Testing of the DWR Aeration Facility Efficiency and Capacity

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Contents

Page

Figures and Tables

Acronyms and Abbreviations

Aeration Facility	Stockton Deep Water Ship Channel Demonstration Dissolved Oxygen Aeration Facility
cfs	cubic feet per second
DO	dissolved oxygen
DWR	California Department of Water Resources
DWSC	Deep Water Ship Channel
ft/sec	feet per second
hr	hour
lbs O_2 /day	pounds oxygen per day
mg/l	milligrams/liter
O_2	oxygen
%	percent
psi	pounds per square inch
RRI	Rough and Ready Island
scf	standard cubic feet

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Summary

Initial testing of the California Department of Water Resources (DWR) Stockton Deep Water Ship Channel Demonstration Dissolved Oxygen Aeration Facility (Aeration Facility) was performed in March 2008 (ICF Jones & Stokes 2008). The initial testing is summarized in the report titled “Initial Testing of Aeration Facility Capacity and Efficiency, August 2008”. Additional testing was conducted periodically during the first year of pilot demonstration operations from May through September 2008. The testing was done to evaluate the oxygen gas transfer efficiency in the U-tubes. A higher efficiency would allow more dissolved oxygen (DO) to be delivered to the Deep Water Ship Channel (DWSC) and would reduce the expense of the liquid oxygen supply.

Initial test results showed that the best measured oxygen delivery capacity at full water flow of about 45 cfs with an oxygen gas supply to water flow (gas/water) volume ratio of about 4% (i.e., 6,480 standard cubic feet per hr [scfh]) was about 8,000 pounds per day (lbs/day). This was less than the design capacity of 10,000 lbs/day. The facility full water flow was less than the design flow of 50 cubic feet per second (cfs). The measured DO concentration range in the facility U-tube discharges was about 41 to 43 milligrams/liter (mg/l). The inflow DO from the DWSC was about 9 mg/l; therefore, the DO increment added at the full water flow of about 45 cfs (~22.5 cfs in each U-tube) was about 32 to 34 mg/l. The initial oxygen transfer efficiency of the facility U-tubes therefore was about 60% at a gas/water ratio of 4%. Changes in the U-tube gas injection apparatus (sparger) that might allow more oxygen gas or smaller bubbles to be injected were considered, and several were implemented during the pilot demonstration operations of the Aeration Facility from May through September 2008. These modifications and the testing results are described in this report.
The gas transfer efficiency testing included different sparger designs, with more holes, and with smaller holes, to provide a greater area for bubble formation. This increase in area reduced the exit velocity of the oxygen gas from the sparger into the water flow in the U-tube. The reduced exit velocity was expected to allow smaller bubbles to form in the U-tube. A sparger also was designed and constructed to allow 120 feet of aeration hose to hang in the U-tube. This dramatically increased the area for bubble formation. Changes also were made to allow the gas pressure at the sparger to be reduced. This was expected to allow smaller bubbles to form, by reducing the “expansion” of the gas as it exited the

sparger into the water, where the pressure was about 10 pounds per square inch [psi]. However, no significant changes in gas transfer efficiencies were observed from any of these changes in the sparger or the gas pressure. The only changes in efficiencies were associated with changes in the gas/water ratio. The gas transfer efficiency was very high (100%) at a gas/water ratio of 1% and declined as the gas/water ratio was increased. The efficiency was reduced to about 50% at a gas/water ratio of 6%. The explanation for these efficiency results is not fully understood, but the measured efficiency and capacity of the Aeration Facility for a range of gas/water ratios are well described. The operation of the Aeration Facility can be planned and managed effectively using the results summarized in Table 2.

Introduction

The Aeration Facility is located at Dock 20 of the Port of Stockton West Complex near the western end of Rough and Ready Island (RRI) in the DWSC. The Aeration Facility design followed the basis of design prepared by HDR Engineering and Jones & Stokes (now ICF Jones & Stokes) in 2004 (HDR Engineering 2004). The Aeration Facility includes two 200-foot-deep concentric U-tubes (i.e., a 20-inch-diameter pipe within a 30-inch-diameter pipe), allowing oxygen to be dissolved or transferred into water that is pumped from the DWSC. The oxygen is injected as gas bubbles at the top of the down-flow U-tubes (tubes A and B), and the gas bubbles are dissolved under relatively high hydrostatic pressure (maximum of 7.25 atmospheres, 100 psi at the bottom of the U-tubes). This design was based on the description and field test results of two similar U-tubes located at paper pulp mills along the Tombigbee River in Alabama (Speece 1996).

This report presents a summary of the testing procedures, measurements, and the estimated oxygen transfer efficiency for various operating conditions tested in March 2008 and periodically during the first year of pilot demonstration operations from May through September of 2008. The Aeration Facility was operated with a “pulsed” strategy (i.e., operated for 4–10 days and turned off for 3–10 days). The shut-off periods were used to identify the DO conditions in the DWSC without the effects of the Aeration Facility, so the effectiveness of the Aeration Facility for increasing the DO concentrations in the DWSC could be evaluated.

Field Testing Procedures

The goal of this testing was to measure the increase in DO concentration from the inlet to the outlet of the U-tubes under normal operation of the Aeration Facility and to calculate the gas transfer efficiency and the DO delivery capacity. Various gas sparger designs were tested for a range of gas/water ratios. The basic steps were to:

1. Operate one or both pumps to provide maximum flow (25 cfs for one, 45 cfs for both) to the U-tube.
2. Add oxygen gas at a selected gas/water volume ratio of between 1% and 6%.
3. Measure the change in DO concentration between the U-tube inlet and outlet.
4. Calculate the gas transfer efficiency for the U-tube and the delivery capacity for the Aeration Facility.

Field Measurements

Two YSI-6600 DO sondes (sensor probes) were installed by the University of the Pacific (UOP) to measure the outlet DO in each U-tube. The inlet DO was estimated from the nearby DWR RRI monitoring station surface sensor or from the YSI probes in the U-tubes when the oxygen gas was shut off. The YSI sensors were calibrated and placed in the flow-through cells and connected with hoses from the outlet ports on each U-tube. Water samples were collected from the outlet ports by UOP for modified Winkler titrations to verify and adjust the DO sensor measurements. All of the test results rely on single “point measurements” with inflow and outflow DO determined with modified Winkler titrations. The continuous DO probes for the inlet and outlet of the U-tubes have not yet been installed at the Aeration Facility. The gas flow rates are determined by visual readings from the gas-flow meters, and the water flow rates are determined by visual reading of the water-flow meters. Because these measurements have some variability, there is some uncertainty in the DO increment, the water flow, the gas supply, and the resulting estimates of gas transfer efficiency and DO delivery capacity. However, measurements of similar conditions yielded efficiencies that are within 5% of each other (See Figure 2).

Test Conditions

Initial testing on March 13 and 18, 2008 used the original 10-hole sparger in both U-tubes, with a range of gas supply rates. The original sparger, constructed by BOC, consisted of a ¾”-inch-inside-diameter stainless steel tubing with ten 1/8-inch-diameter holes placed in two rows with 2-inch spacing across the pipe (with a 90° angle between the rows), that extended across the middle 8 inches of the 20-inch-diameter inner U-tube. Full water flow with a 4% gas/water supply ratio was the assumed full capacity design conditions. Reduced gas supply rates of 3% and 2% also were tested. An increased gas supply ratio of 5% could not be achieved (limited gas delivery capacity) without reducing the water flow. When the water flow was reduced to about half (11 cfs in each U-tube), the water pressure in the U-tube was increased to about 25 psi and the maximum gas supply rate was reduced. The gas supply rate was adjusted to 4%, but the test results indicated a very low efficiency (30%), which may indicate that the gas supply rate was less than indicated by the meter. A reduced water flow was expected to increase the transfer efficiency because the travel time in the U-tube would be increased.

Testing on May 22 and May 28, 2008 was conducted at full water flow rates to compare the gas transfer efficiency for a variety of sparger designs. The gas supply rate was about 3,600 scf/hr or about 1 cfs of gas into each U-tube (with 22.5 cfs of water flow). This represents a gas/water volume ratio of 4.4%, which is about the design ratio for the facility. The goal of the testing was to compare different numbers (area) and sizes of holes for the sparger. The original sparger with ten 1/8-inch holes would require a gas exist velocity of about 1,000 feet per second (ft/sec), assuming the gas is about at atmospheric pressure at the sparger. It was thought that this exit velocity was too high and would tend to form large bubbles once broken off from the sparger by the water velocity of about 10 ft/sec. Before the testing could begin, the pump controls for U-tube A malfunctioned and the pump was not operational for the remainder of the month. Testing was conducted with just U-tube B. The single pump provided a maximum water flow of 25 cfs because there was less head loss through the U-tube and diffuser pipeline. The gas supply rate was adjusted to 4% and 3% for testing on May 22.

Testing of the alternative sparger holes in U-tube B continued on May 28, 2008. A second sparger design increased the number of holes to 40, with ten 1/8-inch holes in four rows around the sparger pipe. This reduced the gas exit velocity to about 300 ft/sec. The third sparger design used 160 1/16-inch holes to retain the 300 ft/sec gas exit velocity but potentially allow smaller bubbles to be formed with the smaller holes. A fourth sparger design used the open end of the ¾-inch-inside-diameter stainless steel pipe. The open-ended pipe gas exit area was similar to the area of the 40-hole sparger and 160-hole sparger.

A fifth sparger design was tested on July 7, 2008. This design used four 30-foot-long sections of Colorite Aeration Tubing (also known as Aerotube)identical to that used at the Port of Stockton oxygen gas bubbler system at Dock 13. The outside diameter of the hose is 1 inch and the inside diameter is 0.5 inches. . The optimal air flow, as stated by the manufacturer, is 0.4 cfm. The bubbles form at “pores” on the surface of the hose, which has an estimated porosity of about 20%. The circumference is about 2.35 inches, so there is about 0.5 in^2 of holes for each inch of hose (0.04 ft^2 per foot of hose). Therefore, the gas exit velocity is likely much less than with the drilled holes in the sparger pipe and was estimated to be only 0.2 ft/sec. The estimated gas exit velocity may be higher if the increasing hydrostatic pressure in the U-tube inhibits the flow of gas through the lower portion of the 30-foot sections of aeration hose.

Testing of alternative sparger designs resumed on July 30, 2008. The factor being evaluated was the gas supply pressure at the sparger. The high pressure of the gas supply line (45 psi) was thought to be limiting the formation of small bubbles. The pressure regulator was reduced to 35 psi. Unfortunately, this reduced the gas delivery rate to a maximum of about 2,400 scf/hr through the original 10-hole sparger, allowing a maximum gas ratio of about 3% with full water flow of 23 cfs. This reduced gas delivery was likely caused by increased head losses along the approximately 100 feet of supply line (¾-inch inside diameter) between the pressure regulator and the U-tubes. Testing of the aeration hose and open-ended pipe sparger was possible at a 4% gas/water ratio. One aeration hose test at a 0.5% gas ratio with the aeration hose indicated a very high efficiency.

Testing with a reduced gas supply pressure was conducted again on September 22 and 25, 2008. Both gas supply lines were connected to a single sparger. This allowed a higher gas ratio to be delivered at a reduced pressure. Additional testing of the aeration hose and the open-ended pipe sparger was conducted at 1% to 6% gas/water ratios. Transfer efficiencies were compared at the original pressure of 45 psi and reduced pressures of between 25 and 35 psi.

Testing Results

Table 1 summarizes the Aeration Facility efficiency testing measurements and results. Measurements in U-tube B on May 22, 2008 were made to verify the initial efficiency testing of the Aeration Facility with the 10-hole sparger. The water flow in U-tube B with just one pump was about 25 cfs. A 4% gas/water ratio with a water flow of 25 cfs gave an outlet DO of 37 mg/l. The inlet DO was about 7 mg/l, the DO increment was 30 mg/l, and the daily DO delivery would be about 4,050lb/day (i.e., 5.4 x 30 mg/l x 25 cfs) for one U-tube operating. The gas supply rate was 3,580 scf/hr, and the DO supply rate would be about 7,160 lb/day (i.e., 2 x gas supply of 3,580 scf/hr). The calculated efficiency of U-tube B was about 56% (i.e., 4,050/7,160). The original testing for the 4% gas/water ratio gave efficiencies of 60% and 62%. The efficiency on May 22 may have been reduced slightly by the higher water flow (25 cfs rather than 22.5 cfs) with a shorter travel time (36 seconds rather than 40 seconds) in the U-tube.

A second test on May 22 was done with a reduced gas supply of 3% (2,440 scf/hr) and a water flow of 25 cfs. The DO increment was reduced to about 25 mg/l, so the daily capacity was about 3,401 lb/day for one U-tube operating, but the efficiency increased to about 70%. The initial testing for 3% gas ratio was about 65%. Because the measurements for the water flow, gas flow, and DO increment (outlet minus inlet) are relatively rough (single point visual measurements with one DO titration for each test), the calculated efficiency and delivery capacity cannot be more accurate than plus or minus 2–3%. The reason(s) for the increased gas transfer efficiency with the 3% gas ratio is not understood; it may be the lower gas exit velocity or the smaller number of bubbles that might have reduced the amount of coalescence (bubbles combining into larger bubbles).

Testing on May 28, 2008 was made with a variety of spargers. The 40-hole sparger efficiency at a 4% gas supply ratio was only about 43%. This is much lower than for the original 10-hole sparger. The 160-hole sparger at 4% gas flow had an efficiency of about 48%. The efficiency of both spargers decreased by about 5% at the higher gas supply rates of about 6% of the water flow.

Testing on July 7, 2008 was made to test the Colorite Aeration Tubing (aeration hose sparger). A total of 120 feet of aeration hose was attached to the sparger (in four 30-foot sections). The test results suggest that the transfer efficiency was not much different from the drilled-hole spargers. This test result suggests that the exit velocity of the gas into the water is not likely a strong factor in bubble size formation. The aeration hose efficiency with a 3% gas/water ratio was 65%.

The efficiency dropped with higher gas/water ratios of 4%, 5%, and 6%, to 60%, 56%, and 52% respectively. The only logical explanation for the reduced efficiency with higher gas/water supply ratio is that bubble coalescence increases with a higher ratio, forming larger bubbles as more bubbles are produced initially with the higher gas supply rate. Water travel time and pressure in the U-tube would be identical for these various gas supply ratios.

Additional testing was performed on July 30, 2008 with a reduced gas pressure of 35 psi (original pressure was 45 psi). At a gas supply pressure of 35 psi, there was not sufficient gas flow from the vaporizers to deliver a 4% gas/water ratio using the 10-hole sparger (assuming full water flow of 23 cfs). To achieve a 4% ratio through U-tube B, the water flow was reduced by partially closing the overhead valve immediately downstream of the U-tube. The lower water flow would allow a longer travel time in the U-tube and was expected to increase the efficiency. The test results were nearly the same as for the higher supply pressure of 45 psi. Comparing the 3% gas/water supply ratios, the original 10-hole sparger gave an efficiency of 75%, the open-ended pipe gave an efficiency of 72%, and the aeration hose gave an efficiency of 70%. These values are slightly higher than the 3% gas/water ratio efficiencies of 65%–68% for spargers and aeration hose with the full pressure of 45 psi.

A final series of U-tube efficiency and capacity tests was made on September 22 and 25, 2008. Comparisons of the open-ended pipe sparger and the aeration hose with gas/water ratios of 1% to 4% were made. Figure 1 shows the YSI and modified Winkler DO measurements made during the September 22, 2008 tests. This provides a good example of the variations in the test DO measurements. The open-ended pipe sparger and the aeration hose efficiency tests yielded nearly the same results.

Figure 2 shows the test results for the aeration hose. Figure 3 shows the results from the open-ended pipe sparger. The measured efficiency at 4% gas/water ratio was 66% at 45 psi and 67% at 35 psi for the pipe sparger. The measured efficiency for the aeration hose with a 4% gas/water ratio was 61% at 45 psi and 70% at 35 psi. These values might be averaged to estimate an efficiency of about 65% for a 4% gas/water ratio. The efficiency for both the open pipe and the aeration hose increased to between 65% and 73%, with an average of about 70% for a 3% gas/water ratio. The efficiency was increased to about 80% with a 2% gas/water ratio and was 100% with a 1% gas/water supply ratio. The aeration hose was tested at higher gas/water ratios of 5% and 6%. The efficiencies were reduced to about 55% and 50% respectively. These results suggest that the gas/water supply ratio is the only major factor controlling the U-tube efficiency at maximum water flow rates of 25 cfs for one tube and 45 cfs for both tubes operating.

Comparison with the Original Design

The design DO delivery capacity for the Aeration Facility was 10,000 lb/day. The design flow was 50 cfs, and the assumed gas transfer efficiency was about 80%. This would provide a DO increment of about 40 mg/l for a 4% gas/water supply ratio because a 1% gas/water ratio will increase the DO concentration by 13 mg/l if the efficiency is 100%. The daily DO delivery to the DWSC can be calculated as:

DO Delivery (lb/day) = 5.4 x Flow (cfs) x DO increment (mg/l)

The actual measured DO delivery capacity was reduced because the maximum flow was 45 cfs, and the measured DO increment was about 35 mg/l for a gas/water ratio of 4%. The maximum daily DO delivery capacity under these operating conditions would be about 8,500 lb/day.

Capacity and Efficiency of the Aeration Facility

The general results of the Aeration Facility testing indicate that regardless of the sparger design (open-ended pipe, small holes in pipe, or aeration hose) the efficiency of the gas transfer (i.e., dissolution) appears to decline with higher gas/water ratios. The overall performance of the facility can be summarized by the increment of DO in the outlet pipe carrying the oxygenated water to the DWSC. To achieve the design capacity of about 10,000 lb/day with the maximum water flow of 45 cfs, the DO increment would need to be about 41 mg/l. However, this DO increment was achieved in only a few tests with the gas/water ratio increased to about 6%. The gas transfer efficiency at a 6% gas/water ratio was only about 50%. This gas/water ratio is approaching the point of maximum capacity, because increasing the gas flow reduces the efficiency, and the DO increment does not increase substantially.

Table 2 summarizes the measured performance of the DWR Aeration Facility for one U-tube operating (25 cfs) and for both U-tubes operating (45 cfs). The capacity will increase with increasing gas/water ratio, from about 1,750 lb/day for a single U-tube with 1% gas/water ratio, to about 5,250 lb/day for one U-tube with a 6% ratio. The DO delivery capacity for operation of both U-tubes increases from about 3,159 lb/day with a 1% gas/water ratio to about 9,500 lb/day with a 6% gas/water ratio. However, because the gas transfer efficiency declines as the gas/water ratio increases, it normally will be more cost effective to operate both U-tubes at the lowest possible gas/water ratio.

Recommendations

The objective for changes in the gas sparger design was to create smaller, finer bubbles and reduce bubble coalescence. Without the ability to visually track and measure bubble size and coalescence in the U-tubes, it was not possible to determine whether the sparger changes produced smaller bubbles or reduced bubble coalescence. It is therefore recommended that a camera and/or a viewing window be installed so that these processes can be observed directly. If it is determined that the bubbles are coalescing , a possible approach for improving efficiency would be to install a screen baffle immediately downstream of the oxygen injection site to break up the larger bubbles . This would be similar to the screen that is used to aerate water from a faucet.

The DWR Aeration facility should only be operated at full design capacity of 10,000 lbs/day if the DWSC DO deficit is greater than 10,000 lbs/day, because the gas transfer efficiency would be only 50%.The DWR Aeration Facility should be operated at the lowest possible (most efficient) gas/water ratio that will supply the needed DWSC DO delivery target (lb/day).

The recommended strategy for the second year of operation for the pilot demonstration of the Aeration Facility is to forecast the needed supplemental DO supply (i.e. estimated DO deficit), and operate the Aeration Facility continuously during the summer and fall DO deficit period to formulate and evaluate the most effective forecasting procedures and operation strategies.

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Table 1. Measurements and Results of Testing of the DWR Aeration Facility in the DWSC during 2008

Date	Sparger	U-Tube	Water Flow (cfs)	Gas Pressure (psi)	Gas Flow (scf/hr)	Gas Supply (lb-O2/day)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O2/day)	Efficiency (%)
13-Mar-08	10-hole	A	23	45	3,230	6,460	3.9	9.0	41.0	32.0	3,992	62
13-Mar-08	10-hole	B	22	45	3,270	6,540	4.1	9.0	43.0	34.0	4,113	63
13-Mar-08	10-hole	A	23	45	2,450	4,900	2.9	9.0	35.0	26.0	3,243	66
13-Mar-08	10-hole	B	22	45	2,440	4,880	3.0	9.0	35.0	26.0	3,145	64
13-Mar-08	10-hole	A	23	45	1,620	3,240	1.9	9.0	27.5	18.5	2,308	71
13-Mar-08	10-hole	B	22	45	1,540	3,080	1.9	9.0	27.0	18.0	2,177	71
13-Mar-08	10-hole	A	23	45	3,400	6,800	4.1	9.0	41.0	32.0	3,992	59
13-Mar-08	10-hole	B	22	45	3,400	6,800	4.2	9.0	43.0	34.0	4,113	60
13-Mar-08	10-hole	A	18	45	3,740	7,480	5.8	9.0	51.0	42.0	4,082	55
13-Mar-08	10-hole	B	17	45	3,770	7,540	6.1	9.0	51.0	42.0	3,924	52
13-Mar-08	10-hole	A	12	45	2,210	4,420	5.2	9.0	29.0	20.0	1,274	29
13-Mar-08	10-hole	B	11	45	2,560	5,120	6.2	9.0	37.0	28.0	1,724	34
18-Mar-08	10-hole	A	23	45	3,400	6,800	4.2	9.1	45.5	36.4	4,423	65
22-May-08	10-hole	B	25	45	3,580	7,160	4.0	7.0	37.0	30.0	4,050	56
22-May-08	10-hole	B	25	45	2,440	4,880	2.7	7.0	32.5	25.5	3,401	70
28-May-08	10-hole	B	26	45	3,730	7,460	4.1	7.0	35.0	28.0	3,856	52
30-Jul-08	10-hole	B	23	35	2,315	4,630	2.8	8.7	36.8	28.1	3,490	75
30-Jul-08	10-hole	B	17	35	2,300	4,600	3.9	8.7	43.0	34.3	3,056	66
28-May-08	40-hole	B	25	45	5,660	11,320	6.3	7.0	40.0	33.0	4,473	40
28-May-08	40-hole	B	25	45	3,600	7,200	4.0	7.0	30.0	23.0	3,130	43

Table 1. Continued

Date	Sparger	U-Tube	Water Flow (cfs)	Gas Pressure (psi)	Gas Flow (scf/hr)	Gas Supply (lb-O2/day)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O2/day)	Efficiency (%)
28-May-08	160-hole	B	26	45	3,750	7,500	4.1	7.0	33.0	26.0	3,580	48
28-May-08	160-hole	B	25	45	5,400	10,800	5.9	7.0	33.0	26.0	3,552	33
7-Jul-08	Hose	B	23	45	2,480	4,960	3.0	6.0	32.1	26.1	3,242	65
7-Jul-08	Hose	B	23	45	3,300	6,600	4.0	6.0	38.5	32.5	4,037	61
7-Jul-08	Hose	B	23	45	5,470	10,940	6.6	6.0	50.3	44.3	5,502	50
7-Jul-08	Hose	B	23	45	3,770	7,540	4.6	6.0	41.0	35.0	4,347	58
7-Jul-08	Hose	B	23	45	4,970	9,940	6.0	6.0	47.9	41.9	5,204	52
7-Jul-08	Hose	B	23	45	4,140	8,280	5.0	6.0	43.1	37.1	4,608	56
30-Jul-08	Hose	B	23	35	2,500	5,000	3.0	8.4	37.0	28.6	3,552	71
30-Jul-08	Hose	B	18	35	2,450	4,900	3.9	8.0	41.0	33.0	3,119	64
30-Jul-08	Hose	B	23	35	500	1,000	0.6	8.2	16.0	7.8	969	97
22-Sep-08	Hose	A	23	34	3,340	6,680	4.0	7.9	45.5	37.6	4,670	70
22-Sep-08	Hose	A	23	30	2,480	4,960	3.0	7.9	37.2	29.3	3,639	73
22-Sep-08	Hose	A	23	27	1,650	3,300	2.0	7.9	30.2	22.3	2,770	84
22-Sep-08	Hose	A	23	25	820	1,640	1.0	7.7	21.8	14.1	1,751	107
30-Jul-08	Open pipe	A	23	35	2,500	5,000	3.0	8.4	36.0	27.6	3,428	69
30-Jul-08	Open Pipe	A	18	35	2,450	4,900	3.9	8.0	41.0	33.0	3,119	64
22-Sep-08	Open Pipe	A	23	30	3,340	6,680	4.0	7.9	45.7	37.8	4,695	70
22-Sep-08	Open Pipe	A	23	30	2,480	4,960	3.0	7.9	38.0	30.1	3,738	75
22-Sep-08	Open Pipe	A	23	35	3,340	6,680	4.0	7.9	44.6	36.7	4,558	68
22-Sep-08	Open Pipe	A	23	28	3,340	6,680	4.0	7.7	43.4	35.7	4,434	66
22-Sep-08	Open Pipe	A	23	28	2,480	4,960	3.0	7.7	37.0	29.3	3,639	73

Table 1. Continued

Date	Sparger	U-Tube	Water Flow (cfs)	Gas Pressure (psi)	Gas Flow (scf/hr)	Gas Supply (lb-O2/day)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O2/day)	Efficiency (%)
25-Sep-08	Open Pipe	A	23	28	1,656	3,312	2.0	9.4	31.6	22.2	2,760	83
25-Sep-08	Open Pipe	A	23	28	828	1,656	1.0	9.4	22.7	13.3	1,654	100
25-Sep-08	Open Pipe	A	23	45	3,312	6,624	4.0	9.3	45.1	35.8	4,441	67
25-Sep-08	Open Pipe	A	23	45	2,484	4,968	3.0	9.3	37.8	28.5	3,542	71
25-Sep-08	Open Pipe	A	23	45	1,656	3,312	2.0	9.2	31.6	22.4	2,785	84
25-Sep-08	Open Pipe	A	23	45	828	1,656	1.0	9.1	23.2	14.1	1,752	106

Table 2. DWR Aeration Facility DO Increment, Efficiency, and DO Delivery Capacity for a Range of Operations

	Water Flow (cfs)	1% gas/water ratio	2% gas/water ratio	3% gas/water ratio	4% gas/water ratio	5% gas/water ratio	6% gas/water ratio
DO Increment (mg/l)		13	22	29	34	36	39
Efficiency		100%	85%	75%	65%	55%	50%
Delivery with 1 U-tube (lb O2/day)	25	1,755	2,970	3,915	4,590	4,860	5,265
Delivery with 2 U-tubes (lb O2/day)	45	3,159	5,346	7,047	8,262	8,748	9,477

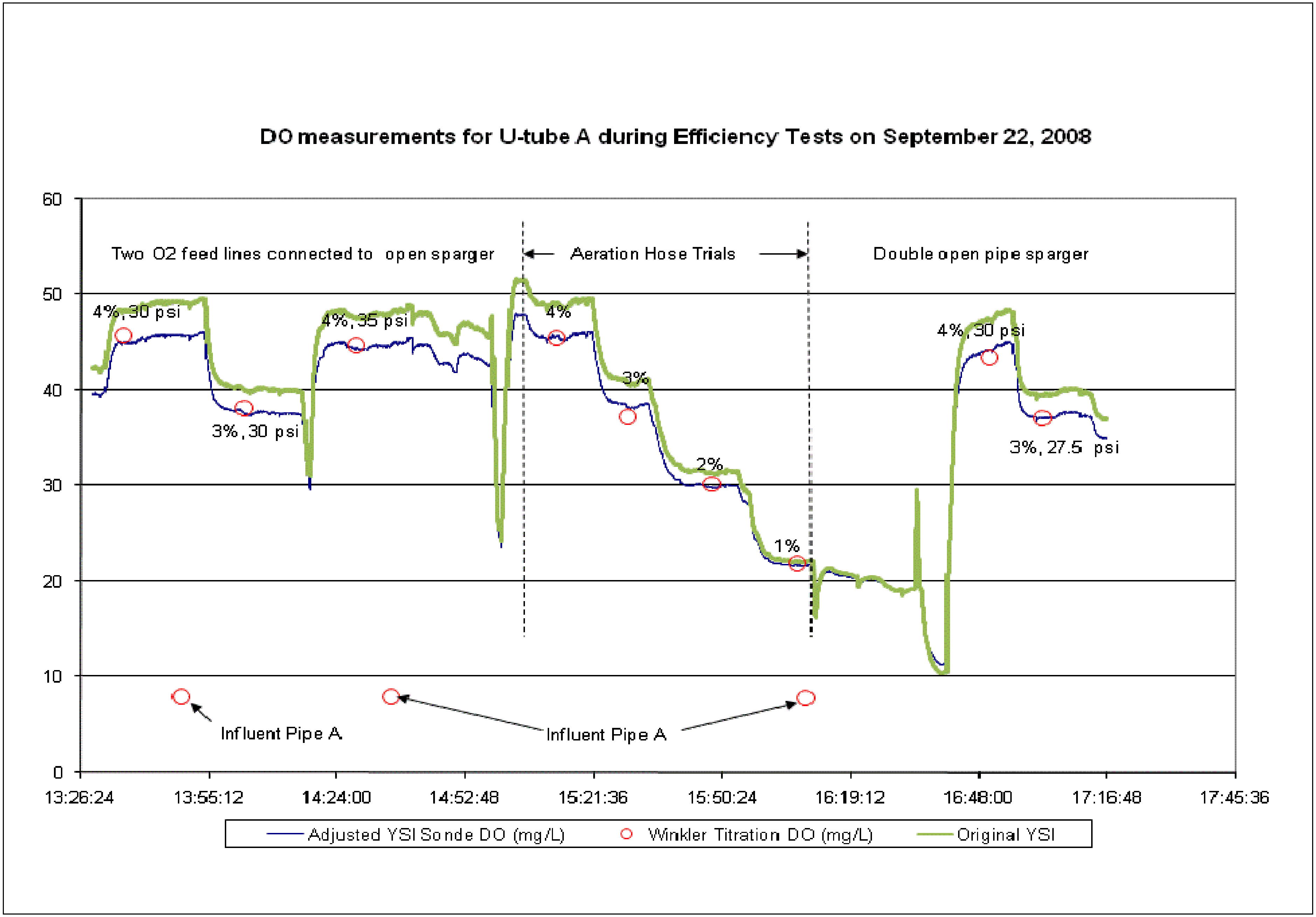

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Figure 1

Modified Winkler and YSI Probe Dissolved Oxygen Measurements in the Inlet and Outlet of U-Tube A on September 22, 2008

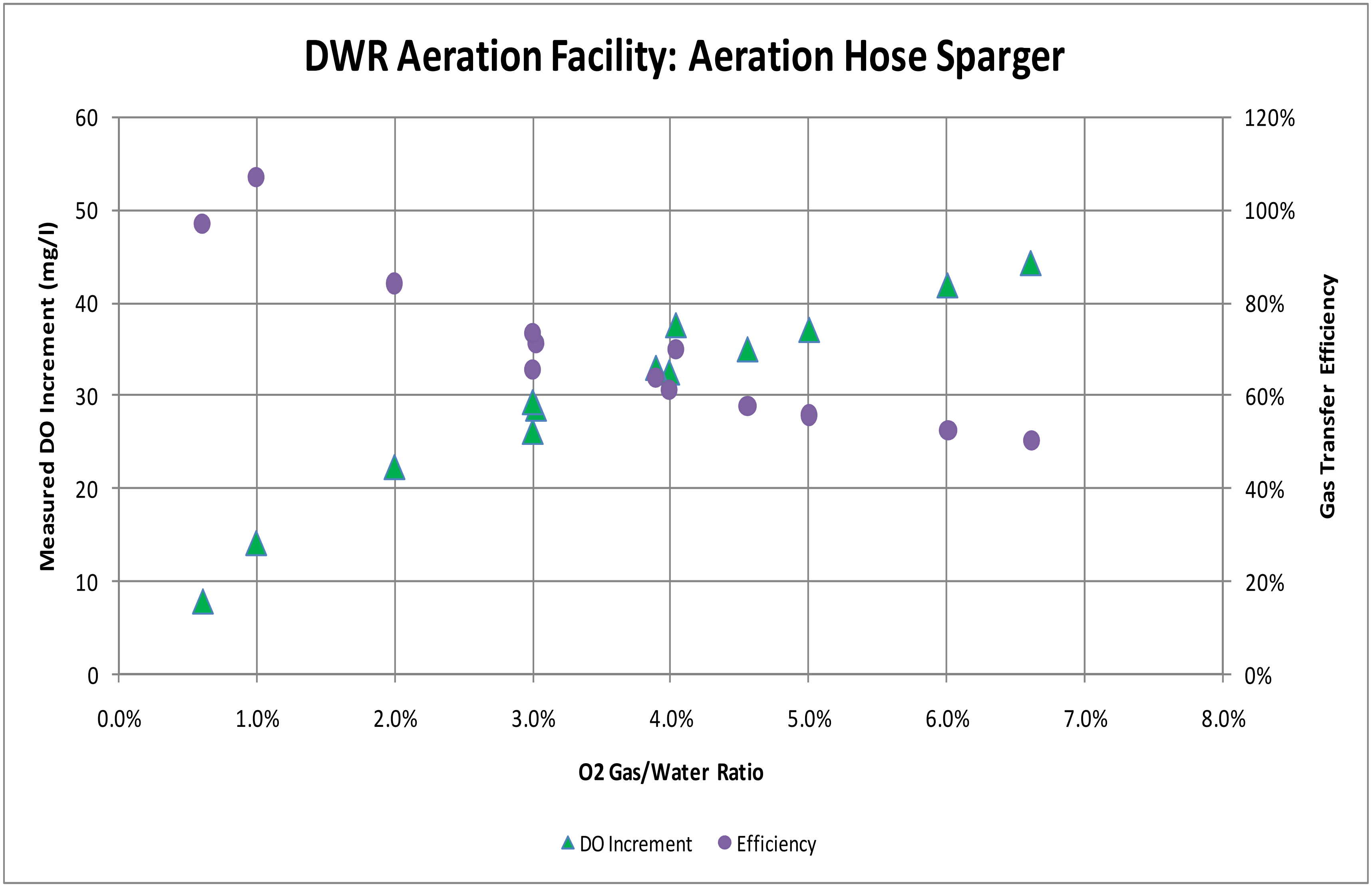

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Figure 2

Measurements of U-Tube DO Increments and Efficiencies for the Aeration Hose Sparger with a Range of Oxygen Gas/Water Ratios

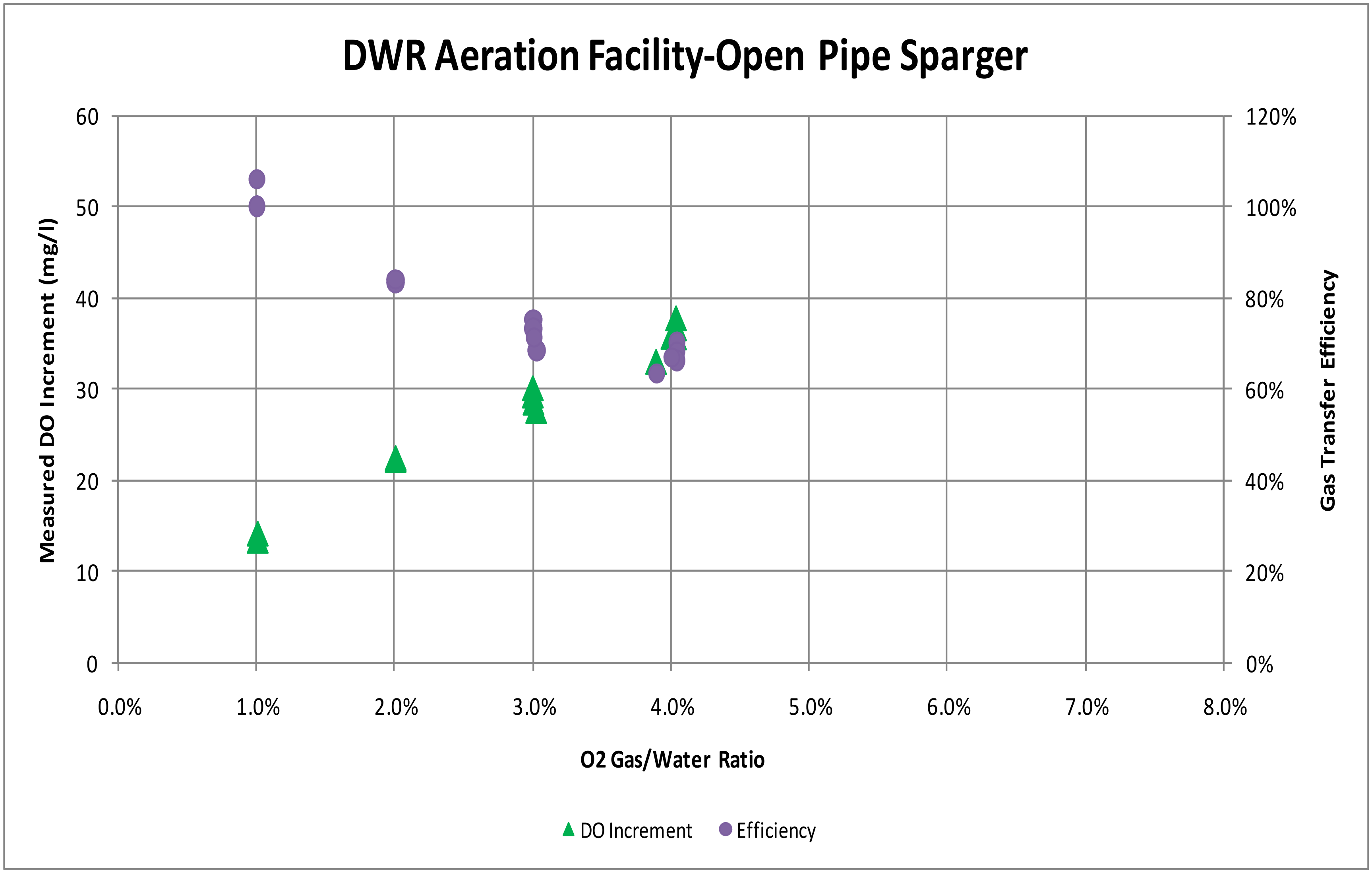

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Figure 3

Measurements of U-tube DO Increments and Efficiencies for the Open Pipe Sparger with a Range of Oxygen Gas/Water Ratios