Airflow rates as high as 700 scfm (ft^3/min at standard temperature and pressure) per turbine were needed with the powerplant operating at full load.

Examining the available drawings for the units (see fig. 1) showed that there were two locations readily available for injecting air into the turbines. The first was a 2-inch diameter pipe leading from the vacuum breaker valve, through the turbine bearing housing, and into the headcover. Once inside the headcover, air would travel through seven, 1½-inch diameter holes present in the crown of runner. These holes exit into the suction side of the runner, approximately even with the trailing edges of the runner blades. The purpose of these holes is to relieve vacuum under the runner when the unit is shut down. In normal operation air would be drawn into the turbine from outside of the powerplant, through a 3-inch line leading from the turbine pit liner to the vacuum breaker valve. The vacuum breaker valve is automatically opened by the gate operating ring when the wicket gates reach a 5 percent opening. For our purposes in these tests the vacuum breaker valve was removed and our air piping was bolted on in place of the vacuum breaker. At the desired airflow rates, friction losses through this route were estimated to be 3-5 psi.

The second option was to inject air through the snorkel tube attached to the bottom of the runner hub. Air reaches the snorkel tube by passing through an assembly of 1-inch pipe down to a hole drilled through the shaft just below the packing box of the unit. A second hole drilled up through the center of the shaft leads to the snorkel tube. The tube itself is a 2½-inch diameter pipe perforated with numerous small-diameter holes. The pipe extends below the runner hub about 18 inches. One purpose of the snorkel tube is to allow air to be injected or naturally drawn into the unit to smooth rough operation in the part-load draft tube surging zone. Airflow into the snorkel tube is controlled by a gate valve in the turbine pit. Normal use of the snorkel tube would also draw air in from outside of the powerplant, through the same 3-inch line connected to the pit liner. To inject air through the snorkel tube in our tests, we disconnected the 1-inch line from the 3-inch line and plumbed the air compressor hoses into the 1-inch line. Pressure losses were not accurately estimated for the snorkel tube option, but were expected to be quite large due to the small size of the piping.

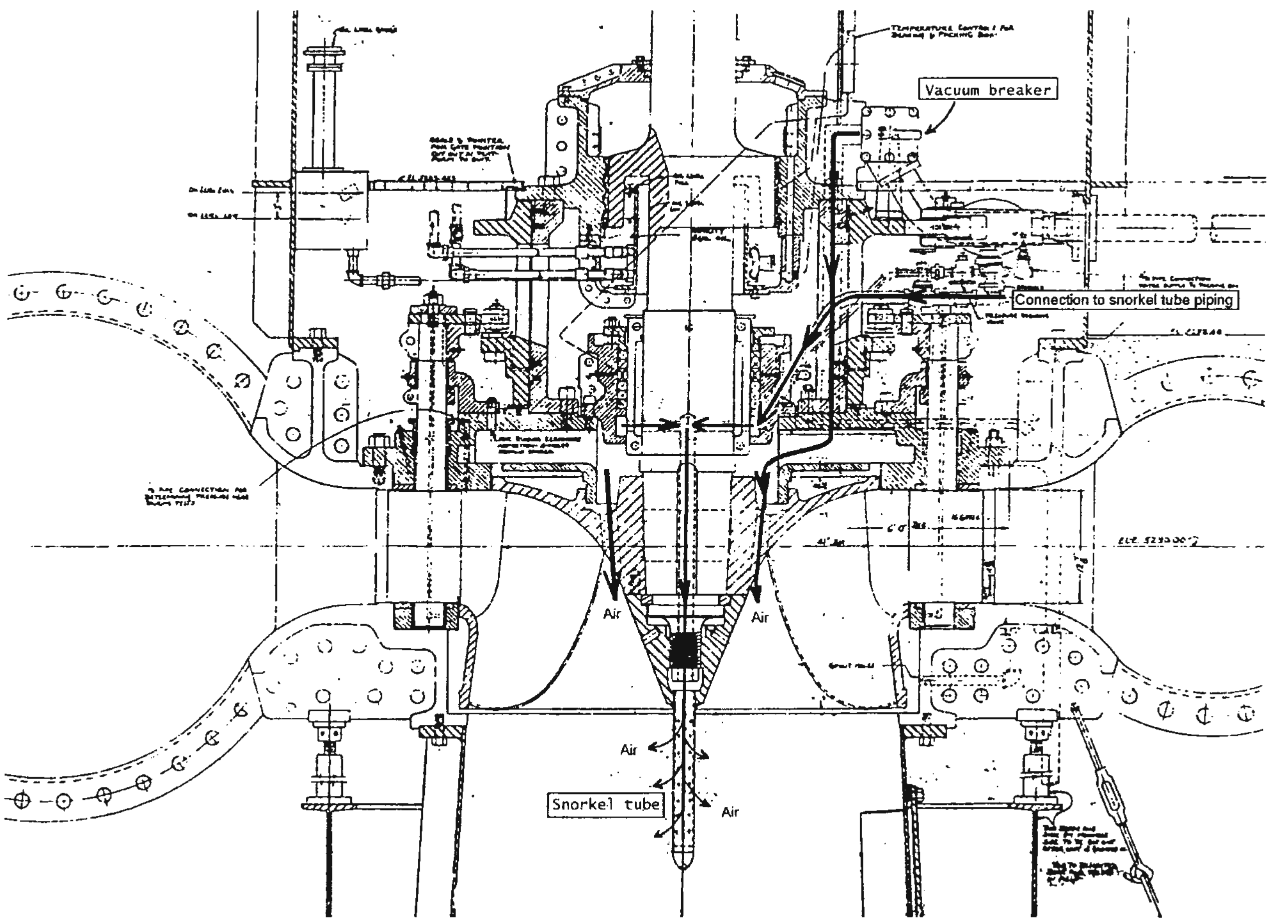

Figure 1. - Cross-section through one of the 2475 kW turbines at Deer Creek Powerplant. Two airflow paths are shown: (1) from the vacuum breaker through the headcover and runner crown ports, and (2) through the shaft and snorkel tube.

Figure 1 shows a turbine cross-section with the vacuum breaker valve and snorkel tube indicated. Heavy lines mark the airflow paths for the two injection options. The preferable location for air injection was the 2-inch line leading to the headcover. We expected that by simply opening the necessary valves, some air could be naturally drawn into the turbine through either the headcover or snorkel tube location. The amount of air drawn in would vary depending on tailwater elevation and wicket gate opening, with more air drawn in at smaller gate openings.

To ensure that 5 percent airflow rates could be obtained, we arranged to rent two compressors capable of providing a maximum flowrate of 750 scfm and a maximum pressure (at zero flow) of 125 psi. To measure the airflow rates we rented one 1000-scfm Hedland flowmeter in Denver (flowmeters with the required capacity were not locally available). Flow into the second turbine was measured using an orifice plate flowmeter obtained from the hydraulics laboratory in Denver. The laboratory shops in Denver also constructed flanges necessary to install the air compressor piping in place of the vacuum breaker valves on the two turbines.

Test Equipment

In addition to the compressors and flowmeters described above, a 2-inch gate valve and brass check valve were installed downstream of the flowmeter on each unit, between the meter and the connection to the turbine vacuum breaker port. The gate valve was used in conjunction with the compressor regulator to throttle the airflow to the desired rates. The check valve provided protection against water coming back up through the vacuum breaker port and entering the flowmeters or compressors.

Pressure gages and pressure transducers were installed immediately upstream of the connection to the vacuum breaker port to allow us to relate the supply pressure to the airflow rate (independent of losses caused by our flowmeters). Temperature sensors were installed on the air piping near the flowmeter locations for use in calculating temperature-corrected airflow rates. On the orifice plate flowmeter, pressure gages were installed upstream and downstream of the orifice plate and a differential pressure transducer was installed across the orifice plate pressure taps. The flowrate through the orifice was calculated from the observed upstream pressure, temperature, and differential pressure.

To monitor shaft runouts at the turbine guide bearing location, two proximity probes were mounted on each unit, at 90° angles around the turbine shaft. The output from these probes was monitored and recorded using a strip chart recorder.

Test Objectives

There were four major objectives for the tests:

1) Establish a range of airflow rates into the turbines and determine the supply pressures required to achieve specific flow rates.
2) Evaluate the effect of air injection on turbine efficiency and power output.
3) Evaluate the effect of air injection on the mechanical operation of the unit (changes in vibrations, shaft runout, or bearing behavior).
4) Determine the effectiveness of turbine aeration for increasing DO concentrations in the river downstream of the powerplant.
5) Develop information needed for a possible permanent installation.

We expected that several variables could affect the performance of the turbines and the effectiveness of the air injection and DO transfer process. Specifically, we wished to test:

1) Variable airflow rates, from 0 to 5%, or higher if possible. Higher airflow rates were expected to increase DO uptake and reduce powerplant efficiency.
2) Aeration through both the headcover and snorkel tube locations.
3) Different wicket gate settings for the turbines, particularly part-load and full-load operations. We expected to see variations in efficiency losses, especially for part-load operation where air injection at other sites has been known to improve turbine efficiency.
4) Variations of water level in the tailrace. We expected that increased tailwater depth would improve the DO uptake by increasing contact time for the injected air bubbles. Also, increased pressure in the draft tube should accelerate the gas transfer process due to the higher affinity for oxygen at higher pressures.

Because the units were not operating at full load during our tests, the full 700 scfm airflow rate was not required to reach a 5 percent air injection rate. The highest airflow rate tested was 650 scfm (5.8 percent by volume) through the headcover location on unit 2. We were unable to inject more than 2.4 percent air into the headcover location on unit 1. The largest airflow rate tested on unit 1 was 450 scfm through the snorkel tube location, or 3.7 percent by volume. These airflow rates were sufficient to obtain DO uptakes in the range of 2.5 to 4 mg/L.

We conducted tests at two intermediate wicket gate settings, 55 and 60 percent. We also tested wicket gate settings of 35 percent on unit 1 and 77 percent on unit 2. An important consideration in the tests was maintaining constant river discharges downstream of the powerplant.

We were able to conduct tests at two different tailwater elevations. The first was the minimum elevation with the tailrace control gates fully lowered. We also tested a 3-ft higher tailwater level. In concert with the high tailwater test, we were also able to measure the DO increase across the tailrace gate structure with a 3-ft drop over the gates.

Test Procedure and Data Collection

The test procedure consisted of establishing desired airflow rates into one or both turbines, and then allowing DO concentrations in the tailrace to stabilize. Airflow rates were ramped up and down at the start and end of the tests to minimize the shock to aquatic life downstream of the powerplant.

Data were collected to permit calculation of the combined turbine and generator efficiency. Bearing temperatures were recorded and shaft runouts were monitored at the turbine guide bearing location. We attempted to monitor vibrations of the turbine guide bearing housing, but could not detect vibrations large enough to register on our sensors.

DO concentrations were measured with portable DO probes, primarily at two locations: (1) the exit from the powerplant into the tailrace, where readings stabilized very quickly, and (2) the downstream end of the tailrace, where concentrations stabilized after about 18 minutes of continuous operation. DO concentrations were also measured every 15 minutes by fixed sensors located in the powerplant and at the downstream end of the tailrace. The measurement in the powerplant was made on the line supplying penstock water to the bearing cooling water system, which should be a good indicator of the DO concentration of the flow entering the powerplant. In addition, DO measurements were occasionally made in the 5 mile reach of river downstream of the powerplant. Nighttime DO measurements were taken at the powerplant and along the length of the river downstream of the plant on Wednesday evening and Thursday morning, August 11-12, with and without turbine aeration. The analysis of the river DO data are not included in this report.

A summary and description of the test equipment is given in table 1.

Table 1. - Test equipment

Parameter	Sensor Description	Sensor Location
Reservoir water elevation	Powerplant readout	Powerplant control room
Tailwater elevation	Measured with taped dropped from plant deck	Stilling basin
Power output	Analog kW meters	Powerplant control room
Water discharge	Badger acoustic flowmeters	Penstocks, readout in control room
Airflow into unit 1 (west unit)	Hedland 1000 scfm flowmeter	Upstream of connection to snorkel tube piping
Airflow into unit 2 (east unit)	1-inch diameter orifice plate in a 1 ½-inch diameter pipe section	Upstream of connection to vacuum breaker port
Injection pressure - unit 1	100 psi pressure gage	Between flowmeter and connection to snorkel tube piping
Injection pressure - unit 2	25 psia absolute pressure transducer	Between flowmeter and connection to vacuum breaker port
Orifice plate pressure differential	Pace KP15 transducer, 25 psi range	Across orifice plate taps - unit 2
Orifice plate upstream pressure	100 psi pressure gage	Upstream orifice plate tap - unit 2
Air temperatures	Kulite RTD temperature sensor	Air piping at flowmeter locations - both units
Shaft runout	magnetic proximity probes	2 at the turbine guide bearing on each unit
Turbine guide and thrust bearing oil temperatures	Powerplant gages	Powerhouse
Incoming DO concentration	DO-DAM	Fixed probe on bearing cooling water line
DO concentration at downstream end of stilling basin	DO-RIVER	Fixed probe installed in stilling well at west side of gate structure
DO concentrations at powerplant face	2W (unit 1) / 2E (unit 2)	Probes hung from catwalk across downstream face of powerplant

Test Sequence

Most of the testing was done with the turbines operating at a partial load setting of 55 to 60 percent wicket gate opening. This is lower than typical operations at this time of year due to recent wet weather in the area and reduced irrigation releases. Best efficiency gate for these units is probably about 80 percent, and typical late summer operations are probably in this range. The plant is generally operated based solely on required downstream water deliveries.

We completed the installation of our equipment on the afternoon of Monday, August 9. We initially connected both compressors so that air would be injected into the headcover location on each unit. We conducted an initial shakedown test that showed there was a substantial blockage of the lines leading to the headcover on unit 1. We were able to inject a maximum of about 2.4 percent air into unit 1. After confirming that there were no problems with our equipment, we changed the setup Tuesday morning to inject air into unit 1 through the snorkel tube location. The remainder of the tests were conducted with this configuration.

On Tuesday August 10 we tested airflow rates of 1, 2, 3, and 4 percent on both units, with the units operating at a 60 percent wicket gate setting. The tailwater level for all of these tests was at elev. 5273.77 ft (the turbine runner exit elevation is 5278.46). Near the end of the day we attempted to raise the tailwater elevation, but our tests were cut short when a close lightning strike caused the units to trip off-line, thus opening the tube valve bypass and violently aerating the tailrace.

On Wednesday August 11 both turbines were operating at wicket gate settings of 55 percent. We tested airflow rates of 4, 5 and 5.8 percent on unit 2. We then tested airflow rates of 4 percent on both units, with the tailrace water level raised about 3 ft. In the afternoon we tested part-load and high-load operation of the turbines, with unit 1 at 35 percent gate and unit 2 at 77 percent gate. Airflow rates of 1, 2, and 3 percent were tested in this configuration. The compressors were set to deliver 3.5 percent airflow for the overnight tests on Wednesday evening and Thursday morning.

On Thursday August 12, we disassembled the equipment and instrumentation. While disassembling the air supply hoses and piping we made additional power output and DO measurements with air being drawn in naturally through the headcover location. The turbines were still operating at 55 percent gate, with the tailwater set at the same low level tested on Tuesday and Wednesday. We were not able to measure actual airflow rates for this condition because our flowmeters had already been removed. We also measured the static vacuum at both injection locations on both units with no airflow into the turbines.

TEST RESULTS

Initial Observations

The tests went as planned, with the exception of the problems experienced with inadequate airflow through the headcover location on unit 1. We did not note any significant changes in shaft runout, bearing temperatures, noise, or vibrations in the powerplant during the four days of testing.

The tests suggested that there was some type of blockage present when we tried to inject air through the headcover on unit 1. The pressure indicated on our gage installed at the vacuum breaker port increased rapidly as we increased the airflow rate above 1 percent. The pressure at this point was also observed to fluctuate wildly, as though some loose material was moving about and blocking the flow of air. The maximum airflow rate we were able to achieve was about 300 scfm, or 2.4 percent by volume.

To obtain the best gas transfer and DO improvement, it was desirable to produce a plume of evenly distributed, finely divided air bubbles in the flow exiting the turbines. Unfortunately, for even small airflow rates (as low as 1 percent by volume) we observed large pockets of air boiling up out of the flow at the downstream face of the powerplant. This was most likely caused by the configuration of the coaxial diffuser-type draft tubes, shown in figure 2. Unlike a more modern formed elbow-type draft tube, these draft tubes exit vertically downward into a large chamber that leads to the downstream face of the powerplant. Once the flow leaves the draft tube, velocities quickly decrease. This allows air bubbles to coalesce and collect at the top of the chamber. When this air reaches the face of the powerplant it immediately boils to the surface. As we injected higher quantities of air the boiling action became more vigorous and the volume of air being lost in this manner increased.

Despite the air loss at the powerplant face, air injection into both units produced a dense bubble plume in the tailrace exiting the powerplant. DO concentrations in the flow exiting the powerplant and at the downstream end of the tailrace were in the range of 3 to 5 mg/L, a significant improvement over the incoming DO concentrations. The partial load operating condition (unit 1 at 35 percent wicket gate setting) produced a sparser bubble plume than all other tests; however, the DO measurements indicated that total DO uptake was actually higher for this case.

DO Measurements

Table 2 shows the different test conditions and the corresponding DO measurements made in the tailrace. All DO probes were calibrated daily during the tests. Four primary measurement locations were used:

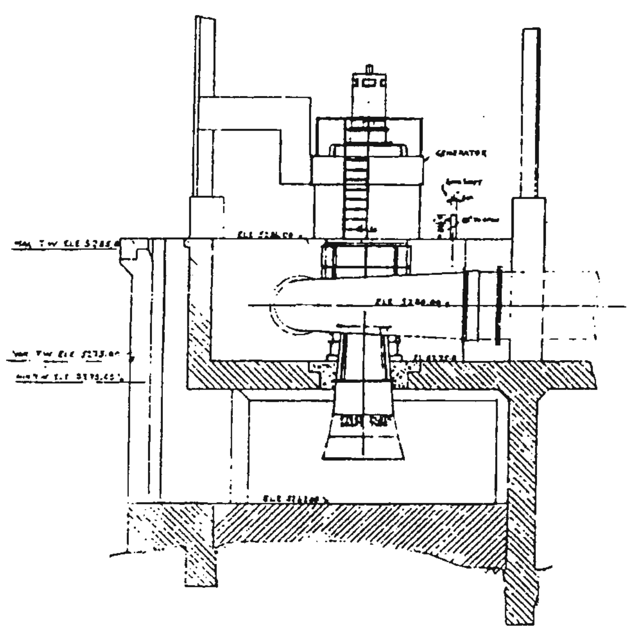

Figure 2. - Elevation view showing the turbine and draft tube arrangement at Deer Creek Powerplant. Flow is from right to left.

1) DO-DAM: This probe was installed in the powerplant to measure the DO concentration of the water entering the bearing cooling water system.
2) DO-RIVER: This probe was installed in a stilling well at the downstream end of the tailrace. The DO-DAM and DO-RIVER probe readings were each automatically recorded at 15 minute intervals throughout the four days of testing.
3) 2W/2E (West/East): Measurements were made with portable DO probes hanging from the catwalk across the downstream face of the powerplant. Measurements at 2W were in the flow discharging from unit 1. Measurements at 2E were in the flow discharging from unit 2.
4) 3W/3C/3E (West/Center/East): The portable probes were also used to measure DO concentrations at the downstream end of the tailrace. Probes were hung from the walkway across the gate control structure. Initial DO measurements showed the flow was well mixed at this point, so the majority of measurements were made in the west gate bay.

For most test conditions multiple DO readings were taken at each of the locations. The data shown in table 2 are the average of these readings. For the DO-RIVER probe there was about an 18-minute lag time between the start of a test and the presence of stable DO concentrations at the probe. This lag time was accounted for in correlating the DO measurements with the corresponding turbine operation and airflow conditions. The DO-RIVER probe readings appear to be significantly lower than the data collected with the portable probes. The DO-RIVER probe readings were also generally lower than the DO-DAM readings when there was no aeration. Apparently, the installation of the DO-RIVER probe in the stilling well limited the flow past the probe. Since the probe itself consumes some dissolved oxygen during its operation, this resulted in systematically low readings. Thus, the majority of the analysis in this report will be focused on the data collected from the portable probes.

Table 2. - DO concentration data

Unit 1		Unit 2			Dissolved Oxygen Concentrations (mg/L)				
Wicket Gates	Airflow (% by volume)	Wicket Gates	Airflow (% by volume)	Combined Airflow	DO-DAM	2W	2E	3W/3C/3E	DO-RIVER
60%	0.00%	60%	0.00%	0.00%	2.38	---	---	---	2.04
60%	2.00%	60%	1.95%	1.98%	2.71	4.60	4.40	4.46	3.75
60%	1.98%	60%	1.79%	1.88%	2.52	4.38	3.87	4.30	3.77
60%	0.99%	60%	0.87%	0.93%	2.59	3.40	3.24	3.49	3.19
60%	3.73%	60%	4.00%	3.87%	2.59	5.10	5.22	5.22	4.49
60%	2.94%	60%	2.94%	2.94%	2.71	4.75	4.61	4.91	4.31
60%	2.91%	60%	2.97%	2.94%	2.76	---	4.69	5.11	4.53
55%	0.00%	55%	0.00%	0.00%	1.50	---	---	---	1.53
55%	0.00%	55%	5.01%	2.49%	1.35	---	5.05	---	2.44
55%	0.00%	55%	5.79%	2.87%	1.51	---	5.34	---	2.90
55%	0.00%	55%	3.94%	1.96%	1.53	---	4.54	---	---
55%	3.59%	55%	3.86%	3.73%	1.40	4.65	4.64	---	3.49
55%	3.62%	55%	3.90%	3.76%	1.30	4.84	4.78	---	3.47
55%	3.74%	55%	3.96%	3.85%	1.62	---	4.79	---	3.92
35%	2.95%	77%	3.06%	3.03%	1.64	4.28	3.45	---	3.33
35%	1.97%	77%	2.00%	1.99%	1.75	3.63	3.20	---	2.88
35%	1.04%	77%	1.12%	1.10%	1.79	2.79	2.62	---	2.53
55%	3.51%	55%	3.47%	3.49%	2.22	5.12	5.28	5.11	4.29
55%	Naturally vented	55%	Naturally vented	Naturally vented	1.96	2.58	3.50	---	---

Airflow rates in table 2 are given in percent by volume. The mass flow rate of air was expressed as an equivalent volume flow rate, assuming air at standard temperature and pressure (101.3 kPa, 15°C). This volume flow rate is then divided by the water discharge to obtain the percent airflow rate. The last line of table 2 shows that natural aspiration through the headcover produced some benefit, although the DO improvement through unit 1 was smaller than that for unit 2 due to the partial blockage of the air line in unit 1 mentioned previously. This benefit will probably vary with wicket gate setting, decreasing as the wicket gates are opened further. Additional measurements of the headcover vacuum pressure at various wicket gate settings would allow for estimation of airflow rates at different wicket gate settings.

Turbine Efficiency

Table 3 shows the head, discharge, and power output data collected during the tests. The efficiency shown in the table is the combined turbine and generator efficiency. Discharge data were taken from the Badger acoustic flowmeters permanently installed on the penstocks upstream of the powerhouse. The reservoir level and tailwater level were recorded for each test point. Power outputs were recorded from the analog kilowatt meters in the powerplant control room. A digital meter also present in the control room did not have sufficient sensitivity for our use.

Table 3. - Power output and efficiency data

	Unit 1					Unit 2				
Total Head (ft)	Wicket Gates	Airflow (% by volume)	Turbine Discharge (ft^3/s)	Generator Output (kW)	Combined Turbine & Generator Efficiency	Wicket Gates	Airflow (% by volume)	Turbine Discharge ft^3/s	Generator Output (kW)	Combined Turbine & Generator Efficiency
139.67	60%	0.00%	202.3	1740	72.8%	60%	0.00%	205.2	1850	76.3%
139.65	60%	1.98%	202.9	1720	71.7%	60%	1.79%	204.8	1790	73.9%
139.65	60%	0.99%	203.3	1750	72.8%	60%	0.87%	205.1	1820	75.1%
139.65	60%	3.73%	202.4	1700	71.1%	60%	4.00%	203.4	1760	73.2%
139.65	60%	2.94%	201.1	1710	71.9%	60%	2.94%	202.1	1760	73.7%
138.15	60%	2.91%	203.1	1680	70.7%	60%	2.97%	200.0	1730	74.0%
139.79	55%	0.00%	190.0	1560	69.4%	55%	5.01%	187.3	1550	69.9%
139.78	55%	0.00%	189.8	1575	70.1%	55%	5.79%	186.4	1540	69.8%
139.77	55%	0.00%	190.4	1570	69.7%	55%	3.94%	187.9	1575	70.9%
139.77	55%	0.00%	188.9	1570	70.3%	55%	0.00%	191.5	1630	72.0%
139.77	55%	3.59%	185.8	1520	69.2%	55%	3.86%	188.3	1580	70.9%
136.77	55%	3.62%	184.2	1500	70.3%	55%	3.90%	184.9	1520	71.0%
136.73	55%	3.74%	183.5	1480	69.7%	55%	3.96%	186.1	1530	71.0%
139.68	35%	2.95%	93.9	575	51.8%	77%	3.06%	281.7	2730	82.0%
139.68	35%	1.97%	94.5	580	51.9%	77%	2.00%	281.6	2750	82.6%
139.69	35%	1.04%	94.4	600	53.8%	77%	1.12%	281.6	2650	79.6%
139.69	35%	0.00%	94.7	570	50.9%	77%	0.00%	282.6	2780	83.2%
139.78	55%	0.00%	181.5	1540	71.7%	55%	0.00%	184.7	1580	72.3%
139.78	55%	Naturally vented	182.8	1520	70.3%	55%	Naturally vented	182.1	1550	71.9%

Injection Pressures

Table 4 shows the injection pressures measured on the two turbines at the various airflow rates tested. All of these data are for injection through the snorkel tube on unit 1 and the headcover location on unit 2. No data were recorded during the shakedown tests on Monday, August 9, when we attempted to inject air through the headcover of unit 1. On unit 1 the pressure was monitored using a standard 100 psi Bourdon tube-type pressure gage and a separate vacuum gage for subatmospheric pressures. On unit 2, where pressures were much lower, the pressure was monitored using a 25 psia absolute pressure transducer. On unit 1 the gage was located on a 2-inch diameter pipe, immediately upstream of our connection to the existing 1-inch piping that leads to the snorkel tube. On unit 2 the pressure transducer was installed on the 2-inch pipe and flange assembly that was bolted onto the turbine bearing housing in place of the vacuum breaker valve. All pressures are reported as gage pressures; atmospheric pressure is zero and negative values indicate subatmospheric pressures. Data collected at the higher tailwater levels are indicated in table 4. Variation of tailwater level did not have a significant effect on the injection pressures at 55 or 60 percent gate. Tailwater variation could have an effect at larger wicket gate openings.

Table 4. - Injection pressures at various airflow rates. Data shown in bold italics were collected at higher tailwater levels.

Unit 1				Unit 2			
Wicket Gate Setting	Airflow (% by volume)	Airflow (scfm)	Injection Pressure (psig)	Wicket Gate Setting	Airflow (% by volume)	Airflow (scfm)	Injection Pressure (psig)
60%	1.98%	241	39.0	60%	1.79%	220	2.6
60%	0.99%	121	11.0	60%	0.87%	107	-0.5
60%	3.73%	453	82.5	60%	4.00%	488	7.4
60%	2.94%	355	63.5	60%	2.94%	356	5.0
60%	***2.91%***	***355***	***63.5***	***60%***	***2.97%***	***356***	***5.0***
55%	0.00%	---	---	55%	5.01%	563	9.0
55%	0.00%	---	---	55%	5.79%	648	10.6
55%	0.00%	---	---	55%	3.94%	444	6.4
55%	3.59%	400	68.0	55%	3.86%	436	6.3
55%	***3.62%***	***400***	***68.0***	***55%***	***3.90%***	***433***	***6.6***
55%	***3.74%***	***412***	***77.0***	***55%***	***3.96%***	***442***	***6.7***
35%	2.95%	166	16.0	77%	3.06%	517	10.0
35%	1.97%	112	5.0	77%	2.00%	338	6.8
35%	1.04%	59	0.0	77%	1.12%	189	4.0
55%	0.00%	0	-6.1	53%	0.00%	0	-6.6

Shaft Runout and Bearing Temperatures

Shaft runouts were measured using paired proximity probes mounted at the turbine guide bearing on each unit. Signals were recorded with and without air injection into the units. Spectral analysis showed the majority of shaft runout was associated with the rotational frequency of the unit. There was a small zone of rough operation between 40 and 50 percent wicket gate opening. Spectral analysis of these signals showed some component of runout occurring at about 25-30 percent of the shaft speed of the unit. This is indicative of typical part-load draft tube surging. There were no significant changes in the shaft runout with air injection.

Bearing temperatures were monitored throughout the testing on the various gages and indicators present in the powerhouse. Temperature changes were generally less than about 5°F and seemed closely related to ambient temperature changes. There were no indications that air injection was affecting bearing performance or bearing life.

ANALYSIS AND DISCUSSION OF TEST RESULTS

DO Enhancement Data

For each of the data points shown in table 2, aeration efficiency and mass percentages of oxygen dissolved were calculated. The aeration efficiency is the ratio of the DO increase to the initial deficit from saturation. This parameter provides a measure of the effectiveness of turbine aeration independent of the oxygen deficit at the time of the test. Mathematically the aeration efficiency is expressed as:

$$E=\frac{C_d-C_o}{C_s-C_o}$$

where: E = aeration efficiency
C_o = incoming DO concentration, mg/L
C_d = downstream DO concentration, mg/L
C_s = saturation DO concentration at water surface, mg/L

The saturation DO concentration is a function of temperature and pressure, and was about 9 mg/L for these tests. The aeration efficiency is related to the deficit ratio, r, another commonly used parameter for analyzing gas transfer.

$$E=1-\frac{1}{r}$$

$$r=\frac{C_s-C_o}{C_s-C_d}$$

The mass percentage of oxygen dissolved was calculated as:

$$M=\frac{(C_d-C_o)Q\gamma}{\frac{f_{O_2}}{60}\dot{V}(\rho_{STP})}$$

where: M = mass percentage of oxygen dissolved
Q = water discharge, ft^3/s
γ = unit weight of water = 62.4 lb/ft^3
V = volume flowrate of air, scfm
ρ_{STP} = density of air at standard temperature and pressure = 0.0765 lb/ft^3
f_{O_2} = mass fraction of oxygen in atmospheric air = 0.2314

The mass fraction of atmospheric oxygen is calculated as the molecular fraction, 20.95 percent, multiplied by the ratio of the molecular weights of oxygen and air (32.000/28.966).

Calculations of aeration efficiency and mass percentage of oxygen dissolved were made for flows through individual turbines, where DO measurements were made at the 2W/2E locations, and for combined total powerplant flows, using the DO measurements at the 3W/3C/3E and DO-RIVER locations. The DO-DAM measurements were used for the incoming DO concentration in all calculations.

Both parameters were plotted against the volume percentage of injected air. Figure 3 shows all of the data with linear regressions and 95 percent confidence limits for different data sets. The data

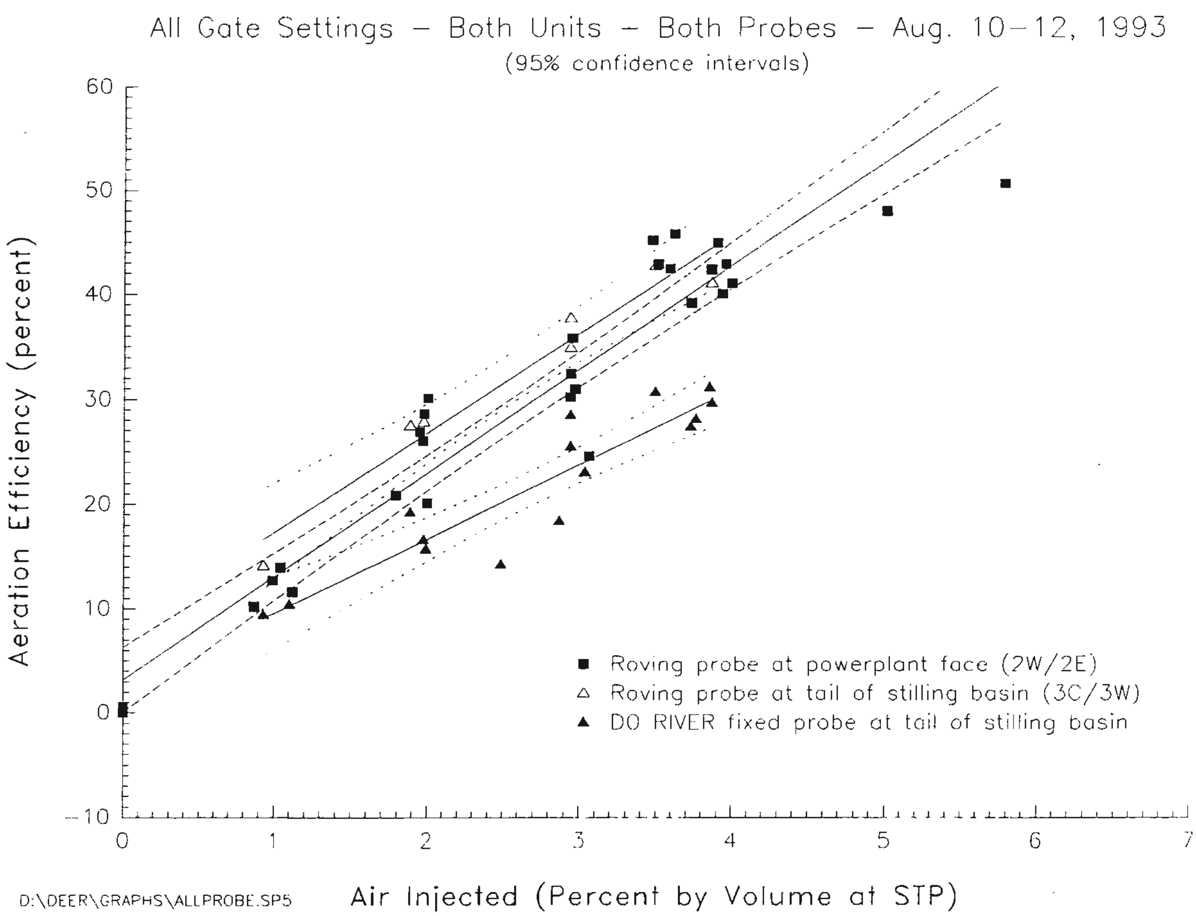

Figure 3. - Aeration efficiency data plotted against airflow rate. Linear regressions and 95 percent confidence intervals are shown.

collected from the portable probes used at the powerplant face (2W/2E) and the downstream end of the tailrace (3W/3C/3E) compare very closely, and show about a 10 percent increase in aeration efficiency for each 1 percent air injected. The data collected from the DO-RIVER location are also shown, but as explained before, the DO concentrations measured with this probe were artificially low due to the lack of adequate flow past the probe.

Figure 4 shows only the data collected at 55 and 60 percent wicket gate openings. These data are for DO measurements made at the powerplant face where the DO uptake through each unit could be determined separately. The figure shows slightly higher aeration efficiencies for unit 1, where air was injected through the snorkel tube, but the difference is not judged to be significant. Both units again show about a 10 percent increase in aeration efficiency for each 1 percent air injected, especially for airflow rates of 4 percent or less. The two data points at higher airflow rates suggest that increases in aeration efficiency are not as great when the airflow exceeds 4 percent. This may be partially due to the boiling action and loss of air discussed previously.

Figure 5 shows aeration efficiencies for the tests with unbalanced powerplant operation. Unit 1 was operated at 35 percent wicket gate opening and unit 2 was operated at 77 percent gate. Aeration efficiencies for unit 1 are significantly higher than those for unit 2, especially at the higher airflow rates. The linear regressions indicate a 12 percent increase in aeration efficiency for each 1 percent

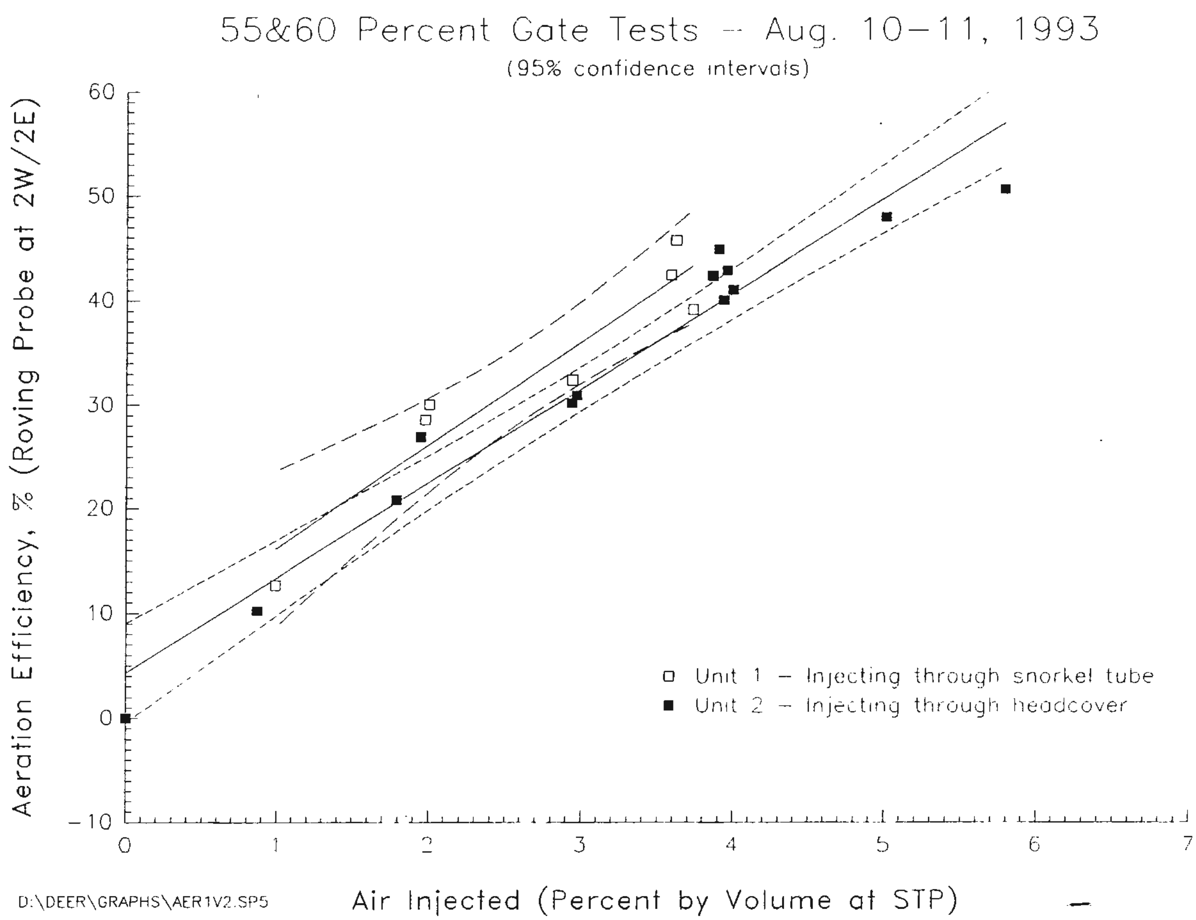

Figure 4. - Aeration efficiency versus airflow rate for 55 and 60 percent wicket gate settings.

injected air through unit 1, but only an 8 percent increase for each 1 percent air injected through unit 2. There are several possible explanations for this behavior. The most likely explanation is that the discharge through unit 2 was about 3 times the discharge through unit 1 (270 ft^3/s versus 90 ft^3/s). Thus, the travel time from the runner to the tailrace is about 3 times longer in unit 1. This provides greater contact time between the injected air and the flowing water and should lead to increased gas transfer through unit 1. A second possible influence is the difference in the flow behavior within the two draft tubes. Unit 2 was operating at close to its design operating condition. Thus, the flow exiting the runner of unit 2 was approximately axial. Unit 1, however, was operating at part-load, far from its design operating point. Francis turbines operating in this range produce strongly swirling flow exiting the turbine runner. This produces unstable flow in the draft tube that forms a corkscrew-shaped helical vortex. This is commonly known as draft tube surging, or the *rough zone*. Air injected into the turbine in this condition might be more effectively mixed with the flowing water. The vortex might also shear the air bubbles into smaller sizes, greatly increasing their surface area. This would lead to increased gas transfer.

Figure 6 shows all of the aeration efficiencies calculated from the portable probe data. This includes aeration efficiencies for the individual turbines and for the powerplant as a whole. Below a 4 percent airflow rate, the aeration efficiencies increase about 10 to 11 percent for each 1 percent additional air injected. The data are sparse above 4 percent, but suggest that aeration efficiency increases are lower.

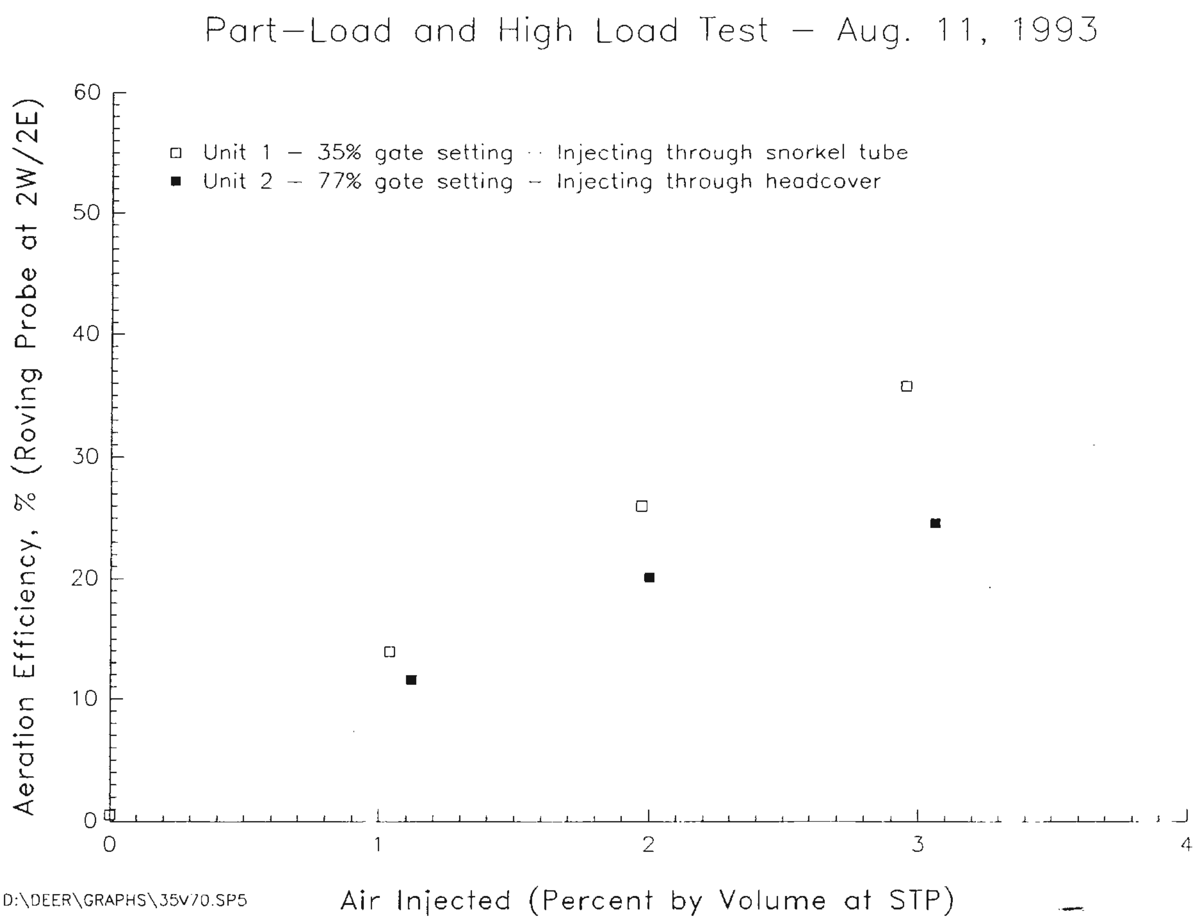

Figure 5. - Aeration efficiency versus airflow rate at 35 and 77 percent wicket gate settings.

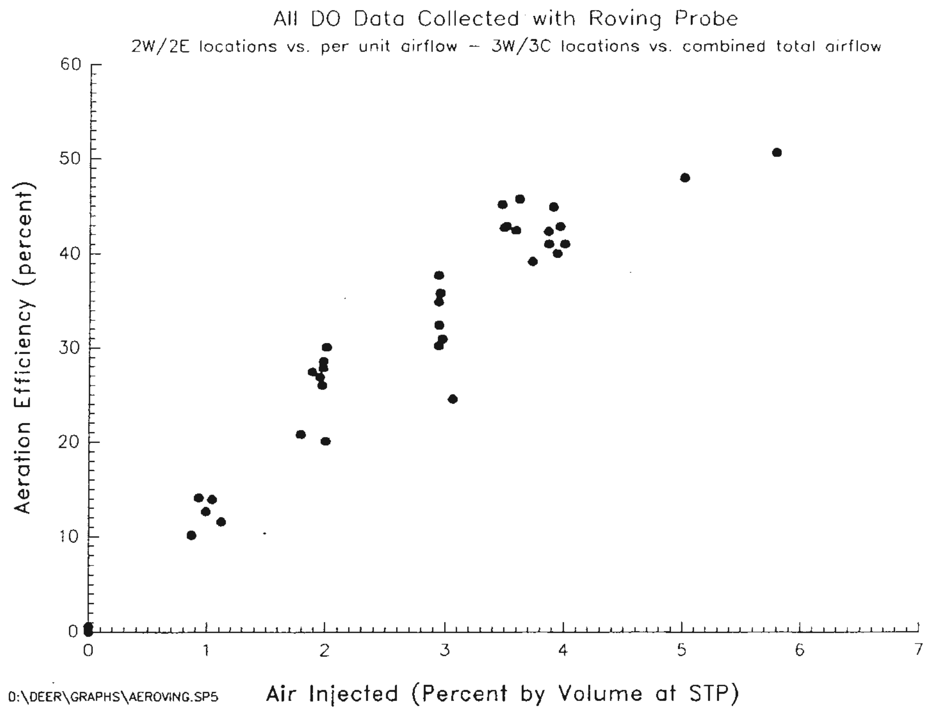

Figure 6. - Summary of all aeration efficiency data computed from measurements made with the portable DO probes.

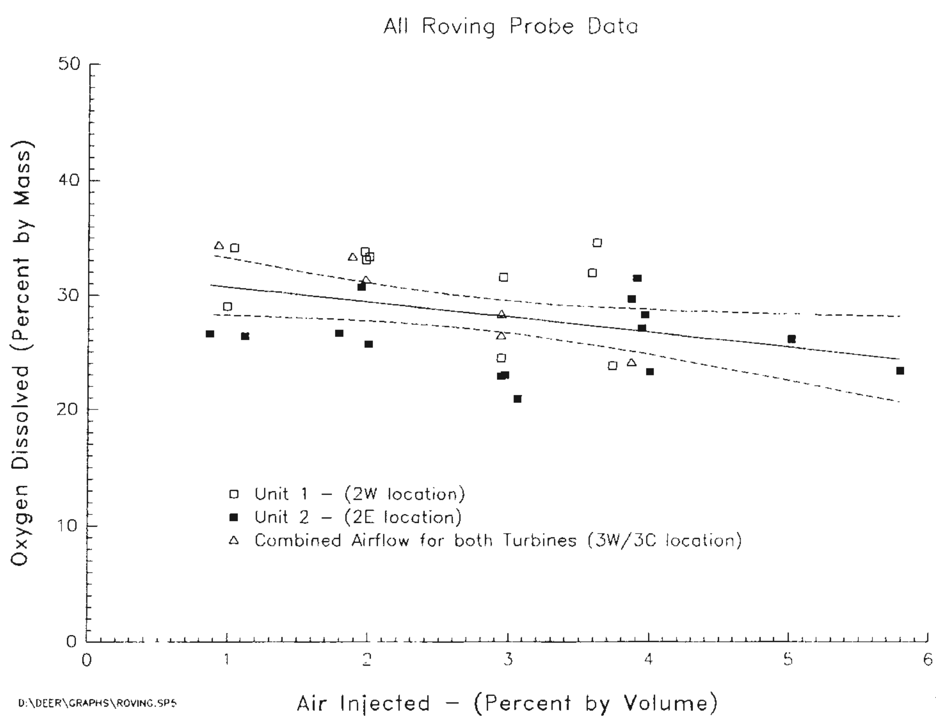

Figure 7. - Mass percentage of injected oxygen taken into solution versus airflow rate.

The second method of evaluating the gas transfer accomplished is the use of the mass percentage dissolved (*M*) parameter defined previously. This parameter is not independent of the initial oxygen deficit, but it does provide a sense of the efficiency of the gas transfer process taking place in the turbine. Higher incoming DO concentrations will yield a reduced mass percentage of oxygen dissolved. Figure 7 shows that approximately 25 to 30 percent of the oxygen injected into the turbines was taken into solution, with the percentage decreasing slightly as the airflow rate was increased. This confirms that over the range of airflow rates tested, increased air injection yields nearly linear increases in downstream DO concentration.

The data were also analyzed to determine the influence of the 3-ft higher tailwater level tested on Wednesday, August 11. The higher tailwater level did not have any significant effect on the aeration efficiency. During this test, we also measured the DO uptake achieved across the tailrace gate control structure with a 3-ft drop. This was done without turbine aeration. Although there appeared to be good air entrainment below the gate structure (the bubble plume was similar to that observed with turbine aeration), the DO increased from 1.21 mg/L in the tailrace to only 2.70 mg/L downstream of the gate structure. The saturation concentration at the time was about 9.05 mg/L. The aeration efficiency across the gate structure was about 19 percent.

Turbine Efficiency

Combined turbine and generator efficiency data were collected at various airflow rates for turbine operations at 35, 55, 60, and 77 percent wicket gate settings. Assuming that generator efficiency was not affected by the air injection tests, changes in combined efficiency can be attributed solely to changes in the turbine efficiency. For similar operating conditions, the efficiency of unit 2 was generally about 2-2.5 percent higher than unit 1. As an example, figure 8 shows the efficiencies of both units at the 60 percent wicket gate setting.

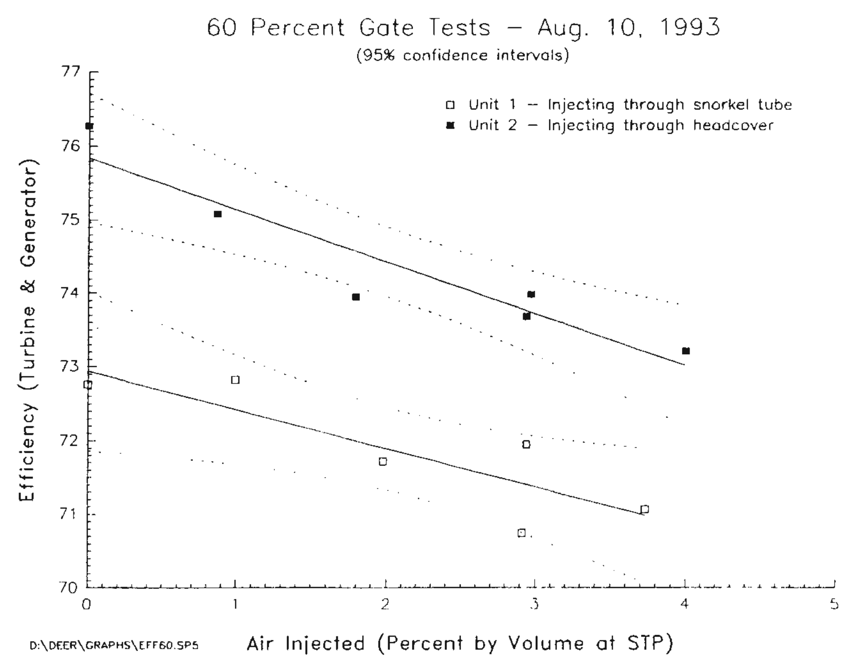

Figure 8. - Combined turbine and generator efficiency at 60 percent wicket gate setting, as a function of injected air. Efficiency losses on unit 1 and 2 were about 0.53 and 0.71 percent, respectively, for each 1 percent injected air.

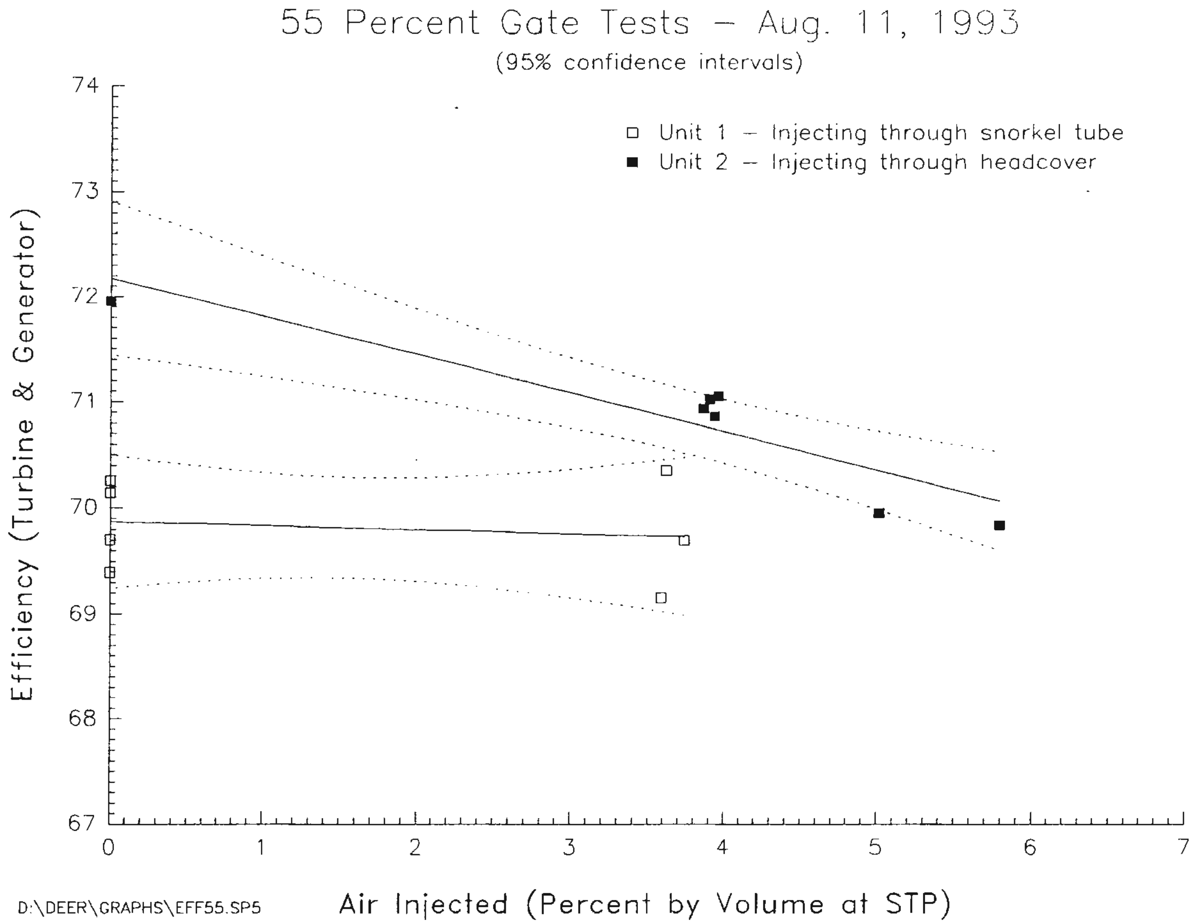

Figure 9. - Efficiency versus airflow rate at the 55 percent wicket gate setting. Unit 1 shows no significant change in efficiency, while unit 2 experienced efficiency losses of about 0.36 percent for each percent of injected air.

At the 55 percent wicket gate setting used for testing on Wednesday August 11, the efficiency data were less conclusive. Figure 9 shows the unit efficiencies at airflow rates up to 5.8 percent. Efficiency losses on unit 2 were about 0.36 percent for each percent of injected air. However, the scattered data collected for unit 1 do not show any significant trend in efficiency related to airflow rate.

To make an effective comparison between efficiency data collected from the two different units and at different gate positions, an efficiency loss compared to the zero airflow condition was computed for each test point. Figure 10 shows these efficiency losses plotted against the airflow rate for the 55 and 60 percent wicket gate settings. Data for the 35 and 77 percent wicket gate settings were not included because those operating conditions were judged to be significantly different from the 55 and 60 percent gate settings. There is considerable scatter in the data on figure 10, probably due to our inability to accurately measure the generator output. The kilowatt gages in the powerplant control room were difficult to read due to fluctuation of the needles. A linear regression on the data shown in figure 10 indicates about 0.32 percent efficiency loss for each additional percent of injected air.

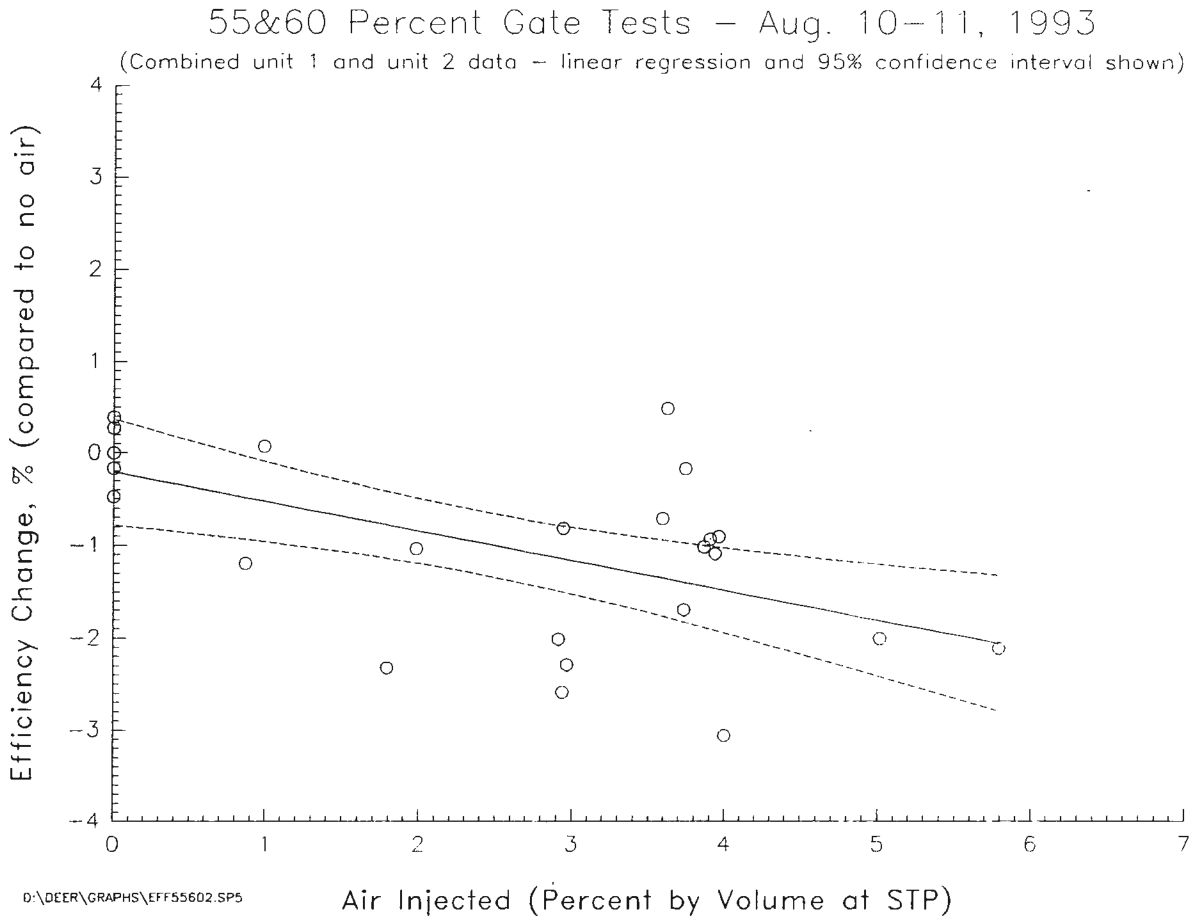

Figure 10. - Efficiency changes as a function of injected air, at 55 and 60 percent wicket gate settings. Efficiency loss is about 0.32 percent for each 1 percent injected air.

The few data points collected at 35 and 77 percent wicket gate settings were not sufficient to draw any definite conclusions. At 77 percent gate the injection of 1 percent air into unit 2 produced an efficiency loss of over 3.5 percent. However, airflow rates of 2 and 3 percent produced efficiency losses of only 0.6 and 1.2 percent, respectively.

Unit 1 operating at 35 percent gate experienced efficiency increases at all airflow rates. A 1 percent airflow rate produced an efficiency increase of nearly 3 percent, while airflow rates of 2 and 3 percent only increased efficiency about 1 percent. Although these data are sketchy, the general trend was expected. The part-load draft tube surge, or rough zone, described earlier typically produces surging flow in the draft tube that leads to efficiency losses. Air injection tends to break up the surging flow and produce efficiency increases in many cases. The reservoir head during our tests was near maximum, which limits the extent and severity of the rough zone. However, at lower reservoir levels the rough zone is usually larger and more severe. Thus, during drought years turbine aeration may be desirable for its efficiency benefits over a wide range of wicket gate settings.

To summarize, efficiency losses in the range of normal powerplant operations were between 0.3 and 0.7 percent for each 1 percent air injected. At low load conditions aeration may increase turbine efficiency.

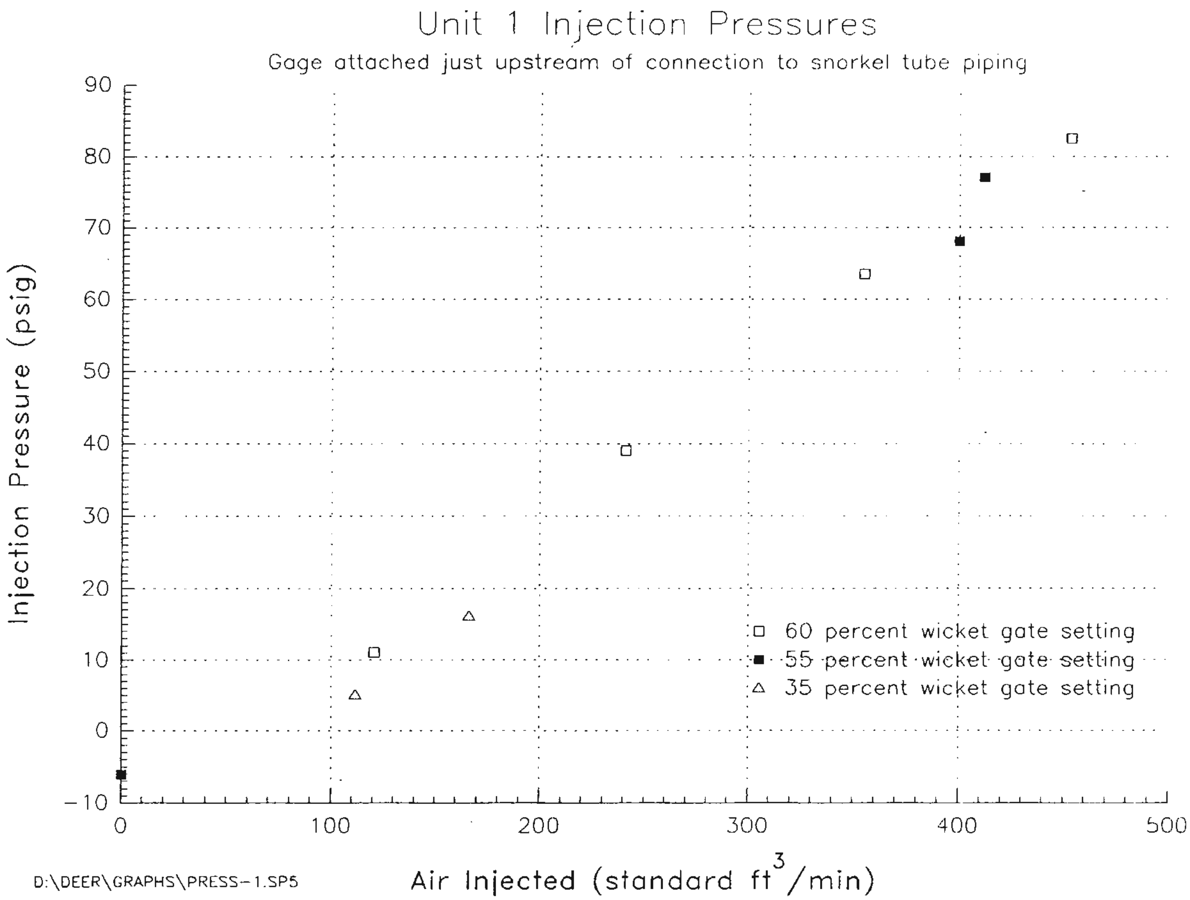

Figure 11. - Injection pressures for unit 1, measured just upstream of the connection to the snorkel tube piping.

Injection Pressures

To determine the type and size of blower or compressor required to implement turbine aeration on a permanent basis, air pressures were measured just upstream of our connection points to the turbine piping. Figures 11 and 12 show the injection pressures measured on units 1 and 2, respectively. The pressures shown are referenced to the local atmospheric pressure.

Injection pressures required for the snorkel tube location on unit 1 were quite high. The highest airflow rate we achieved during the tests was about 450 scfm, and required an injection pressure of over 80 psi. To supply 4 percent air at the maximum turbine discharge would require 720 scfm of air. Thus, if this location were chosen for a permanent air injection installation, a compressor with a much higher maximum pressure capacity than that used for this test would be required. Extrapolating from the data collected in these tests, a pressure of about 150 psi would be required at a flowrate of 720 scfm. This is probably not feasible.

The injection pressures required for the headcover location on unit 2 were much more reasonable. The 55 and 60 percent wicket gate tests produced similar results; an injection pressure of 10 psi produced airflows of just over 600 scfm. At 77 percent gate the pressures required were slightly

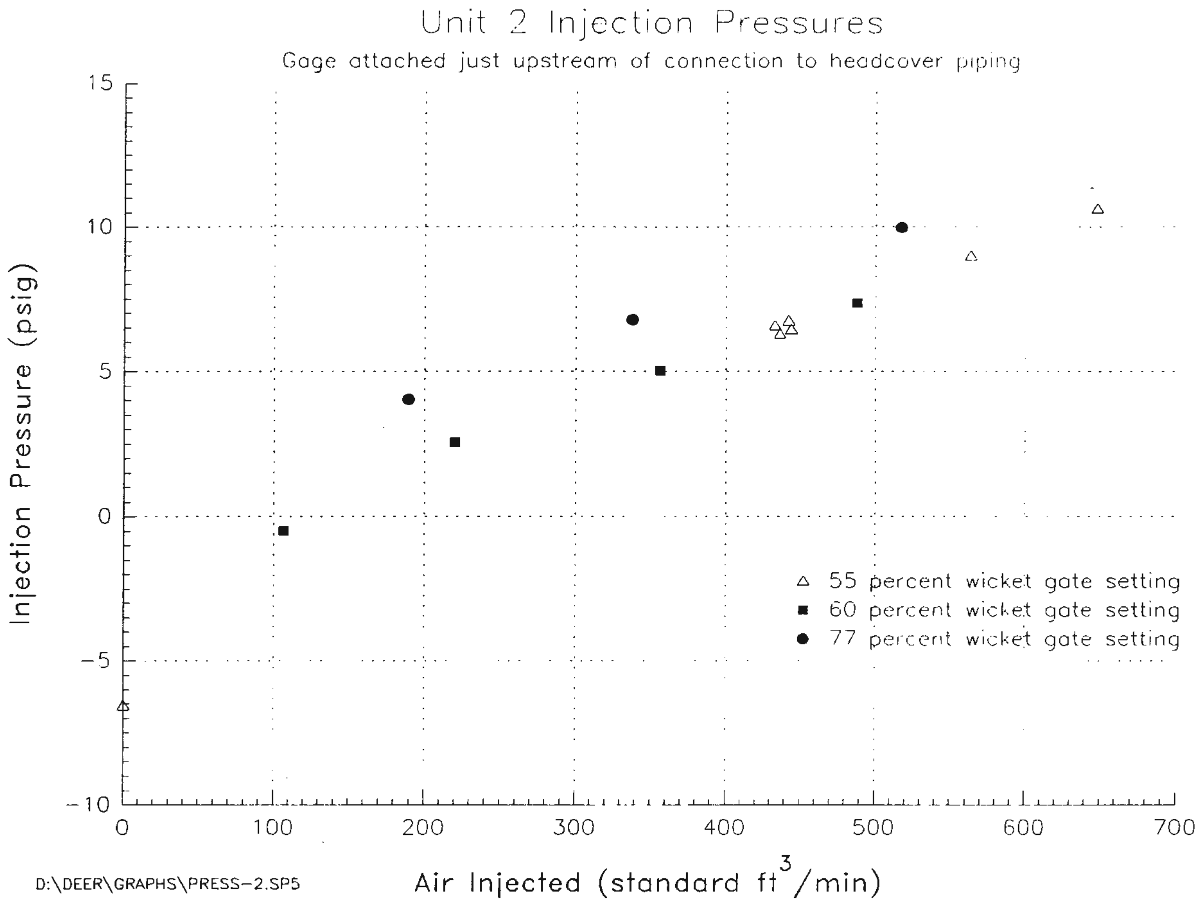

Figure 12. - Injection pressures for unit 2, measured just upstream of the connection of air supply piping to the 2-inch line leading to the headcover.

higher, with 10 psi producing an airflow of 520 scfm. Typical axial flow blowers operate in the range of 10-20 psi. Extrapolating from the data collected in these tests, 720 scfm could be supplied by a blower and piping combination that provides 12-14 psi at the connection to the vacuum breaker port (the connection point used for these tests). Operation above 77 percent gate will probably require slightly higher pressures. We were unable to provide 720 scfm for these tests because the compressors used were better suited to high pressures than high flowrates.

The pressure data collected show that an axial flow blower would be suitable for a permanent installation. These blowers are typically sized to provide a maximum pressure of 10-20 psi, and for a given airflow rate, have much lower capital and operating costs than a high pressure compressor.

DISCUSSION OF AERATION ALTERNATIVES

Turbine Aeration

Turbine aeration could be readily implemented at Deer Creek Powerplant, in a manner similar to that used for these tests. The best route for injecting air is through the headcover. This requires the removal of the vacuum breaker. Air injected into the units would serve the same purpose that the vacuum breaker originally served (admitting air to the headcover at wicket gate settings below 5 percent open). The tests showed that air injection should not produce any harmful vibrations that could affect the wear of bearings or seals.

Other locations originally considered for air injection were the snorkel tube and the draft tube mandoor (using an air slot constructed around the throat of the draft tube). These tests showed that the snorkel tube was not large enough for the airflow rates required. To inject air through the draft tube mandoor, extensive modifications would be required. There would not be any particular advantage to injecting through the mandoor.

The injection pressures measured in this test showed that air could be injected through the headcover route using a low pressure blower, rather than the large compressors used for the test. Two inquiries in the Denver area indicated that a 15 psi, 750 scfm blower and motor system (blower, 100 hp motor, belt drive, and inlet filter) would cost $10,000-$17,000. Such a system could provide 4 percent airflow rates even with the turbines operating a full load. A 10 psi, 750 scfm system would cost about $6,000-$7,000, but would only provide 2.9 percent airflow when the turbines are operating at full load. Flowmeters to measure and set the proper airflow rates would cost about $1,000. The total capital cost to install a 15 psi turbine aeration system on both units would be roughly $20,000-$35,000.

The tests also showed that some DO enhancement could be obtained simply through natural aspiration of the turbines at partial wicket gate openings. To implement this option the vacuum breaker could be removed or blocked open, allowing air to be drawn in through the headcover. Tests done at a 55 percent wicket gate setting on unit 2 showed that natural aspiration produced an aeration efficiency of 22 percent, comparable to the effect of manipulating the tailrace gate control structure. The efficiency loss for unit 2 was 0.4 percent when naturally aspirated. The airflow rate was not measured, but was probably about 2 percent, or 250 scfm, based on the aeration achieved. As discussed earlier, the amount of air naturally drawn into the units should vary with tailwater elevation and wicket gate setting. As the tailwater level is raised or the wicket gates are opened further, the airflow will probably be reduced. Also, as the wicket gate opening is increased, water discharged through the turbines increases, thus reducing the percentage flowrate of air. Additional tests would be required to determine the amount of air that could be drawn in naturally at various gate settings. An estimate of airflow rates could be made if the vacuum pressure were measured on the downstream side of the vacuum breaker valve for a range of wicket gate settings.

One disadvantage of turbine aeration (or any option that achieves aeration using atmospheric air) is the possibility for nitrogen supersaturation in the tailrace. Dissolved nitrogen is not necessarily depleted in the incoming water, and when air is discharged deep into the tailrace, dissolved nitrogen concentrations will rise (there is still a deficit to drive the nitrogen transfer because the saturation concentration increases with pressure and is higher at the bottom of the tailrace). Dissolved nitrogen concentrations were not measured during these tests.

Manipulation of Tailrace Gate Control Structure

The tests performed on the gate structure at the downstream end of the tailrace showed that a 3 ft drop over the gate control structure produced only a 19 percent aeration efficiency compared to aeration efficiencies of about 40 percent with 4 percent air injected into the turbines. Power losses for this option are directly related to the loss of head, and would be 2.5 percent at the powerplant's rated head of 120 ft. The significant advantages of this option are the absence of capital costs and the straightforward implementation.

This option could also be combined with turbine aeration, using injected air or natural aspiration. If these alternatives are combined, further testing as described above should be done to determine the amounts of air that could be naturally aspirated at large wicket gate settings and with higher tailwater conditions.

Oxygen Injection into Penstock

Oxygen injection into the penstock has not yet been tested at this site. However, the Tennessee Valley Authority (TVA) is presently testing an oxygen injection system at their Tim's Ford Powerplant, with promising results. The system injects molecular oxygen into the penstock several hundred feet upstream of the powerplant using garden-type soaker hoses attached to the floor of the penstock. This produces very fine oxygen bubbles that are readily dissolved as the flow travels down the penstock. Typically about 90 percent of the injected oxygen is taken into solution. A likely location for injecting oxygen at Deer Creek Powerplant would be in the penstocks just downstream of the slide gates in the interior of the dam. This location is about 650 ft upstream of the powerhouse.

Capital costs for this type of system are large. The system requires storage tanks, vaporizers, and flow metering equipment to store and dispense the oxygen, which is transported to the site and stored in liquid form. Typical capital costs incurred by TVA have been about $100,000. In addition, oxygen costs are significant, but can be reasonably estimated in advance (see table 5). There are no significant efficiency losses for this type of system because only a small percentage of the injected oxygen is still in gaseous form when it reaches the powerplant. Another advantage is that there is no possibility of producing nitrogen supersaturation.

Aeration Weirs

A variety of aeration weirs could be constructed in the river downstream of the powerplant. Alternatives include simple straight weirs with low drop heights or complex labyrinth weirs that reduce the unit discharge to maximize aeration efficiency. Costs for construction will vary widely depending on site conditions and the type of weir. There are conflicting objectives in locating weirs along the river reach, with a need to improve DO concentrations as far upstream as possible, while minimizing the effect of raised river levels on power generation. Weir heights should also be kept relatively low in the interest of recreational safety and minimizing the impact on fish movements in the river. The aeration performance will decrease as the drop height is reduced. Aeration performance will also vary as a function of discharge, with more aeration as the discharge is reduced.

Given the heavy recreational use of the Provo River, a straight, low-drop structure would probably be most appropriate. To obtain a rough estimate of the number of weirs required, the data of Avery and Novak (1978) were used to estimate the aeration efficiency of such a structure in the Provo River. The weir crest length was assumed to be 75 ft and the river discharge was assumed to be 600 ft^3/s. The drop-heights were limited to 0.5 meters (1.64 ft). The aeration efficiency of a single weir based on these assumptions would be about 8 percent. With this efficiency, a series of 3 weirs would raise the DO concentration from 2 to 3.6 mg/L (similar to the 20 percent aeration efficiency achieved with 2 percent airflow into the turbines). To match the performance of a 4 percent airflow rate into the turbines, 6 weirs would be required. This would raise DO concentrations from 2.0 to 4.8 mg/L.

Diffusers in Tailrace

Diffusers could be used to inject air or oxygen into the tailrace. Air compressor/blower requirements would probably be greater than for the turbine aeration option due to the higher static pressure at the bottom of the tailrace (static pressure on the headcover injection location was subatmospheric). Air volumes required would probably be as large or larger than for the turbine aeration option. A significant disadvantage of this alternative would be the possibility of the diffusers being damaged each time the tube valve bypass operates at the powerplant.

Cost Summary

A summary of the estimated capital and operating costs of the turbine aeration, gate manipulation, penstock oxygen injection, and aeration weir options is given in table 5. The capital costs are comparative only; they are based on price quotes for obtaining the required mechanical equipment in Denver, or on TVA experience with typical penstock oxygen injection systems. Actual installation costs of the system and supporting equipment or structures at the powerplant are not included. The operating costs are calculated for 20 and 40 percent aeration efficiencies, assuming an initial DO concentration of 2.0 mg/L and saturation concentration of 9.0 mg/L. This yields final DO concentrations of 3.4 mg/L and 4.8 mg/L, respectively. Other assumptions used for these calculations are:

All options

- Rated power output of 2475 kW per generating unit
- Rated head of 120 ft
- Discharges of 300 ft^3/s per turbine (implies combined generator and turbine efficiency of 81 percent)
- Power value and power costs of 6¢/kWh

Turbine aeration option

- 2% air injection (360 scfm) to achieve 20% aeration efficiency
- 4% air injection (720 scfm) to achieve 40% aeration efficiency
- 1.0% efficiency loss with 2% air injection
- 2.0% efficiency loss with 4% air injection
- Power required to run blowers is proportional to flowrate and injection pressure and is 100 hp at 750 scfm, 15 psi. This yields 80 hp for 720 scfm and 21 hp for 360 scfm.

Gate manipulation option

- Tailwater raised 3 ft to produce 20 percent aeration efficiency (actual aeration efficiency was 19 percent)

Penstock oxygen injection

- 90 percent of injected oxygen is absorbed by water
- Oxygen costing \$80/ton (typically \$60-\$100/ton)
- No efficiency losses

Table 5. - Summary of comparative estimated costs for DO enhancement options.

Alternative	Initial Capital Cost ($)	Operational Costs ($/month)	Lost Power Revenue ($/month)	Total Operational Costs and Lost Revenue ($/month)
20% Aeration Efficiency				
Turbine aeration (system also capable of providing 40% efficiency)	**$20K-$30K**	$1,376	$2,174	**$3,550**
Gate manipulation	**$0**	$0	$5,435	**$5,435**
Penstock oxygen	**up to $100K**	$6,139	$0	**$6,139**
Aeration weirs	**3 weirs, unknown cost**	$0	$0 if weirs sited far enough downstream	**$0 if far enough downstream**
40% Aeration Efficiency				
Turbine aeration	**$20K-$30K**	$5,242	$4,348	**$9,590**
Gate manipulation	**$0**	---------- Not feasible ----------		
Penstock oxygen	**up to $100K**	$12,278	$0	**$12,278**
Aeration weirs	**6 weirs, unknown cost**	$0	$0 if far enough downstream	**$0 if far enough downstream**

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